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JANUARY 7, 1980

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MASTER

BATES SOLAR INDUSTRIAL PROCESS-STEAM APPLICATION

PRELIMINARY DESIGN REVIEW

**DOE CONTRACT NO.
DE-FC03-79CS30312
(UNCLASSIFIED)**

BATES

**SUBMITTED TO: UNITED STATES
DEPARTMENT OF ENERGY/SAN**

**BY: BATES CONTAINER, INC.
6433 DAVIS BLVD.
FORT WORTH, TEXAS 76180**

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January 8, 1980

U.S. Department of Energy
San Francisco Operations Office
1333 Broadway
Oakland, CA 94612

DOE/CS/30312--T3

DE82 007179

ATTENTION: Janet M. Neville

REFERENCE: Contract No. DE-FC03-79CS30312

ENCLOSURE: Bates Solar Industrial Process-Heat Application:
Preliminary Design Review, January 7, 1980

Gentlemen:

Bates Container, Inc. is pleased to submit the enclosed copies of the preliminary design review for your review and comment. Bates and its subcontractor, The BDM Corporation, will be prepared to review the design and respond to your questions during the briefing scheduled for January 22 in Oakland.

Additional distribution of this report is being made according to your instructions. If you require any additional information, please feel free to contact me.

Sincerely,

Bates Container, Inc.

for Warren H. Bates
Chairman of the Board

WHB/lp

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CHAPTER I

EXECUTIVE SUMMARY

A. PROGRAM OVERVIEW

Bates Container, Inc. (BCI) and its prime subcontractor, the BDM Corporation, have completed the Preliminary Design Report (PDR) for Phase One of the Bates Solar Industrial Process Heat (SIPH) Project. This project is part of the Cycle IV SIPH Program under the auspices of the Department of Energy, San Francisco Operations Office in the Agricultural and Industrial Process Heat Division. Bates sees its role in the application of SIPH in its Ft. Worth plant as an integral part of the DOE national effort for the industrialization and commercialization of solar energy systems. The specific objectives of this project are shown in figure I-1.

1. Apply available technology in large scale solar systems for industry to lessen significantly fossil fuel consumption.
2. Advance the technology through past experience to produce innovative concepts.
3. Demonstrate the competitiveness of above-ground installations.

Figure I-1. Bates Solar Industrial Process Heat Objectives

To meet these objectives, BCI is retrofitting its container plant in Ft. Worth for solar generation of process steam. In the design, Bates has incorporated a team approach with The BDM Corporation which has a record of successful and innovative solar projects. Along with BCI's extensive experience in the container industry, a successful integration of industrial and solar technology has resulted.

B. APPLICATION DESCRIPTION

1. Application and Rationale

Bates Container, Inc. (BCI) is a rapidly growing organization involved in the production of cardboard containers. The current Bates facility shown in figure I-2 is located between Dallas and Ft. Worth. BCI is expanding its facilities to include a cardboard corrugation fabrication facility to supply stock for the manufacture of containers. Currently the raw stock is purchased from outside suppliers. The bids

I-2

Figure I-2. Aerial View of Bates Container, Incorporated Plant

for the construction of the corrugation facility have recently been released and the corrugator machine has been purchased and transported for storage at the Bates facility. The factory will be constructed and in operation in late 1980.

The Bates operation is an outstanding choice for retrofitting of SIPH production for several reasons, as shown in figure I-3. First, the location at Ft. Worth, Texas places the corrugation facility within the Sunbelt and provides a very high level of direct normal solar radiation. Second, the positive match-up between the industrial demand and the available solar energy and the area is ideal for solar power applications. Also, positive correlation between energy demand and solar availability has eliminated the requirement for thermal energy storage in conjunction with the solar system. Most importantly, as a process steam application, the facility represents a very large potential market for solar industrial process steam applications. For example, in the Ft. Worth area there are nearly twenty corrugator facilities and numerous other industries requiring approximately 380°F steam. These can be served by the solar system that has been designed which should be considered as a 380°F steam nozzle rather than as part of a corrugator assembly. Because of the location in an industrialized area, the demonstration of the technical and economic viability of this SIPH application will directly support the commercialization of solar thermal energy systems in the industrial sector. Specifically, a successful demonstration will spur solar development in the rapidly growing and highly visible Dallas-Ft. Worth region. Additionally, BCI recognizes the impact of future cost increases in fossil fuels and potential nonavailability of conventional gas and some fuel oils and strongly supports the development of alternative fuel options. BCI intends to cost share to the maximum extent possible for a small business.

One of the problems facing many industrial solar applications is land availability at reasonable costs, since desirable industrial locations are usually located on land valued up to several dollars per square foot. The Bates application affords an opportunity to address this key hurdle to more rapid solar expansion with an above-ground structure over an existing building. The design team has originated a concept for an above-ground mounted collector system which is proving extremely competitive with ground mounted systems in industrial areas. Even in the PDR stage where design constraints and costs are conservatively set high, the roof mounted array for Bates is showing a cost advantage over ground mounted alternatives because of land costs. The competitive cost comparison is especially exciting as it expands the possibilities for retrofits in applications where land is simply not available at any cost, a situation true of many industrial applications. The easy application of the present design concept to new construction where the collector support structure can also be an integral part of the roof ceiling construction promises to open up to solar many new cost effec-

tive above-ground applications.

Furthermore, as data and performance evaluations begin to become available from various DOE cycles, Cycle IV is the first set of applications that may be fully able to take advantage of past experience. The choice of an experienced design team allows full use of past results to generate innovative designs.

1. Sunbelt location.
2. Excellent solar energy/process demand correlation.
3. Nationally visible location at center of large rapidly developing industrial area/Dallas-Ft. Worth.
4. Commonly required steam conditions (200 psi).
5. Demonstrates competitiveness of roof-mounted structures necessary for industrial solar proliferation.

Figure I-3. Bates Ft. Worth Location Advantages

2. Corrugator Facility Description and Load

The expansion of the existing BCI plant to house the corrugator and associated raw and finished stock involves construction of a large structure of about 80,000 square feet directly south of the existing plant as shown in the plot plan, figure I-4. The corrugator is a large serial machine of over 300 feet in length that operates with large quantities of moderate pressure (200 psi) steam. It is in conjunction with this machine that a SIPH retrofit application is proposed. Although the building and machinery for the addition have not been completed at the time of this writing, it is expected that operations will begin in late 1980.

Figure I-5 shows a layout of components on the Langston corrugator. The corrugation line is approximately 305 feet long, 75 feet wide and about 20 feet high, therefore requiring a separate building from the existing warehouse and production facility. It is essentially an entire factory composed of over 60 steam vessels, steam separators, steam lines and condensate lines supplying heat for the process. During normal operation up to five rolls of kraft paper of varying widths, depending on the weight and width of board to be produced, feed simultaneously into different points in the line to produce double faced board, which will account for about 90% of the production. Double face board is the

Figure I-4. Plot Plan - Bates Container, Inc., Fort Worth, Texas

THE LANGSTON CORRUGATED MANUFACTURING SYSTEM... with INSTANT ORDER CHANGE

The LANGSTON CORRUGATED MANUFACTURING SYSTEM with INSTANT ORDER CHANGE offers immediate and long-range profitability. It is a system designed for optimum performance now — by eliminating order change slowdowns, minimizing waste, and providing ease of operation through automatic setups — and in the future — through adaptability to developing technology. In addition, Langston offers, as it has traditionally, full service capability and total after-service responsibility. Just another way that Langston, the only single source corrugator manufacturer, provides machinery not only for today, but also for tomorrow — with a wealth of yesterday's experience.

Double Faces

- WABF TRU, minimizes wastage through automatic temperature regulation
- Large volume steam chests provide for proper curing
- No speed reduction for order changes — minimizes scrap
- Variable roller weight control for light or heavy board bonding
- Automatic bore lift eliminates stem head board when machine stops

Hi Speed Rotary Shear

- Enables instant order change by cutting web at the proper time

- Makes single cut at 650 feet per minute (178 m/min)
- Upper knife is motor driven, lower knife is fixed
- Automatic spike removal capability available

Web Diverter/Director (Jaw Shear)

- Diverts web to either level of shiver scores
- Lateral support and direct web
- Simple, fast release for mechanics

Automatic Shiver Scorer

- Dual paper line results in no stop — no slowdown of machine speed
- Programmable set up
- Capable of up to 10 order changes per hour
- Expandable shafts for positive head lock up
- Completely automatic and highly versatile — Langston exclusive
- Run or load down to meet specific needs — a Langston exclusive

Web Diverter/Director (No Cutoff)

- Diverts and shivers web from either cutoff station from either shiver in one station
- Simple, fast release mechanism
- Programmable set up for continuous run

Direct Drive Cutoff

- Instantaneous response to order change — within a single revolution of the knife cylinder
- • 0.010 in. (- 0.002 mm) achievable cutting accuracy
- 100 horsepower dc motor drives each knife cylinder
- Each knife cylinder independently controlled and programmed
- Hardened precision ground spur gears
- Easy backlash adjustment on all gear sets
- Pressurized forced lubrication system ensures longer bearing and gear life

Sheet Delivery

- Automatic sheet delivery eliminates bottlenecks of manual take off
- Available as single, double or triple units
- Handles sheets from 22 in. to 300 in. (559 mm to 7620 mm) in length

- Solid state logic control provides for automated operation

Full Service Capability

- Highly trained field service force
- Around the Clock Parts Service
- Factory & After Market Installations
- Pre-Installation Planning & Consultation

Total After Sale Support

- Longest Continued Training Service
- In Plant Crew Training

• gile

- Comprehensive Operation and Maintenance Manual
- Thorough Parts Catalogs
- Environmental Service Bulletin

Let your Langston sales engineer show you how the present INSTANT ORDER CHANGE SYSTEM opens the gateway to the future.

Langston
A MEMBER OF THE MILLER GROUP

Figure I-5. Langston Corrugator

familiar single layer of corrugated fluting faced on both sides with paper. Steam at 370°F, 175 psi, is used in the forming and glueing process and to plasticize the kraft paper for fluting. Heat is also necessary for the starch gelling, glueing and drying processes so that an instant bond is achieved. Finished and intermediate products at different points in the line are conveyed by rollers above the machine. The drying, trimming, cutting, and forming machinery are at the end of the line.

The conventional energy system consists of a fossil-fired steam generator sized at 350 boiler horsepower, producing a peak of 12,000 pounds of steam per hour at the required conditions. This is sized to satisfy the peak steam requirement for heavy duty board construction. The boiler is a package unit fitted for dual fuel firing.

The corrugation plant is scheduled to operate on a 7 day week with about 8 hours of operation per day to match solar system production. At present, about 800,000 square feet of cardboard are processed per day into boxes. This translates to an hourly average of about 5500 pounds of steam, requiring about 5.5×10^6 Btu's per hour input to the system. On some occasions higher steam loads will be required for extra weight cardboard processing. Cardboard processing rates are relatively constant throughout each day and for all days in a year. Heat requirements are, therefore, fairly constant throughout the year. About 60% of the steam produced and supplied to the corrugation machine is consumed during the process. The remaining 40% is returned as liquid at one atmosphere to the condensate tanks where water makeup is provided. This fluid is then recirculated through a feedwater pump to the boiler.

C. SOLAR SYSTEM DESCRIPTION

The combined corrugator-SIPH system is shown in the overall system schematic, figure I-6. The solar system will satisfy the average daily demand and will operate in parallel with the fossil boiler which will provide supplementary steam when necessary.

The solar energy system uses linear parabolic trough (LPT) concentrators to provide thermal energy to a nonfired steam generating unit to produce the requisite steam for the corrugator. The baseline LPT is the T-700, fabricated by Solar Kinetics, Inc., of Dallas, Texas, with a 7-foot aperture. The collector array will be mounted on the roof of the corrugation facility because it has proved to be the most cost effective approach to the current application. The design incorporates a total of 34,720 square feet of aperture. With the available insolation in the Dallas/Ft. Worth area, this size array will produce the requisite 5500 to 6000 pounds of steam. Additional collectors would result in wasted energy or require quantities of thermal energy storage since typical demand of the corrugation machine is matched. At this time, storage is

Figure I-6. Schematic of Solar Industrial Process Steam System

not deemed cost effective. If, in the future, the steam demand is increased, there is sufficient roof area on the older Bates facilities to retrofit and expand the solar system and to install thermal energy storage. However, it was not considered appropriate for this application at the current production levels, nor was it considered appropriate to propose oversized systems requiring large quantities of thermal energy storage in response to the PON.

The schematic of the solar energy system in figure I-6 shows that the solar collectors operate with an outlet temperature of approximately 500°F which is controlled by thermally actuated valves located at the end of each collector row. There are 31 rows each 160 feet in length. The thermal working fluid selected is Therminol-55, which is transported through the fluid/heat transport subsystem to the nonfired steam generator located in the mechanical room within the building. The Therminol-55 approaches the steam generator with a temperature of 500°F and returns to the collector system at a temperature of about 390°F. The nonfired steam generator operates in parallel with a dual fuel fossil boiler. Steam is released into a steam manifold and supplied to the corrugator unit. A control valve mixes the steam from the solar system with that provided by the conventional fossil boiler unit when the system is operating in an augmentary mode. For most clear working days a stand alone solar operation is sufficient for two hours around solar noon.

The controls of the solar system are hard wired such that its operation is for the most part completely automated. A data acquisition system is included and will utilize the same transducers that are used for control purposes with appropriate signal isolation. The data acquisition system provides for storage of the data as well as real time data display reduction and analysis. The philosophy behind the instrumentation and data acquisition system design is that after completion of Phase III in the program, the data acquisition system may be removed and the solar system will continue to operate as designed.

D. SYSTEM PRELIMINARY FINDINGS AND SYSTEM PERFORMANCE PROJECTION

The most important conclusion of the preliminary design task is that the roof mounted system can be implemented cost-competitively with a ground based system. The key factors contributing to this are the innovative integral collector/structure design and the high cost of land adjacent to the Bates Container Plant at \$2 to \$3 per square foot, which is typical for industrial/commercial property. Figure I-7 compares the preliminary capital costs of three collector mounting alternatives for the Bates Solar Industrial Process Heat array. Configuration A represents the completely roof-mounted structure that has evolved after substantial trade-offs and design refinements which are fully documented in section III-C of this report. Option B is a mounting scheme with one-half the array above a parking and loading area that is necessary

I-10

		CONFIGURATION		
	ROOF STRUCTURE INTEGRAL OPTION (A)	PARKING LOT ROOF (1/2) GROUND MOUNTED (1/2) OPTION (B)B		GROUND MOUNTED OPTION (C)
		PARKING LOT	GROUND	
JOISTS	\$101,000	\$ 50,500	0	0
COLUMNS	90,000	59,400	0	0
PIERS	12,000	8,000	0	0
ROOFING	0	98,000	0	0
LAND	0	0	77,000	153,000
SITE PREP	0	0	38,000	75,000
COLLECTOR	775,000	388,600	437,000	874,000
BALANCE OF SYSTEM	<u>268,000</u>	<u>780,000</u>	<u>7,000</u>	<u>231,000</u>
TOTAL	1,250,000	1,440,000		1,333,000

Figure I-7. System Capital Cost Trade-off Analysis

for the Bates facility, with the balance ground mounted on presently vacant land adjacent to the plant. Option C is a completely ground mounted facility which would require acquisition of additional adjacent land for sufficient area to contain the collectors. As the preliminary capital cost figures indicate, the roof-mounted integral structure is slightly (about 10%) less expensive and clearly competitive. This is primarily because of the high land cost and the elimination of the collector pylon and ground pier costs. The innovative mounting design for the roof uses the joist support members to support the collectors directly without the use of pylons as shown in figure I-8. It is clear that in a non-retrofit situation the lower part of the support structure could be the superstructure for a roof and ceiling so that a substantial offset in collector mounting costs could be realized by the cost sharing with a roof frame. Another advantage of a roof-mounted structure is that its costs are a depreciable quantity.

A philosophy of using tested and proven components has been adhered to throughout all design stages to ensure a cost effective and minimum risk system for construction in the near term (approximately one year). Several key areas have called for innovative and deeper analysis. These are: one, the roof-mounted structure; two, selection of the optimal heat transfer subsystem pipe and insulation sizing; and projections of system performance. In the first area of a roof-mounted structure Bates believes that an innovative and economical foundation design has been introduced to meet the stringent requirements of the Ft. Worth building code, representative of most codes in the sunbelt, relative to wind structural survival conditions of 25 psf (100 miles per hour). A further constraint of structural independence from the existing building has been met.

A sketch of the structure used to support the collectors is shown in figure I-8. Two key features of the design are that the collector is an integral part of the joist structure, thus lessening substantially the moment loads resulting from an above structure mounting scheme; and that the collector rows follow the slight one in twelve slope on the roof. As a result of extensive and continuing tradeoff studies, the arrangement and sizing of the joist components is being optimized. It is believed that further gains will be recognized from the results of a cost tradeoff of longer joist spans and heavier columns to support the mounting structure. Final costs in the range of \$5-6 per square foot of aperture for structure costs compared to \$6 and more for a ground-mounted system after adding in pylon and pier costs should result for the integral sloped concept. It should be noted that a study of the incident angle losses of the sloped mounting shows negligible effect.

In the heat transfer subsystem a very interesting tradeoff is nearly finished. It involves the concept that smaller pipe diameters engender greater pumping losses but suffer smaller heat losses. Since

Figure I-8 Design Concept for Bates Above-Ground Structure

both are energy costs, there must exist for given flow rates and temperature conditions, an optimal size pipe, type, and thickness of insulation. Furthermore, the sensitivity of this optimum to differing energy escalation scenarios will have an effect. The optimal results for each set of factors can be used to size and design a least cost piping array. These considerations are treated quite extensively in this report. The preliminary design piping layout is shown in figure I-9.

Key to assessing the economics of any solar system is the projected output. A selection of the best available insolation and collector performance data has enabled high confidence predictions of performance per square foot of collector arrays on an hourly and annual basis. This projection has taken into account shadowing, cosine/incident angle effects, thermal losses, ambient temperature, and piping losses. The estimated net system output has been projected to be about 7.95×10^9 Btu's per year before startup losses. Additionally, an accurate estimate of startup losses at about 5.7% for the preliminary heat transport system has been generated.

The present system preliminary capital costs are about \$157 per million Btu's per year slightly (about 5%) above the DOE guidelines. Bates has great confidence that the final design will incorporate refinements to bring this cost well within the \$150 guideline.

In summary, Bates believes that the PDR will show that substantial progress has been made in addressing the difficult problem of an above-ground structure in an economical and practical manner and that this solution is a system that is easily adaptable to retrofit as well as new solar applications. Furthermore, it is believed that the basic engineering tradeoffs and analyses that are integral to all design projects have been or will be accomplished thoroughly in the near future.

Figure I-9. Preliminary Design of Piping Layout

1600 YALE BLVD., S.E. - ALB., NM	
TITLE:	
THERMAL SYSTEM	
DATES SOLAR INDUSTRIAL STEAM INSTALLATION	
DRAWN: K. COX & R. BRANDT 13-60	DWG. NO.
SCALE: NONE	SK-505

CHAPTER II OVERVIEW

A. PROGRAM PLAN

1. Program Approach

Bates Container, Inc. (BCI), recognizing that the management of a pioneering project to use solar energy in powering its new corrugator in Fort Worth is a highly challenging opportunity, has assembled an outstanding team for design and implementation. BCI is using the team approach since it is a small business which has not embarked on high technology projects of this magnitude in the past. Through BCI's effective application of its prime subcontractor, The BDM Corporation, which has an outstanding record of work in solar energy, the project is proceeding in a cost-effective and timely fashion. In management decisions and cost control, BCI is using procedures that it has found successful in past capital expansion projects and which have enabled it to grow into a multimillion dollar operation.

An overview of the Bates Solar Industrial Process Heat (SIPH) project is provided in figure II-1 which shows the critical path within the system. The first phase, funded by the current contract, results in a detailed design of the system with all necessary construction drawings and specifications required for procurement. The second phase involves the installation, checkout, and preliminary operation of the SIPH. The third phase consists of the continued evaluation of the solar system over a 30-month period after which BCI will continue to operate the system as a commercial power source.

Figure II-1. Program Overview

2. Program Schedule and Work Breakdown

The statement of work that BCI and the primary subcontractor, BDM, are executing during Phase I describes the procedures the company is using to implement the managerial processes for this project.

Phase I (shown in figure II-2) consists of five primary tasks as specified in the Statement of Work: 1.1, Preliminary Design; 1.2, Economic Analysis; 1.3, Environmental Assessment Analysis; 1.4, Safety Analysis; 1.5, Detail Design.

In the preliminary design, the concepts of design have been evaluated to ensure that all solar and steam generating subsystems are appropriate and where possible, optimal for the given application. The first step that BCI/BDM has performed is a detailed delineation of the system requirements. The team has identified and obtained data pertaining to the load, environment, and all system interfaces. Detailed hourly insolation and ambient weather conditions have been developed. These data have been used in a system performance model developed by BDM to provide detailed resolution on system performance. Likewise, demand scenarios for annual production at Bates Container will be developed so that accurate estimates for the quantity of fossil-generated steam can be obtained. Specific requirements of systems interfacing, most importantly the solar steam generator to the conventional steam manifold system, the collector to the building structure, and the solar-controlled system to the conventional steam control system, are described to support subsequent component design and specification.

With the information available from the system requirement definition, the BDM Corporation is responsible for performing subsystem analyses and selection and providing the preliminary system design. In this effort, detailed engineering analyses as well as system level analyses have been incorporated to specify the hardware to be used in the Bates solar steam generation system. Engineering sketches of each of the major subsystems and system interfaces are provided in this preliminary design document (PDR).

The PDR includes these minimum requirements:

- (1) Delineation of system requirements
- (2) Results of system level analyses (performance projections)
- (3) Engineering diagrams, sketches, etc., of the proposed steam generating system

The second task begun during the PDR stage of Phase I, is an economic analysis. BDM has developed a detailed cost breakdown structure which identifies all capital costs associated with the solar steam generating system. Likewise, a cost breakdown structure has been

Figure II-2. Bates Process Steam Application - Phase I
Work Breakdown Structure (Major Items Only)

developed to identify the costs associated with the operation and maintenance of the overall system. Conforming to the approved DOE life cycle costing algorithms, BDM has performed a preliminary life cycle cost analysis and examined sensitivities to factors specified in the DOE Contractor Guidelines. The intermediate and final results of the economic analysis will be communicated in monthly reports and will be documented in their entirety in the draft and final report phases.

The third task that has begun at the PDR and is to be completed during Phase I is the environmental assessment and analysis. The BDM Corporation, in cooperation with Bates, will provide a detailed description of the cardboard corrugation facility at Bates and a description of the existing environment to include all meteorological data as well as physical and institutional data pertaining to the project. All potential environmental impacts are being identified. These will include potential toxic hazards associated with the high-temperature organic-based thermal working fluid, reflection potential associated with the solar concentrators, economic impacts, and potential influences on codes and local regulation. All specific actions which Bates has initiated or plans to initiate in conjunction with the solar system to comply with all Federal, regional, state, and local ordinances and regulations will be described in detail. A draft copy will be delivered to DOE by February 15, 1980.

Safety analysis is the fourth major task to be conducted during Phase I. BDM will address all potential hazards to the system, including scenarios showing possible damage or failure of the solar system due to adverse operating conditions or operational excursion. Any and all personnel hazards will be identified and consequence analysis of each hazard delineated. Specific design aspects and/or operational procedures required to eliminate consequence of adverse conditions either to the solar system or personnel will also be identified and discussed in detail. All safety requirements which are part of this task will be included in the detailed design. A final draft copy will be delivered to DOE by March 1, 1980.

The final task during Phase I will be detailed design. The primary objective of this task is to produce necessary engineering documentation and drawings required to implement construction, fabrication, and installation of the proposed solar system. All data obtained in the previous Phase I tasks will be included in the final design, and all subcomponent hardware and interfaces will be specified for construction, assembly, and installation. Operating modes will be identified and defined which will in turn support specific operating and maintenance procedures to be documented at a later date in the contract. The detailed design will be reviewed at the 80 percent level to allow sufficient time for any required modifications identified during the review. All required documentation will be provided to DOE two weeks prior to the 80 percent design review to allow complete evaluation of the system

design. Subsequent to the review, necessary modifications will be implemented by BDM and construction drawings will be available for Phase II contractor development.

Program management will be an ongoing effort through all of the program. Program management will be responsible for all documentation provided to DOE and for the efficient execution and control of program activities.

B. ANALYSIS OF PLANT AND PROCESS

1. Introduction

Bates Container, Inc., is a rapidly growing organization involved in the production of cardboard containers. One of the major markets for Bates containers is the meat packing and shipping industry. The current Bates facility, shown in figure II-3, is located in North Richland Hills, an industrial suburb of Fort Worth, Texas, and produces a business volume of about 10 million dollars per year. Bates is in the process of expanding their facilities to include a cardboard corrugation fabrication facility to supply the cardboard stock required for the manufacture of the various containers which they produce. Currently the raw stock is purchased from outside suppliers. The bids for the construction of the corrugation facility have recently been released, and the corrugation assembly has recently been purchased and transported for storage at the Bates facility. The corrugator facility will be constructed and in operation in late 1980.

The Bates operation is being proposed as a solar industrial process steam retrofit application for several reasons. First, the location at Fort Worth, Texas, places the corrugation facility within the sunbelt and provides a very high level of direct normal solar radiation. Second, the positive match up between the workload and the available solar energy is ideal for solar power applications. Also, positive correlation between energy demand and solar availability has eliminated the requirement for thermal energy storage in conjunction with the solar system. Most importantly, as a process steam application, the facility represents a very large potential market for solar industrial process steam applications. For example, in Fort Worth there are nearly 20 corrugator facilities and numerous other industries requiring approximately 380° F steam. The proposed system should be considered as a 380° F steam nozzle rather than as part of a corrugator. The Solar Energy Research Institute has estimated that the total potential market for process steam at temperatures above 350° F is 27.8 Quads per year. Because of the location in an industrialized area, the demonstration of the technical and economic viability of this solar industrial process steam application will directly support the commercialization of the solar thermal energy systems in the industrial sector.

Bates recognizes the possibility of future cost increases in fossil fuel and potential nonavailability of conventional fossil fuels and strongly supports the development of alternative fuel options. It will cost share to the maximum extent possible as a small business. Bates is arranging for a commercial loan for this purpose and is willing to extend their participation to the limit prescribed by the commercial lending institutions.

II-7

Figure II-3. Aerial View of Bates Container, Incorporated Plant

2. Plant and Process Description

The Bates Container Corporation is a closely held company which produces corrugated cardboard cartons from sheet corrugated cardboard. It is located in North Richland Hills, Texas, a commercial/industrial area about 15 miles from the center of downtown Fort Worth. The exact address is 6433 Davis Blvd., Fort Worth, Texas 76180. The existing plant consists of a factory to house machinery, offices for management and personnel, and a machining shop area. It comprises about 79,500 square feet of building, and is serviced by Company-owned trucks for delivery of orders.

The Bates Container plant layout is shown in the plot plan, figure II-4. The present factory, warehouse and office facility are located on the north end of the property. They are bounded on the west by a railroad siding and on the east by Davis Blvd.

The expansion of the existing Bates plant involves constructing a large structure of about 76,000 square feet directly south of the existing plant as shown in the plot plan. This building will house the corrugator and associated inventory, raw, and finished stock. The corrugation machine is a large linear machine of over 300 feet in length that operates with large quantities of moderate-pressure steam. It is in conjunction with this machine that a solar industrial process steam application is proposed. Although the building and machinery for the corrugation machine do not exist at the time of this writing, it is expected that operations in the new building will begin in late 1980. For purposes of this project the term 'current' shall refer to time periods after completion of the additional plant since Phase II funding occurs well after building construction has begun. Thus, the application is considered to be a solar retrofit of an existing facility. The corrugation machine is a serial process system in which roll stock is treated by a variety of steam-driven heating, drying, and mechanical processes resulting in sheet corrugated cardboard. This system manufactured by the Langston Machinery Company is recognized in the industry to be of excellent design and high quality from both process and energy use standpoints.

Figure II-4. Bates Container, Inc.
Plot Plan

Figures II-5 and II-6 show a layout of components and a sketch of the corrugation steam system. The corrugation line is approximately 305 feet long, 75 feet wide and about 20 feet high, therefore requiring a separate building from the existing warehouse and production facility for containment and inventory of raw and finished paper. It is essentially an entire factory composed of over 60 steam vessels, steam separators, steam lines and condensate lines supplying heat for the process. During normal operation, up to five rolls of kraft paper of varying widths, depending on the weight and width of board to be produced, feed simultaneously into different points in the line. For common double face board, which will account for about 90 percent of the production, a single layer of fluting is faced on both sides with paper. The other 10 percent will be double wall composed of two layers of fluting sandwiched between three sheets of paper. For double face board, the first stage of production is preheating two sheets of raw stock to 370° F between long (up to 85") steam rollers. This temperature is critical to the forming and gluing process. The paper is plasticized and able to be corrugated or "fluted" at instantaneous rates up to than 600 feet per minute and average rates of about 300 fpm. In the double deck single-facer the flute is made, glue is applied to one side and the single face is adhered to it. Heat is necessary for the starch gelling, glueing and drying processes so that an instant bond is achieved. In the figure, the one-deck single-facer then applies glue and the second face under the same temperature conditions. The double-facer and double-gluer are used for double wall board and perform similarly. Finished and intermediate products are conveyed by rollers above the machine. The final drying, trimming, cutting, and forming machinery are at the end of the line.

Widths of board up to 85" can be produced depending on the size of the roll stock mounted on the mill roll stands. Roll stock inventory and finished products are located in the same building.

LANGSTON STEAM CIRCULA-

TING AND DRAINAG SYSTEM

Figure II-5. Langston Steam Circulation and Drainage System

THE LANGSTON CORRUGATED MANUFACTURING SYSTEM... with INSTANT ORDER CHANGE

The LANGSTON CORRUGATED MANUFACTURING SYSTEM with INSTANT ORDER CHANGE offers immediate and long range profitability. It is a system designed for optimum performance **now** - by eliminating order change slowdowns, minimizing waste, and providing ease of operation through automatic setups - and **in the future** - through adaptability to developing technology. In addition, Langston offers, as it has traditionally, full service capability and total after service responsibility just another way that Langston, the only single source corrugator manufacturer, provides machinery not only for today, but also for tomorrow - with a wealth of yesterday's experience.

Double Faces

- WARP TROL minimizes warpage through automatic temperature regulation
- Large volume steam chests provide for proper curing
- No speed reduction for order changes minimizes scrap
- Variable lift weights count for light or heavy board bending
- Automatic lift lift eliminates seven foot board when machine stops

Hi Speed Rotary Shear

- Enables instant order change by cutting web at the proper time

- Makes a single cut at 650 feet per minute (198 m/min)
- Upper knife is motor driven, lower knife is fixed
- Automatic splice removal capability available

Web Director (Director from Shear)

- Directs web to either level of slitter/scorer
- Tables support and direct web
- Simple fast deflector mechanism

Automatic Slitter-Scorer

- Dual paper line results in no scrap—no slowdown of machine speed
- Programmable set up
- Capable of up to 20 order changes per hour
- 4 squarable shafts for positive head lock up
- Consequently, automatic and highly variable
- Auxiliary manual station for special orders—a Langston exclusive
- Two or four bar models to meet specific needs—a Langston exclusive

Web Director (Director to Cutoff)

- Directs and directs web into either cutoff station from either slitter/scorer station
- Simple fast deflector mechanism
- Programmable set up for continuous run

Direct Drive Cutoff

- Instantaneous response to order change—within a single revolution of the knife cylinder
- 0.030 in. (0.762 mm) adjustable cutting accuracy
- 100 horsepower dc motor drives each knife cylinder
- Each knife cylinder independently controlled and programmed
- Hardened precision ground spur gears
- Easy backlash adjustment on all gear sets
- Perforated feed lubrication system ensures longer bearing and gear life

Sheet Delivery

- Automatic sheet delivery eliminates backlashes of manual take off
- Available as single, double or triple units
- Handles sheets from 22 in. to 300 in. (559 mm to 7620 mm) in length

- Solid state logic control provides for automated operation

Full Service Capability

- Highly trained field service force
- Around the Clock Parts Service
- Turnkey & Mini Turnkey Installation
- Pre-Installation Planning & Consultation

Total After Sale Support

- Longest Continuous Training Service
- In Plant Crew Training
- plp
- Comprehensive Operation and Maintenance Manuals
- Thorough Parts Catalogs
- Environmental Service Bulletin

Let your Langston sales engineers show you how the present INSTANT ORDER CHANGE SYSTEM opens the gateway to the future.

Langston
A WEALTH OF THE PAST'S EXPERIENCE

Figure II-6. Langston Corrugator

3. System Operational Requirements

a. Conventional Boiler Duty and Steam Requirements

The fossil fired steam generator is sized at 350 boiler horsepower (11.72×10^6 Btu/h) producing a peak of 12,075 pounds of steam per hour at approximately 381°F and 200 psi. This is sized to satisfy the peak steam requirement in column 2 of figure II-7. The boiler will be a packaged unit featuring firetube and sheet construction and forced draft combustion and fitted for dual fuel firing. The boiler conversion efficiency on both gas and #6 fuel oil is expected to be about 80 percent. This results in fuel consumption of about 14,650 CFH of 1000 Btu gas or 97.5 GPH of heavy fuel oil.

The corrugation plant is scheduled to operate on a 5-to-7 day week with about 8 hours of operation per day. At present, about 800,000 square feet of cardboard are processed per day into boxes. This translates to an average of approximately 300 ft/min operation of the corrugation. To satisfy this requirement, the corrugation machine would require roughly 50,000 pounds of steam per day at 370°F, requiring about 1000 Btu/lb. Using an assumed efficiency of about 80 percent for the boiler, this translates into a requirement of about 62×10^6 Btu/day heat input to the boiler. Taking boiler efficiency into account about 50×10^6 Btu/day is actually fed into the steam. The average hourly usage is about 5,500 lbs/h of steam, requiring about 5.5×10^6 Btu/h input to the steam. On some occasions, higher steam loads will be required for extra-weight cardboard processing, hence, the oversize boiler. Cardboard processing rates are relatively constant throughout each day and for all days in a year. Heat requirements are, therefore fairly constant throughout the year.

About 60 percent of the steam produced and supplied to the corrugation machine is consumed during the process. The remaining 40 percent is returned as liquid at 1 atmosphere to the condensate tank where water makeup is provided. This fluid is then recirculated through a feedwater pump which provides the required boiler operating pressures.

Some of the special conditions for the proper operation of the corrugator are that steam superheat is not allowed and that steam pressure must remain within 5 psi of rating. Provision must be made for rapid rise from idle condition to full load in less than 5 minutes without appreciable pressure drop because of the danger of "backflow" through the corrugator since steam is cascaded through the system.

Process Steam Requirements

BCC Corrugator

Required
Boiler Duty

Steam temperature	371 ⁰ F 3 ⁰ F (188 ⁰ C 1.7 ⁰ C)	
Steam pressure	175 5 psi (120kPa 34kPa)	
Peak demand	10,500 lb/hour (4753 kg/h)	11.42 x 10 ⁶ Btu/h (3346kW)
Average demand	5,500 lb/hour (2268 kg/h)	5.5 x 10 ⁶ Btu/h (1581kW)
Idle demand	1,000 lb/hour (454 kg/h)	1.09 x 10 ⁶ Btu/h (3.9.4kW)
Makeup	40 - 60% @ 70 ⁰ F (21.1 ⁰ C)	
Feedwater return	212 ⁰ F @ 14.7 psia (100 ⁰ C @ 101.4 kPa)	

Figure II-7. Conventional System Steam Requirements

b. Solar Steam Production Sizing and Impact

The solar array has been sized according to two criteria: (1) To match the average corrugator load of about 5500 pounds of steam per hour; and (2) To fit onto the roof of the structure housing the corrugator. These two requirements have fixed the array size at 34,720 square feet with a net peak output of slightly over 5500 pounds of steam at noon. This choice implies that all the energy produced by the system is consumed by the process without the requirement of storage which is not seen to be the objective of the Cycle IV SIPH procurements. The system will be in parallel with the fossil boiler which provides make-up when required.

Figure II-8 shows the average hourly power required by the corrugator superposed in the solar system output for the 3 key days of the year. The asymmetric profiles are a consequence of using the actual available insolation measurements on these days. The solar output is generated from the computer model described in subsequent sections. An obvious excellent correlation is obtained between process demand and solar system supply. Such that every clear day of the year the Solar system is able to displace fossil from 2 to 3 hours about Solar noon.

Note that the hours of operation are somewhat extended for the corrugator. This is to reflect the willingness on the part of Bates' management to schedule working shifts around solar noon to take advantage of solar energy savings. Additionally, extension of the work week from 5 days is expected in order to satisfy demand for corrugated board. Overall, the impact of the solar system on production scheduling should be minimal because of the parallel configuration with the fossil boiler.

Figure II-8. Solar Energy Supply vs. Process Requirement

CHAPTER III

SYSTEM/SUBSYSTEM ANALYSIS

A. SYSTEM OVERVIEW

The overall Bates SIPH application is shown in the schematic of figure III-1. It shows the solar array of linear parabolic troughs which provides steam through an oil/water heat exchanger. The exchanger operates in parallel with a conventional fossil boiler. Chapter III describes each of the subsystems shown and describes the overall systems analysis work that has been completed in the Preliminary Design Task of Phase I. The chapter is divided in the following fashion to correspond with the systems analysis and subsystems:

- (1) Performance Modeling which describes the insolation and system efficiency to project an annual energy production.
- (2) Collector Mounting which describes the analysis completed for quantification of the mounting structure requirements and the trade-off studies that were made comparing different mounting schemes and the recommended design.
- (3) The Collector Subsystem which describes the baseline linear parabolic trough solar collector.
- (4) The Heat Transfer Fluid which describes the selected heat transfer fluid Therminol-55.
- (5) The Heat Transport and Distribution Subsystem which shows the piping configuration and contains a detailed study of the trade-off of pipe diameter and insulation selection based on heat loss versus pumping loss considerations and piping configuration.
- (6) The System Layout showing the relative locations of the subsystems and components.
- (7) The Master Control Subsystem which describes the control elements and data acquisition scheme.

Figure III-1. Schematic of Solar Industrial Process Steam System

B. PERFORMANCE MODELING

1. Solar System Hourly Performance Model

An essential part of determining the value of the Bates solar process steam application is an accurate projection of useful energy delivered. In this analysis a computer model of the baseline solar collector performance combined with weather data has been used to predict annual performance as depicted in figure III-2.

Key to the projection is the accurate representation of four areas: (1) Historical local weather conditions and insolation; (2) Collector performance as a function of insolation operation conditions and geometry; (3) Parasitic costs of both thermal and pressure losses; and (4) Energy requirements of the process as a function of time. For all areas, the ensuing analysis has used the best quality data available. For insolation and weather data, a comparison of sources has resulted in the adoption of the SOLMET data as most representative of the Dallas-Fort Worth Area. For collector performance, predicted values supplied by the manufacturer and verified by data from tests at Sandia Laboratories in Albuquerque have been used. This test series is the most current and consistent set on parabolic troughs and are representative of industry performance. Parasitic losses have been projected for the purposes of the PDR from manufacturer's data and widely accepted procedures for heat loss and pumping power costs. Process energy requirements have been quantified based on Bates' long experience with corrugators and information from the corrugator manufacturer.

- FUNCTION OF
 - OPERATING TEMPERATURE
 - INSOLATION
 - AMBIENT TEMPERATURE
 - WIND
 - ORIENTATION & SPACING

- INSOLATION
- AIR TEMPERATURE
- WIND

- HEAT LOSS THROUGH PIPING
- PUMPING POWER REQUIREMENTS

- NET USEFUL OUTPUT
- HOURLY DAILY SUMMARIES
- PROCESS REQUIREMENTS

Figure III-2. Solar Process Energy Output Model

2. Weather and Insolation Data for Fort Worth

a. General Meteorological Description

The location of Bates Container, Inc., in Fort Worth, Texas, combines the advantage of the excellent solar environment typical of the southwest United States with the industrial opportunities of the Dallas-Fort Worth area. Fort Worth is located in north central Texas about 250 miles north of the Gulf of Mexico near the boundary between two major climatic zones. The one to the west is classified as semi-arid, steppe climate, and the one to the east is warm, temperate, with rainy winters and hot, dry summers. The mean afternoon high temperatures vary from about 55°F in midwinter, to about 93°F in midsummer. During the winter, occasional days are encountered that stay below freezing all day. The annual minimum temperatures encountered are in the range 15-20°F. Temperatures as high as 110°F are encountered on rare occasions. Fort Worth has 2405 heating degree days per year.

Throughout the year, rainfall occurs more frequently during the night. Usually, periods of rainy weather last for only a day or two, and are followed by several days with fair skies. A large part of the annual precipitation averaging about 32 inches results from thunderstorm activity, with occasional heavy rainfall over brief periods of time. Greatest amounts of rain occur during the months of April and May. July and August are relatively dry months. Thunderstorms occur throughout the year, but are most frequent in the Spring. Hail falls on about two or three days a year, ordinarily with only slight and scattered damage. Windstorms occurring during thunderstorm activity are sometimes destructive. Snowfall is rare with a measurable fall occurring only once in an average year.

Relatively severe weather is a part of the Fort Worth climate. Thunderstorms occur commonly from April through October, with peak activity in May. Convective thunderstorms are likely to occur in the afternoon and early evening during this time, with the remainder associated with frontal systems. Tornadoes are not uncommon in Texas and are accepted as normal environmental hazard. Most tornadoes occur in April, May, and June during the warm hours of the day. Hurricanes are very rare in Fort Worth. Prevailing winds are strong (10-20 mph) but high winds (40 mph) are unusual.

Prevailing weather trends indicate some of the implications for solar collection. During the winter, there are many bright clear days with few clouds and an intense blue sky. There are also days with complete overcast. The winter days tend to be either very good or very bad for solar collection. In the summer, there is some solar availability on almost every day. However, small broken stratocumulus, especially in the afternoon, can make the actual pattern of availability variable during a particular day in the summer.

Fort Worth has an excellent record of percent possible sunshine as shown in figure III-3. The annual average of possible sunshine between sunrise and sunset is approximately 68%, and varies from 56% in January to a high of 78% in July and August.

Figure III-3. Percent of Possible Sunshine Between Sunrise and Sunset at Fort Worth

b. Fort Worth Performance Model Insolation Data

The SOLMET insolation and meteorological data base with an hourly resolution was selected as the input to the performance model. The rationale and accuracy assessment of the choice are described below.

In order to predict performance of the solar system, a computer model with one-hour time steps was used. The hourly resolution was decided upon because it allows comparison of solar system output and process requirements on an hourly rather than average day basis. Additionally, the cosine/incident angle and ambient temperature effects on trough performance are better accounted for. There was therefore a requirement for weather data on an hourly frequency.

The most complete source of hourly insolation values for the Fort Worth area is the SOLMET data tapes available from the National Climatic Center. Fort Worth is fortunate to be one of the 27 locations for which the tapes exist. The data consist of an historical base over a period of 23 years of meteorological and solar radiation measurements corrected for all known errors with missing observations inserted using regression and interpolation. A Typical Meteorological Year (TMY) has been defined for each site. The TMY is assembled from a set of typical months so that from the years of data available for Fort Worth, the most typical January, February, etc. are selected for the TMY. The data have been recommended by Sandia Laboratories as being the best currently available.

Data points available consist of total insolation, direct normal insolation, ambient temperature, dew point and wind speed and direction as shown in figure III-4. It should be noted that most sites did not have direct normal insolation (DN) measurement devices and that these values have been reconstructed using correlations between DN and total horizontal measurements. To verify the consistency of these correlations, two further data sources which have published insolation data for the region were examined. These were a study by Randall and Whitson for Fort Worth and extensive studies by Rapp and Hoffman of Fort Worth and Fort Hood for which excellent DN readings have been taken. Fort Worth is about 120 miles south of Fort Hood. These were compared on the basis of monthly and to annual total DN energy values. This comparison is shown in figure III-5 and shows no meaningful differences between the SOLMET tapes and Randall and Whitson correlations. The Fort Hood values are expected by experienced observers to be about 10% below Fort Worth because of cloudiness due to its proximity to the Gulf and are, indeed, 10% lower. For the performance model, an edited version of the SOLMET tapes has been used consisting of hourly values for DN insolation, air temperature and wind speed for the period from 5 am to 9 pm for each day of the TMY.

Figure III-4. SOLMET Weather Tapes

<u>MONTH</u>	<u>SOLMET DN (Btu/ft²)</u>	<u>Randall & Whitson DN (Btu/ft²)</u>	<u>Rapp for Fort Hood, DN (Btu/ft²)</u>
January	33160	33810	34660
February	34200	35250	35580
March	48370	43540	40740
April	39890	41290	38230
May	45480	47080	39640
June	56740	55450	48780
July	62770	60130	52870
August	60300	57110	51100
September	51790	47640	42730
October	49040	47080	46680
November	40910	34140	35470
December	36070	35280	34220
<u>Total</u>	<u>558720</u>	<u>537800</u>	<u>500700</u>
<u>Deviation</u>		<u>-3.7%</u>	<u>-10.4%</u>
			(as expected) for Fort Hood cloudiness

Figure III-5. Comparison of Annual Total DN Insolations for Fort Worth and Fort Hood Regions

3. Collector System Modeling

a. Performance Factors

The baseline collector system for the purposes of this analysis is the Solar Kinetics, Inc., 7-foot linear parabolic trough designated the T-700. It is described in detail in section III-C below. Alternative collectors can be expected to exhibit approximately similar performance characteristics. The collector system is to be composed of 31 rows, each 160 feet long totaling approximately 35,000 square feet of aperture. The system will be mounted with axes aligned in an east-west direction on either side of a slightly peaked roof at about a 5 degree slope as shown in figure III-6.

The key factors affecting collector performance and output are insolation and operating temperature with the system geometry influencing incident angle and shadowing effects. Ambient wind conditions have an effect which has not been quantified well and have not been considered. This is not expected to be of major importance since the performance data used in the model are based on 10 to 12 mph winds which is the annual average for the Fort Worth location.

The alternatives for collector array orientation are either a north/south or east/west collector axis. In general, the N/S choice provides about 12% more collected energy annually because of incident angle effects. However, it has markedly different (2 to 1 variation) daily profiles through the year while the E/W orientation has nearly identical daily profiles throughout the year. This is shown in figure III-7 for typical insolation profile.

In the present application, several factors favor the E/W orientation in spite of its slightly lower energy output. The N/S system is summer peaking or, alternatively, requires the most fossil fuels during the peak residential demand winter months. With the current and projected fuel shortages, the winter period would be most likely subject to reduced supplies to industry as well as demand and peak surcharges. The E/W choice avoids this because of its uniform daily peak. It also displaces fossil in about the same amount each day for the same period of time, and is thus a simpler system to operate and to schedule around. Study has shown that E/W permits closer spacing of rows. The spacing between consecutive collector rows, measured in apertures (1 aperture = 7 feet), determines the effect of intra-array shadowing and impacts the overall area required for the collector array (not mirror area), the heat transport subsystem (HTS) size, pumping costs, and fluid volumes in the HTS. Since the proposed design is limited by area, another factor favoring the E/W is its closer spacing allowance. Finally, the E/W orientation of the new building provides a simpler manifolding and header arrangement for an E/W array.

Figure III-5., Solar Collector Array on Peaked roof

Figure III-7. Insolation Profiles for E/W and N/S Axis Orientations

b. Solar System Row Spacing and Incident Angle Effects

The geometric effects which influence collector performance by lessening the effective aperture area are inter row shadowing and the incident angle effect coupled with the roof tilt. The spacing between rows has been selected as 15' (~2.1 apertures). Additionally the effect of the 4.76 degree roof tilt has been investigated and found to have a negligible effect on system performance.

The results of an analysis which compares the amount of incident energy lost for different inter-row spacings of collectors because of intra-array shadowing and end effects is shown in figure III-8. The effect of spacing closer than about 2 apertures causes a rapid increase from the 3% in shadowing effects between rows at low sun angles thus, the selection of about 2.1 apertures.

Another geometric factor is the incident angle effect arising from the single axis tracking characteristic of linear troughs. The calculations for an east-west array orientation mounted on a flat surface are presented in numerous sources. The analysis results given below for the $\pm 4.76^\circ$ tilted roof is an extension of work done by Veneruso at Sandia Laboratories.* Using the definitions in figure III-9, the incident angle, β for a tilted field can be obtained from:

$$\sin \beta = \cos \alpha (\cos a \sin \theta - \sin a \cos \gamma \cos \theta) - \sin \alpha \sin a \sin \gamma$$

In contrast to the same expression for a flat field which is:

$$\sin \beta = \cos \alpha \sin \theta$$

In spite of the differences in the expressions a comparison of the two values at noon of summer solstice at 32 degrees north latitude shows $\beta_{\text{flat}} = 0$ degrees and $\beta_{\text{tilt}} = -4.8$ degrees, a negligible difference in cosine/incident angle effect of $\cos(-4.8)/\cos(0) = .9965$ or about 0.35%.

Further comparison has shown that the tilting of the array symmetrically such as the peaked roof in the current configuration about the north-south direction has a negligible effect in a $\pm 5^\circ$ tilt. Nevertheless, all subsequent analysis uses the tilt incident angle expression.

* Veneruso, Anthony "Tracking Angles and Rates for Single Degree of Freedom Solar Collectors." SAND76-0027

Figure III-8. Shadowing-Aperture Spacing Analysis

Figure III-9. Definitions for Incident Angle Analysis

c. Collector Performance Parameters

The efficiency e , of the collector system may be expressed as:

$$e = \frac{\text{Optical efficiency} \cdot \text{DN} - \text{Thermal losses}}{\text{Net DN}}$$

This expression represents thermal losses from the receiver tube through convection and radiation in Btu/hr/ft² of aperture. The optical efficiency consists of the product of four terms: (1) ρ - the reflectivity of the mirror surface, with an average value of 0.83 for FEK-244; (2) τ - the transmittance of the annular cover glass made of Pyrex 7740 with an average value of 0.90; (3) α - the effective absorptivity of the black chrome selective surface coated on the receiver tube with a value of 0.96; and (4) g - the geometric intercept factor representing mirror and surface imperfections with a value of 0.98. Their product is 0.702. The net DN insolation term is the product of the incident angle cosine and the measured direct normal insolation. It is evident that quantification of the thermal loss term as a function of operating and ambient temperature remains in order to calculate collector efficiency curves.

Solar Kinetics, Inc. (SKI) has provided an efficiency versus collector temperature curve shown in figure III-10 from which may be derived a thermal loss relation of the form:

$$L = 1.28 \cdot (11.4065 - .0469 \cdot T + 1.385 \cdot 10^{-4} T^2)$$

$\frac{\text{BTU}}{\text{hr-ft}^2 \text{ aperture}}$

where L is the thermal loss and T is the average collector temperature $[(T_{in} + T_{out})/2]$ plus the difference between 60°F and the ambient air temperature. Figure III-11 shows efficiency versus insolation for the operating condition of about 450°F and 500°F for the $T=700$.

The curves show that at the operating condition of about 450°F average temperature the collector efficiency ranges from about 45% at 100 Btu/hr/ft² of net DN insolation (usually attained within an hour of sunrise) to about 63% at a full sun.

Using the results of the preceding sections, a performance projection can be produced.

Figure III-10. SKI T-700 Solar Collector Efficiency Vs. Temperature

Figure III-11. Efficiency Vs. Insolation SKIT-700 Solar Collector
(Reproduced from mfr. data)

4. Annual Performance Projection

A high confidence estimate for the net annual energy production of the Bates Solar Process Steam System resulting in a value of 233,000 Btu/year/ft² of collector aperture at the collector outlet thermal losses in the preliminary piping layout and insolation design are 1.9 percent of this figure so that the net thermal energy delivered to the non-fired steam generator is 229,000 Btu/year/ft² aperture. Preliminary calculations indicate annual average di-urnal start-up requirements to be about 5.7 percent of the collector outlet output. It is expected that some design improvements and further insulation trade-offs in this area will lessen these losses. Figures III-12, III-13 and III-14 show daily performance profiles for the key days of the year, summer solstice, equinox and winter solstice. Shown on the left is the gross energy output per square foot of aperture superimposed on the direct normal insolation. On the right is the instantaneous collector efficiency. Note that the insolation data are from the SOLMET tapes. Figure III-15 shows a stair-step for the output of the collector field normalized to a square foot of collector at noon of summer solstice. The instantaneous overall system is quite high at about 62 percent.

Figure III-12. Daily Performance Profile per Square Foot of Collector - Summer Solstice

Figure III-13. Daily Performance Profile (1 ft² aperture) Equinox

Figure III-14. Daily Performance Profile (1 ft² aperture)
Winter Solstice

Figure III-15. Stairstep for 1 ft² of Collector Aperture - Summer Solstice

C. SOLAR SYSTEM STRUCTURAL DESIGN AND ANALYSIS

1. Introduction

The BCI design team has originated a concept for above-ground mounted collector systems which is extremely competitive with ground-mounted systems in industrial areas. Even in the PDR stage where design constraints and costs are conservatively set high, the roof-mounted array for Bates is showing a slight cost advantage over ground mounted alternatives because of land costs. The competitive cost comparison is especially exciting as it expands the possibilities for retrofits in applications where land is simply not available at any cost, a situation true of many industrial applications. The easy application of the present design concept to new construction where the collector support structure can also be an integral part of the roof/ceiling construction promises to open up to solar many new cost effective above ground applications.

The approach shown schematically in figure III-16 was used in accomplishing a preliminary design for the structure supporting the 35,000 ft² array of solar collectors for the Bates solar process steam installation and consisted of:

- (1) Establishing an applicable set of design considerations around cost and safety;
- (2) compiling the appropriate design criteria;
- (3) researching wind loading approaches and realistic wind coefficients to establish design loads;
- (4) reviewing limitations and constraints of the Bates building as regards locations of support columns, loading docks, and entryways;
- (5) generation and analysis of several design concepts and iteratively evolving a recommended design.

Figure III-16. Structure Flow Chart

The recommended preliminary design is shown conceptually in figure III-17 and consists of a sloped frame of steel open web joists supported with steel I-beams on reinforced concrete piers. The design features vertical joists capable of carrying upward and downward wind lift loads and horizontal joists for carrying wind drag loads in any direction. The frame/column system is designed to withstand winds up to 100 mph in any direction. Large horizontal joists are incorporated along every other collector row to resist the drag loads and provide a walkway for maintenance of the collectors. Folding hand rails are featured to comply with OSHA safety requirements and minimize shading effects.

Further details are given in the following sections in which each of the major sections of the design approach are discussed.

Figure III-17. Design Concept for
Solar Collector
Support Structure for
Bates Installation

2600 YALE BLVD. SE ALB. N.M.	
TITLE: ISOMETRIC-ARRAY SUPPORT STRUCTURE BATES SOLAR INDUSTRIAL STEAM INSTALLATION	
DRAWN: K. COX 1-4-80 SCALE: NONE	DWG NO SK-507

2. Design Considerations

The structural system required to support successfully an array of parabolic trough solar collectors is a function of the following design considerations:

1. Collector Wind Area (35,000 ft²)
2. Number of rows and row length
3. Number of drive plyons per row
4. Unobstructed rotation of collectors. (See figure III-18b)
5. Minimum impact on building (independent structure)
6. Minimum impact on plant operation
7. Minimum shading
8. Maximum safety and security
9. Appearance
10. Minimum Cost
11. Conformance with Ft. Worth, Texas Building Codes.

Regarding collector wind area, a collector system of approximately 35,000 ft² of aperture are required to satisfy the steam requirements for operation of the Langston corrugator. This area can be achieved using 31 rows of SKI T-700 collectors or equivalent (reference 1), with each row consisting of eight collector panels as shown in figure III-18a. An eight panel collector row will span the width of the building for an above building design. Also, installation of the array above ground level, preferably above the new addition of the Bates facility, will provide maximum safety and security, efficient use of land and minimum shading.

For minimum impact on plant operation, it is desirable to provide a support structure completely independent of the Bates building. However, due to the width of the building, a completely independent structure may not be economically feasible because of the long span (~160'). It is proposed to utilize intermediate support columns adjacent to those of the building. This concept will avoid additional columns in areas of traffic within the building. A trade-off study of comparing longer spans and fewer piers with the current design is in progress. Other building constraints are discussed below in section 5.

Another design requirement which must be considered in the collector support structure is provision for unobstructed rotation of the collectors. Intermediate supports between collector panels must allow for unobstructed rotation of the collector receiver tube which is one continuous member across a row. (See figure III-18).

Also, the support structure should utilize maximum efficiency of members which will minimize material costs. To this end, BDM has conducted tradeoff studies of various beam types and selected open web steel joists for the most cost effective support structure.

The open web joist system and unbraced I-beam columns provide a system which should be an aesthetically pleasing addition to the Bates facility.

Figure III-18. Details of SKI T-700 Collector Row

3. Design Criteria

The following design criteria have been established based on review of the Statement of Work as referred in the contract, the Fort Worth Building Code, and of potential environmental conditions in the Fort Worth area:

1. 90 MPH wind (Survival condition with collector stowed)
2. 40 MPH wind (Operational condition with collector in any attitude)
3. 25 PSF Wind Load (100 MPH, Survival condition from Building Code with collector stowed)
4. Structure Weight Loads (Collector system plus support structure)
5. 0 to 100°F Temperature Conditions.

Wind Pressure

Forces on structures or objects as a result of wind are a function of wind dynamic pressure (q), structure area, and structure wind coefficients. Area and wind coefficients will be discussed in section 4. In order to establish wind pressure values for design calculations, it is necessary to compare the wind velocity and wind load design criteria listed above. This is accomplished using the definition of dynamic pressure:

$$q = 1/2\rho V^2$$

where ρ = air density and V is the air velocity.

A density of .084 lb/ft³, which corresponds to an elevation of 700 ft. for the Dallas-Ft. Worth area, and a temperature of 0°F, gives the following value of q:

<u>Wind Velocity</u>	<u>Dynamic Pressure, q</u>
90 MPH	22.8 lb/ft ² (PSF)
40 MPH	4.5 lb/ft ² (PSF)

Since the wind pressure of 25 PSF from the Fort Worth Building Code is a larger wind pressure than the pressure corresponding to a 90 MPH wind, the 25 PSF criteria is used for survival conditions. For reference the wind pressure map and table for wind pressure versus height from the Building Code are shown in figure III-19.

Other Criteria

Other criteria such as the temperature range of 0 to 100°F. will present no design problems since the structure will be relatively insensitive to temperature loading. Also, snow loads will not present any significant loading since the collector will be stowed in a nearly vertical position during snow storms and the open web joint system will not accumulate significant snow loading.

UNIFORM BUILDING CODE: WIND PRESSURES FOR VARIOUS HEIGHT ZONES
ABOVE GROUND¹

HEIGHT ZONES (in feet)	WIND-PRESSURE-MAP AREAS (pounds per square foot)						
	20	25	30	35	40	45	50
Less than 30	15	20	25	30	35	40	45
30 to 49	20	25	30	35	40	45	50
50 to 99	25	30	40	45	50	55	60
100 to 499	30	40	45	55	60	70	75
500 to 1199	35	45	55	60	70	80	90
1200 and over	40	50	60	70	80	90	100

¹See Figure No. 4. Wind pressure column in the table should be selected which is headed by a value corresponding to the minimum permissible, resultant wind pressure indicated for the particular locality.

The figures given are recommended as minimum. These requirements do not provide for tornadoes.

Figure III-19. Wind Pressure Requirements From the Uniform Building Code

4. Wind and Weight Loading

a. Structure Weight Criteria

Reference 1 lists the weight of a T-700 collector system as 4.0 lb/ft^2 of collector area for a standard six panel collector. Since the Bates installation advocates the use of 8 panel rows, BDM has added 10% to the Reference 1 weight to account for any differential weight in developing a row of 8 panels. Each panel then weighs $140 \text{ ft}^2 \times 4.0 \text{ lb/ft}^2 \times 1.10 = 616 \text{ lb}$. Adding 50 lb. to allow for mounting structure at drive pylons then gives the collector row weight distribution shown in figure III-20.

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Collector Weight Loads shown in KIP's. (1 KIP = 1000 LB)

Figure III-20. Collector Weight Distribution

Wind Loading - General

Forces and moments induced by winds impacting the collector system and support structure are given by

$$D = q A C_d S_d$$

$$L = q A C_L S_L$$

$$M = q C A C_M S_M$$

where

D refers to drag.

L refers to lift.

M refers to moment.

$q = 1/2\rho V^2$ (dynamic pressure)
= 25 PSF (See section III.3.a)

C_i = Wind coefficient or shape factor; $i = D, L, M$

A = Representative area compatible with coefficient C_i
= $20' \times 7.417' = 148.34 \text{ ft}^2$ (148.4 ft^2 used in analysis)

S_i = Scale factor relating a specific collector to experimental wind coefficient data

Forces and moments are described in terms of the orthogonal coordinate system shown in figure III-21. Also shown in figure III-21 are the designations used to describe collector geometry.

Wind coefficients and scale factors are discussed below.

(a) Wind Forces Coordinate System

(b) Positive Force and Moment Designations

Figure III-21. Force and Moment Geometry for LPT Wind Load Analysis.

b. Wind Coefficients

As noted above, the force and moment loading of objects or structures in a wind flow field depends on the geometrical properties of the object. Geometric properties are accounted for using wind coefficients from experimental data.

For the parabolic trough shapes of the solar collectors, two sources of wind coefficient data were reviewed--a Sandia Corporation report (reference 3), and the Hoerner book (reference 2).

Reference 3 includes a comprehensive set of wind coefficients from two wind tunnel tests. The first test was conducted on single parabolic trough collector modules by the Vought Corporation. The second series of tests was run in the Meteorological Wind Tunnel of Colorado State University (CSU) where both single collectors and multiple module arrays were studied. The general configuration of the collector arrays tested during the CSU wind tunnel tests is shown in figure III-22. The various combinations of row arrangements tested are listed in table III-1.

Results of the CSU tests for drag, lift, and pitching moment coefficients are shown in figure III-23 for shielded and unshielded rows of collectors. From these figures a set of coefficients was selected for use in preliminary design calculations. Table III-2 summarizes the range of drag, lift, and pitching moment coefficients from the reference 3 data, includes data points on drag from reference 2, and lists the coefficients used by BDM for preliminary design of the Bates collector support structure.

The reference 2 drag coefficient shows a drag coefficient of 2.3 for a parabolic shape oriented convex side into the wind while the reference 3 drag coefficient for a comparable attitude is 1.7. This difference is believed to be attributable to the small L/C ratio of 2.75 for the collector tested at CSU compared to very large L/C ratio for results given by Hoerner. For the collector oriented with convex side into the wind, table III-2 shows a drag coefficient of 1.3 for reference 3 and 1.2 for reference 2 indicating that for this orientation, the drag coefficients are less sensitive to L/C ratios.

Since the reference 3 data includes two independent tests, is current, and was a direct test of parabolic trough collectors of discrete lengths, this data was used as the basis for selecting the design coefficients used by BDM and shown in table III-2. It should be noted that for unshielded collectors the coefficients at the -20° stow angle were selected and since the data for the shielded collectors was inconsistent as regards collector attitude, the maximum or envelope values of coefficients were used for shielded collectors. The -20° stow angle is based on mounting considerations and a compromise between minimum drag attitudes for shielded and unshielded collectors.

NOTE: ALL INDIVIDUAL TROUGHS HAVE ASPECT RATIO $L/C = 3.75$ AND RIM ANGLE $\phi = 90^\circ$

Figure III-22. General Collector Array Configuration for CSU Tests from Reference

TABLE III-1. COLLECTOR CONFIGURATIONS FOR CSU TESTS FROM REFERENCE

Configuration Number	Number of Rows Ahead of Metric Row	Number of Rows Behind Metric Row
5	0	0
6	0	1
7	1	1
8	2	1
9	4	1

Lateral Force Coefficient vs. Pitch Angle for
 Multiple Row Arrays at 0° Yaw Angle

Figure III-23(a). Lateral Force Coefficient vs. Pitch Angle for
 Multiple Row Arrays at 0° Yaw Angle

Figure III-23(b). Lateral Force Coefficient vs. Pitch Angle for Collector Arrays at 0° Yaw Angle

Figure III-23(c). Lift Force Coefficient vs. Pitch Angle for Multiple Row Arrays at 0° Yaw Angle

Figure III-23(d). Pitching Moment Coefficient vs. Pitch Angle for Multiple Row Arrays at 0° Yaw Angle

TABLE III-2. WIND COEFFICIENT SUMMARY

	C_D	C_L	C_M	REMARKS
From Reference 3 (Sandia)				
Unshielded	0.3 to 1.8	-1.7 to 1.8	-0.5 to 0.2	Coefficient range for 360° rotation of collector
Shielded	0.1 to 0.6	-0.3 to 1.0	-0.4 to 0.1	
From Reference 2 (Hoerner)				
Unshielded	(2.3) 1.2	-- --	-- --	
Selected for Bates Collector Support Design				
Unshielded	1.6	1.0	-0.2 to 0.0	Collector at pitch angle of -20°
Shielded	0.5	1.0	-0.4 to 0.1	Worst case data over 360° range of pitch angle
<p>NOTES:</p> <p>1. Coefficients are defined as</p> $C_i = \frac{F}{qA}$ $C_m = \frac{M}{qCA}$ <p>2. Pitch angle is defined as rotation of focal line from horizon</p>				

c. Scale Factors and Design Wind Loads

Since the reference 3 data contained some parametric studies for variations in parameter ratios involving mounting height (H/C), gap between panels (G/C), collector panel length (L/C) and row spacing (R/C), where C is the collector chord, scale factors were compiled to account for these geometric variations between the reference 3 collectors tested and the T-700 collector proposed. Table III-3 shows the scale factors for drag, lift, and moment coefficients as a function of the various parameter ratios. For the effects of gap spacing and row spacing, there was insufficient data to predict scaling factors with confidence so values of 1.0 were assumed for these parameter ratios.

TABLE III-3. SCALING FACTOR FOR T-700 COLLECTORS

			SCALING FACTOR (S_i)		
PARAMETRIC RATIO			S_D	S_L	S_M
	T-700 (Bates Installation)	REF 3			
H/C	≈ 1.0	≈ 1.0	1.0	1.0	1.0
L/C	2.7	3.74 & 9.97	1.0	0.9	0.9
G/C	0.11 to 0.14	0.1 to 0.2	1.0	1.0	1.0
R/C	2.15	Various	1.0	1.0	1.0

Design Wind Loads

Design wind loads were calculated for winds along the system x-axis and for winds oblique to the system x-axis.

x-Winds

For winds along the x-axis, it was assumed that the outer two panels on each row could be unshielded and the inner six panels would probably be shielded as shown in figure III-24. It was also assumed that a barrier or wind screen would be used on the ends of the building, so all rows would essentially see the same wind loading for a given wind direction. Using these assumptions and the wind load expressions (Section 4.a) the set of drag, lift, and moment loads shown in figure III-25 were calculated for a 25 PSF dynamic pressure, the coefficients selected for design, in figure III-25, the scale factors of table III-3, and the collectors in the selected stow position of -20° . Also shown in figure III-25 are the moment loads or drive torques at the drive pylons.

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Figure III-24. Assumed Wind Load Pattern for Winds Along the System X-Axis

Winds in (-x) Direction

For wind loads in the opposite direction (minus x-direction) the lift forces will be upward but smaller in magnitude and the drag forces will also be opposite and smaller in magnitude (based on reference 3). For design purposes the lift and drag loads shown in figure III-25 above are used for winds from either direction (N or S). Drive torques shown are assumed to act in the directions shown.

Oblique Winds

For winds oblique to the system x-axis, a portion of each collector row will be unshielded and a portion will be shielded, depending on the wind angle ψ . In addition, lift and drag coefficients will vary with ψ .

Two cases were studied to establish wind loads for oblique winds: (1) One panel unshielded and seven shielded and (2) Two panels unshielded and six shielded. Figure III-26 shows the two cases and the designations used for wind reactions on a typical panel.

Drag and lift forces are calculated as before except that wind coefficients (C_f) were selected from reference 3 at specific wind angles ψ . Collector design loads for oblique winds are calculated in tabular form in table III-4 for the two cases, $n = 1$ and $n = 2$. The total drag and lift loads for one row of eight panels are given by

$$R_{DY} = n (2R_{DYU}) + (8 - n) (2R_{DYS})$$

$$R_{LZ} = n (2R_{LZU}) + (8 - n) (2R_{LZS})$$

where

R refers to reaction
Y refers to component along the y-axis
Z refers to component along the z-axis
D refers to drag
L refers to lift
U refers to unshielded
S refers to shielded
n refers to number of unshielded panels

Figure III-25. Wind, Drag, Lift, and Moment Loads for Preliminary Design (Plus Crosswinds)

COLLECTOR REACTIONS

$$\alpha = \text{TAN}^{-1} \left(\frac{R}{nL} \right)$$

$$\alpha = \text{TAN}^{-1} \left(\frac{15}{1 \times 21} \right) = 35.5^\circ$$

$$\psi = 90 - \alpha = 54.5^\circ$$

OUTER PANEL UNSHIELDED ($n = 1$)

$$\alpha = \text{TAN}^{-1} \left(\frac{15}{2 \times 21} \right) = 19.6^\circ$$

$$\psi = 90 - \alpha = 70.4^\circ$$

Figure III-26. Oblique Wind Loading Geometry

TABLE III-4. WIND DRAG AND LIFT FORCES FOR OBLIQUE WINDS

DRAG FORCES											
n	α	ψ	$C_{DU}^{(1)}$	D_U	D_{YU}	R_{DYU}	$C_{DS}^{(2)}$	D_S	D_{YS}	R_{DYS}	R_{DY}
1	35.5°	54.5°	1.1	4.08	3.32	1.66	0.4	1.48	1.21	.605	11.8
2	19.6°	70.4°	0.8	2.97	2.80	1.40	0.3	1.14	1.05	.525	11.9
LIFT FORCES											
n	α	ψ	$C_{LS}^{(1)}$	L_U	L_{ZU}	R_{LZU}	C_{LS}	L_S	L_{ZS}	R_{LZS}	R_{LZ}
1	35.5°	54.5°	1.0	3.34	3.34	1.67	1.0	3.34	3.34	1.67	26.7
2	19.6°	70.4°									

(3)

$$\begin{aligned}
 D_U &= 9 A C_{DU} S_V \\
 D_S &= 7 A C_{DS} S_V \\
 L_U &= 7 A C_{LU} S_L \\
 L_S &= 7 A C_{LS} S_L
 \end{aligned}$$

$$\begin{aligned}
 q &= 25 \text{ PSF} \\
 A &= 148.3 \text{ ft}^2 \\
 S_D &= 1.0 \\
 S_L &= 0.9
 \end{aligned}$$

- (1) Based on reference 3 data for C_i is a function of ψ
 (2) Based on general trend of shielded drag coefficients being approx. 1/3 of unshielded drag coefficients
 (3) Insufficient data available on C_L vs ψ

5. Mounting Constraints

Building Considerations

Design objectives for the collector support system include minimum impact on plant operation and structural independence from the building.

Since normal plant operation requires clear traffic area within the plant for moving large rolls of stock, and clear traffic areas outside the plant for loading and trucking, the effects of support columns must be minimized. This can be accomplished by installing support columns at or adjacent to existing columns.

A review of the building layout shows a structure of rigid frames spaced generally at 35 feet, each supported by the frame ends and two interior columns, except in the area of the corrugator as shown in figure III-27. In the area of the corrugator, one of the interior columns has been omitted at each frame to allow access to the corrugator during operation. This area then dictates a free span of 105 feet for the collector support structure. In all other areas, the span requirement is 63 feet. A study was made to determine the most cost-effective approach for bridging the 105 foot span.

Another important consideration regarding the existing new Bates building is the effect on the building of the collector support structure. A completely independent support structure is desirable but not necessarily economical or dynamically feasible at reasonable cost. The free span required to clear the entire width of the building would be greater than 150 feet in all areas of the building and the support structure cost might be substantial. A compromise approach is proposed in which the collector support structure is supported at columns adjacent to the existing column. This concept requires additional columns (and piers) at each of the existing columns and limits span requirement to 105 feet and 63 feet for an eight panel collector. The proposed preliminary design is based on these span requirements. The proposed concept has all the outside support columns completely independent of the building and all interior columns adjacent to existing columns. A flexible seal would be used at interior column roof penetrations to provide an environmental seal and maintain an independent support structure.

Figure III-27. Frame Structure of
Bates Building and
Grid Designation

Beam Tradeoff Studies

Three beam types were investigated to determine the most cost-effective means of bridging the 105 foot span prestressed concrete beams (double tee and I), steel I-beams, and open web joists. The result of this study are shown in figure III-28 and clearly indicate that open web joist beams would be the most economical support beams. Consequently, all support concepts considered were based on the use of open web steel joist beams.

LF = LINEAR FT.

PLF = POUNDS PER LINEAR FT.

		WT (PLF)	FAB. COST	INSTALL. COST	TOTAL COST	REMARKS
CONCRETE	8 DT 42	453 LT-WT	\$46/LF	\$8/LF	\$54/LF	W=WT. ONLY
	TYPE III I	583 NORM. WT.	\$61/LF	\$7/LF	\$68/LF	W=WT. ONLY (LAT. LOAD PROBLEM)
STEEL I						
W 30X99		99	\$40/LF	\$10/LF	\$50/LF (\$5250 PER BEAM	W=292PLF
OPEN WEB JOIST						
60 DLH 12		31	\$10/LF	\$3/LF	\$13/LF (\$1365)	W=292 PLF

Figure III-28. Beam Trade-Off Study

6. Analysis of Collector Mounting Structure

a. Overview

A typical section of the proposed collector support system in the area of the corrugator is shown in figure III-29. Collector joists support the collector vertically along each collector row and provide attachment points for the collector bearing blocks. Joist girders support the collector joists and provide support between columns. Large lateral joists, laying flat, support the collector drag loads and provide a maintenance walkway. Analysis of each of the primary structural members is presented. The joist network is supported by steel columns and reinforced concrete piers.

Analysis Approach

Design wind loads from sections 4 were used to size the vertical and horizontal open web joists for vertical (lift) and horizontal (drag) loads for the 105 foot and 63 foot spans. The reactions of these joists on the supporting joist girders were used to size the joist girders. Joist girder reactions were used to size support column and finally column loads used to size the piers under each column.

For this preliminary design analysis, all joists were sized on the basis of limiting deflections at each joist center to a maximum of 1/240 feet. The deflection criteria of 1/240 provides conformance with the building codes and drives the design toward a stiff structure which is desirable from a dynamics standpoint. It is important to maintain structural natural frequencies above the dominant wind frequencies.

Joist sizes were based on the standard load and deflection capabilities listed by the Vucraft Corporation (reference 4), one of the leading manufacturers of open web joists.

For this preliminary analysis, open web joist sizes were generally based on simply supported beam assumptions.

Column sizes were based on AISC recommended practices (reference 5) and concrete piers were sized using the approach outlined in reference 6.

Figure III-29. Collector Support System Member Designations.

b. Joist and Column Loading Detailed Loading Analysis

The vertical joists occur at each collector row and are sized on the basis of vertical wind loads and a deflection of $1/240$. Two spans are required, 105 feet and 63 feet.

Figure III-30 shows the equivalent uniform loads and selected joist sizes to limit deflection to $1/240$ under vertical wind loads or live loads (LL) for the two spans. Also shown are the joist weights, the total load capability of the joist to limit tensile stress to 30,000 psi, and the joist selected.

Horizontal Joists

Figure III-31 shows the equivalent uniform loads, horizontal reactions in the x direction, and selected joists to limit deflection to $1/240$, for wind drag loads in the x direction. Note that one horizontal joist occurs every two collector rows so this joist carries drag loads of two collector rows.

Longitudinal Joists

These Joists run longitudinally along the length of the building at collector panel gaps and react the collector moment loads caused by drag loads at height (H) and drive pylon torque loads. In addition, they transmit the collector drag loads to the horizontal joists. Figure III-32 shows collector wind loads at joist row B the corresponding moment induced in the longitudinal joist, and a joist selection based on LL for two conditions of joist end fixity (SS and FF).

Figure III-33 shows the same information for the drive pylon joist rows.

Joist Girders

Joist girders are selected from design guide tables of reference 4 using the joist girder loads of table III-5. Since the reference 4 joist girders tables do not list loads which produce deflections of $1/240$, the joist girders are selected on the basis of concentrated loads at panel points, and deflection is then checked.

Joist girder calculations for rows A, F, and I are shown in figure III-34, for wind LL. In all cases deflections under wind loads of the girders selected are less than the selected limit of $1/240$.

Columns

Typical columns supporting the collector support structures are shown in figure III-35. Columns for the preliminary design are I-beam section, free of lateral supports between the piers and collector joist girders, and carry lift and drag reaction as shown.

All column sizes were based on the design procedures outlined in part 3 of the AISC Handbook (reference 5). A preliminary size was obtained by calculating the required section modulus (S) for column bending loads at the base of the column for wind drag loads along the system X-axis, using

$$S_{REQ'D} = \frac{M_x}{F_b}$$

where M_x = bending moment for X-wind loads.

F_b^x = allowable bending stress

$F_b = 0.6 F_y \times 1.33$ (using the permissible one-third increase in 1.5.6 of reference 5.

$F_y = 36$ KSI (allowable yield stress for A36 structural steel)

Axial stress (f_a) in columns was calculated using $F_a = F_z/A$ where F_z is the wind load at column in system Z axis and A is the cross sectional area of column. Allowable axial stress was taken from table I-36 of reference 5 based on kl/r where k is the end fixity factor (= 1 figure III-35), l is the column length and r is the column radius of gyration about the load plane of interest. Since f_a/F_a was always less than .15, the following interaction formula was used to check column adequacy.

$$\frac{f_a}{F_a} + \frac{f_b}{F_b} \leq 1.0 \quad \frac{f_a}{F_a} \leq .15$$

Finally, column bending stresses were checked for oblique winds using the loads from table III-4 ($S F_y$) and assuming these loads to be distributed evenly between the 3 or 4 columns (see figure III-35) at a given grid line. Calculations and beam properties are shown in tabular form in figure III-36.

$$V_A = 1.67 + 4(3.34)/2 = 8.35K$$

$$V_F = 3.34 + 4(3.34)/2 = 13.36$$

$$V_I = 1.67 + 2(3.34)/2 = 5.01$$

VERTICAL JOIST WIND LOADS AND REACTIONS

105' SPAN

$$W_e = 4 \times 3.34/105 = 127 \text{ PLF}$$

JOIST REQ'D	W_{LL}	W_{TL}	W_{WJ}
48LH12	135 PLF		31 PLF
52DLH10	156		27
			USE 27 PLF

63' SPAN

$$W_e = 2 \times 3.34/63 = 106 \text{ PLF}$$

JOIST REQ'D	W_{LL}	W_{TL}	W_{WJ}
28LH05	97		16
28LH06	126		19
			USE 18 PLF

Figure III-30. Collector Joist Loads
Vertical Joists

$$H_A = 5.94 + [21 (3.72) + 42 (3.72) + 63 (3.72) + 84 (7.80)]/105 = 16.7^k$$

$$H_F = 3.72 + [21 (7.80) + 42 (3.72) + 63 (3.72) + 84 (3.72)]/105 + [21 (7.80) + 42 (3.72)]/63 = 17.0^k$$

$$H_I = 5.94 + [21 (3.72) + 42 (7.80)]/63 = 12.4^k$$

Horizontal Joint Wind Loads and Reactions

105' Span

$$W_e = [7.80 + 3 (3.72)]/105 = 180 \text{ PLF}$$

Joist Req'd:

$$52DLH12 \quad W_{LL} = 1.86 \text{ PLF} \quad W_{TL} = 263 \text{ PLF} \quad W_{WT} = 31 \text{ PLF}$$

63' Span

$$W_e = [3.72 + 780]/63 = 183 \text{ PLF}$$

Joist Req'd:

$$32LH08 \quad W_{LL} = 188 \quad W_{TL} = 259 \quad W_{WT} = 21$$

Figure III-31. Horizontal Collector Joints

WIND LOADS ON LONGITUDINAL JOISTS (Joist Rows B, D, H)

For an 18" deep Longitudinal joist and 52" deep collector joist
 $H \cong 52 - 18/2 + 4 = 47"$

The concentrated moment load in the longitudinal joist is

$$M_R = 47 (3.90) = 183.3 \text{ IN-K (15.3 FT-K)}$$

Assuming a simply supported (SS) Joist

$$M_{\max} = w\ell^2/8$$

$$w_{\text{REQ'D}} = 8M/\ell^2 = 8 (15.3)/(15)^2 = .544 \text{ KLF (544PLF)}$$

Assuming a Fixed-fixed (FF) Joist

$$M_{\max} = w\ell^2/12$$

$$w_{\text{REQ'D}} = 12M/\ell^2 = 12(15.3)/(15)^2 = .816 \text{ KLF (816PLF)}$$

Using Joist 18LH02, $w_{LL} = 1576\text{PLF} > 816\text{PLF}$

$$w_{WT} = 13 \text{ PLF}$$

Figure III-32. Longitudinal Joist Loads

LOADS SHOWN
FOR ROW C

WIND LOADS ON LONGITUDINAL JOISTS (DRIVE PYLON ROWS C, G)

For an 18" deep longitudinal joist and 52" deep collector joist

$$H \cong 52 - 18/2 + 4 = 47"$$

$$M_R = 47(1.86) + 414 = 501.1 \text{ IN-K (41.8 FT-K)}$$

Assuming an SS joist

$$W_{REQ'D} = 8m/l^2 = 12(41.8)/(15)^2 = 1.485 \text{ KLF (1.485 PLF)}$$

Assuming an FF joist

$$W_{REQ'D} = 12m/l^2 = 12(41.8)/(15)^2 = 2.229 \text{ KLF (2229 PLF)}$$

Using Joist 18LH05,

$$W_{LL} = 2263 \text{ PLF} > 2229 \text{ PLF}$$

$$W_{WT} = 17 \text{ PLF}$$

Figure III-33. Longitudinal Joist Loads In Drive Pylon Joist Rows

TABLE III-5. JOIST GIRDER LOADS

	JOIST GIRDER A	JOIST GIRDER F	JOIST GIRDER I
COLLECTOR WIND LIFT (LL)			
WIND OVERTURNING MOMENTS, D&H (LL)			
COLLECTOR WT. (DL)			
COLLECTOR JOIST WT. (DL)			
HORIZ. JOIST WT. (DL)			
LONGITUDINAL JOIST WT. (DL)			
JOIST GIRDER WT. (DL)			
TOTAL REACTORS (DL ONLY)			
TOTAL REACTIONS (LL ONLY)			
TOTAL REACTIONS (DL + LL)

Deflection at midspan is given by:

$$\delta = \frac{2Wa^2(2-x)^2}{6EI2^3} [(3b+a)(2-K)-3b2]$$

$$\delta(\text{in}) = .194 \frac{W(\text{KG})}{I(\text{in}^4)}$$

DEFLECTION OF FIXED-FIXED BEAM

JOIST GIRDERS AND DEFLECTIONS AT MIDSPAN								
JOIST GIRDER ROW GRID LINES (4-8)	W (K)	P (K)	JOIST GIRDER DESIGNATION	d (in)	I ^x (in ⁴)	g (in)	2/240 (in)	W _{wt} (PLF)
A		3 (4**)	40G7N4K	40	1058	1.53	1.75	21
F	13.4	6	40G7NGK	40	1323-1588	1.63-196	1.75	23
I	5.01	2(4**)	40G7N2K	40	1058	1.53	1.75	<21 (use 19)

* I = .027 NP²d (reference 4)

** Smallest Listed For 35' Span in reference 4

Figure III-34. Joist Girder Sizing and Deflections

TYPICAL COLUMNS AT GRID LINES 4-8

TYPICAL COLUMNS AT ALL GRID LINES EXCEPT 4-8

TYPICAL COLUMN LOADS

COLUMN AND FIXITY ASSUMPTION
FOR K_L/γ

Figure III-35. Typical Collector Support Columns

COLUMN SELECTION FOR X-LOADS														
GRID LINES	ROW	N ¹	ℓ (FT)	F _x (K)	M _x (IN.-K)	S _{REQ'D} (IN. ³)	BEAM REQ'D	F _t (K)	f _u (KSI)	$\frac{K\ell}{r}$	F _a (KSL)	f _b (KSI)	$\frac{F_a + F_b}{F_a \cdot F_b}$ (3)	WT. (K)
1, 15	A, I	4	34	>12.4	5059.	>176.	W14x167 ²	>10.0	.204	63.6	17.04	18.9	.67	22.7
1, 15	D, F	4	36	10.7	4622.	161.	W14x167 ²	>16.7	.340	67.3	16.64	17.3	.62	24.1
2,3,9,10,11,12,14	A, I	14	34	12.4	5059.	176.	W14x111	10.0	.306	65.5	16.84	28.6	1.0	51.8
2,3,9,10,11,12,14	D, F	14	36	10.7	4622.	161.	W14x103	16.7	.551	69.6	16.43	28.1	1.0	51.9
4,5,6,7,8	A,	5	34	16.7	6814.	237.	W14x150	16.7	.379	64.0	17.00	28.3	1.0	25.5
4,5,6,7,8	F	5	36	17.0	7344.	256.	W14x167	26.7	.544	67.3	16.64	27.5	.99	30.0
4,5,6,7,8	I	5	34	12.4	5059.	176.	W14x111	10.0	.306	65.5	16.84	28.6	1.0	<u>18.9</u>
														225.9

CHECK COLUMN STRESSES FOR OBLIQUE WINDS				
GRID LINES	ROW	F _y (K)	M _y (IN.-K)	(f _b) _y (KSI)
1, 15	A, I	11.9/4=2.97	1212	12.0
1, 15	D, F	2.97	1283	12.7
2,3,9,10,11,12,14	A, I	2.97	1212	19.5
2,3,9,10,11,12,14	D, F	2.97	1283	22.3
4,5,6,7,8	A,	11.9/3=3.97	1620	17.9
4,5,6,7,8	F	3.97	1715	16.9
4,5,6,7,8	I	3.97	1620	26.0

(2) USE LAYER SECTION ON END COLUMN SINCE ENDS ARE UNSHIELDED.

(1) N= TOTAL NUMBER OF COLUMNS OF LENGTH ℓ AT GRID LINES SHOWN.

(3) $F_b = 0.6(36)(1.33) = 28.7$ KSI

BEAM PROPERTIES
BEAM	A	d	b _j	AXIS x-y			AXIS y-y			
				I	S	R	I	S	R	
W14x111	32.7	14.37	14.62	1270.	176.	6.23	455	62.2	3.13	
W14x103	30.3	14.25	14.57	1170.	164.	6.21	420	57.6	3.72	
W14x150	44.1	14.88	15.51	1790.	240.	6.37	703	90.6	3.99	
W14x167	49.1	15.12	15.60	2020.	267.	6.42	790	101.	4.01	

Figure III-36 Collector Columns

c. Pier Design and Analysis

Comprehensive criteria for the foundation design were defined. These criteria consisted of foundation loads, performance requirements and geotechnical parameters. The applied loads are the same as the design criteria for the independent roof structure discussed earlier in this section. Worst case is any applied load of 25psf with the collector stowed. The preliminary foundation concept has been evaluated against the following performance requirements:

- (1) Ability to support applied foundation loads with desired factors of safety of approximately 1.50 in the worst case situation.
- (2) Permanent displacement under maximum loading conditions: +0.2 inch either vertically or horizontally.
- (3) Miscellaneous:
 - familiarity of contractors with the construction technique
 - interference with the collector array operation
 - location of base of the foundation below the frost line.

In addition to these requirements, the foundation costs have been kept to a minimum. It will be possible to use a cylindrical reinforced concrete pier design under the field conditions we have for the Bates project.

Subsurface conditions for the site consist generally of the followings stratigraphy from reference 7:

<u>DEPTH (Feet)</u>	<u>STRATUM DESCRIPTION</u>
0.0 - 7.0	Dark brown to tan and gray silty sand becoming a clayey sand then sandy clay.
7.0 - 13.0	Tan and gray jointed clay with sand and iron ore seams up to four-inches thick.
13.0 - 23.0	Tan and gray jointed shaley day with some lime stone and shale seams.
23.0 - 37.0	Gray shale with some blue limestone layers and seams.

Cylindrical reinforced concrete piers which meet the criteria for the performance requirements are considered to be the most cost-effective foundation system for use with the solar-collector arrays independent roof structure. A flight auger can be utilized to advance the hole of the proper diameter to the required depth and the hole will remain open without the use of forming until the concrete is poured. Minimum pier size will be 18" d with a maximum pier size of 30" 2 d for the longer clear span over the corregator. Only the interior building pins (29) will be affected by the solar collector array structure. Figure III-37 shows the soil reactions used for rigid piles in cohesive soils (from reference 6) and table III-6 show the piers required at the collector support columns.

Table III-6. PIER SCHEDULE FOR COLLECTOR SUPPORT SYSTEM.

GRID LINES	ROW	PIER SIZE
1, 15	A	24" X 27'
1, 13	D F	24" X 27'
2, 3, 9, 10, 11, 12, 14	A C	18" X 27'
2, 3, 9, 10, 11, 12, 14	D F	18" X 27'
4, 5, 6, 7, 8	A	24" X 27'
4, 5, 6, 7, 8	F	24" X 27'
4, 5, 6, 7, 8	C	18" X 27'

Figure III-37. Soil Reactions for Rigid Piers and Piers Schedule

7. Support Structure Concept Trade Studies

The first approach considered towards developing a structure and support the 3400 ft collector array was to mount the collector in a flat array (uniform height) over the Bates building using the standard 53 inches high SKI collector mounting pylons mounted to a joist girder network. This configuration, designated A, shown in figure III-38, demonstrated three major design points:

- (1) Mounting the collectors above the joist frame system using standard pylons required large support members to react the large overturning moments ($D \times H$) caused by collector drag loader (D) at pylon height (H).
- (2) Mounting the collectors in a flat array above the joist frame system minimizes collector shielding and required a more substantial joist and column support structure because of wind loads on the joist frame system as well as the collectors, (i. e. there is no common shielding between joists and collectors).
- (3) Due to the sloped roof of Bates building the column lengths required and maintains a flat collector array are substantial (approximately 50 feet).

a. Configuration A. Raised Pylons, Flat Array (Elevation View)

b. Configuration A. Raised Pylons, Flat Array (Isometric View)

Figure III-38. Collector Support Configuration A

Based on these considerations, configuration B was developed (figure III-39a) in which the pylons were eliminated, a different joist network was developed using vertical and horizontal joists long each collector row, the array was sloped to conform to the roof geometry, and columns were used at each collector row. Configuration B accomplished the following:

- (1) Moving the collector array down into the joist network eliminated the pylons, and allowed mutual shielding of collectors and joists.
- (2) Collector overtiming loads were greatly reduced by lowering the collectors.
- (3) Sloping the collector system vastly reduced exterior column length requirements, resulting in considerable cost savings.

Since configuration B required one set of columns per collector row (columns at 15'), and columns within the building represent a traffic obstruction problem for plant operation, an alternate configuration (B1) was considered in which columns were spaced at 35' and large joists were used along rows of columns to support the collector joists. One drawback of configuration B was the somewhat limited rotation into a stow position so this area was investigated.

Configuration C (figure III-39b) was investigated to provide more freedom of rotation of the collector into a more optimum stowed position attitude and still maintain the integral design and provide common wind shielding between joists and collector. However, configuration C required a notched collector joist to accommodate the collector receiver tube which is continuous across a half-row of collectors and this configuration also creates shading of the collector in operational attitudes.

a. Configurations B and B1. Integral Structure, Sloped Array (Elevation View)

b. Configuration C. Slotted Joists (Elevation View)

Figure III-39. Collector Support Configurations B, B1, and C

Configuration D (figure III-40a) is a variation of B except that diagonal members are used to carry joist overturning loads. However, the vertical loads would not be effectively reacted using D unless columns were used at each collector row, also, walkways would be difficult install and utilize because of the diagonal members.

A review of configurations A through D showed that the collector support system must include:

- (1) Vertical joists to carry the vertical wind (weight) loads between columns.
- (2) Horizontal joists to carry wind drag loads between columns.
- (3) Columns spaced at 35' (minimum) to coincide with interior columns and minimize interior traffic problems.
- (4) Some diagonal braces to react wind overturning moments (especially at the drive pylons).
- (5) Maintenance walkways to allow safe access to collectors.

Based on these requirements and the configuration weights and estimated costs as shown in table III-7, configuration E was selected for the preliminary design as a cost-effective means in safely supporting the collector system. This configuration is shown in figures III-40b and III-41. A stow angle of approximately 35° can be achieved which is a good compromise stow position based on the minimum drag attitude of approximately 65° for unshielded collector's and approximately 30° for shielded collectors. Minimizing drag loads reduces column sizes and cost.

One final configuration which would eliminate the problem of installing interior columns and which appears to be structurally feasible from a statics viewpoint is to provide a joist network which free spans the width of the building'. This design has not been pursued initially because the long span requirements (168' for an eight panel collector) imply a low frequency structure which would be undesirable from a dynamics standpoint. However, the dynamics of the 168' span should be investigated.

a. Configuration D. Diagonal Braces (Elevation View)

b. Configuration E. Integral Structure, Large Horizontal Joist (Elevation View)

Figure III-40. Collector Support Configurations D and E

TABLE III-7. CONFIGURATION WEIGHT AND COST SUMMARY

CONFIG.	VERT.	JOIST HORIZ.	WTS. (klb) LONGIT.	JOIST (klb)	TOTALS (k\$)	COLUMNS (klb) (k\$)	PIERS (k\$)	OTHER (k\$)	TOTAL (k\$)
A	147	76	114	337	135	368 147	30 (1)	15 (2)	32.7 (3)
B	105	108	41	254	102	263 105	38 (1)	10 (2)	255 (3)
B-1	105	108	96	309	124	241 96	24 (1)	10 (2)	254 (3)
C	147	61	83	291	116	241 96	24 (1)		236 (3)
D	SLIGHTLY LESS THAN B								
E	107	59	69	235	94	226 91	23 (1)	10 (2)	218 (3)

CONFIG.REMARKS

A	15 ROWS LONG COLUMNS, FLAT ARRAY, RAISED PYLONS, LATERAL SUPPORT JOISTS
B	31 ROWS SHORT COLUMNS, SLOPED ARRAY
B-1	15 ROWS SHORT COLUMNS, SLOPED ARRAY, INCREASED JOIST SIZES TO SPAN 35'
C	15 ROWS SHORT COLUMNS, SLOPED ARRAY, NOTCHED JOISTS, LATERAL SUPPORT JOISTS
D	31 ROWS SHORT COLUMNS, SLOPED ARRAY, DIAGONAL BRACES
E	14 ROWS SHORT COLUMNS, SLOPED ARRAY, LARGE HORIZONTAL JOISTS/WALKWAY

NOTES

- (1) PIER COSTS INCREASED BY 100% TO ACCOUNT FOR INTERIOR COLUMN INSTALLATION.
- (2) BRACES TO REACT COLLECTOR OVERTURNING (ESTIMATE).
- (3) COST DOES NOT INCLUDE STAIRWAYS, PAINTING, STEEL GRATING, AND HANDRAILS FOR WALKWAYS.

8. Conclusions

In accomplishing the preliminary design of the collector mounting structure, the following conclusions can be made:

- (1) An integral mounting structure sloped along the Bates' facility roof contour has been proven to be cost effective and structurally sound and in conformance with the most stringent requirements of the Ft. Worth Uniform Building Code. The design was the result of extensive cost trade-off analysis of a number of different structural designs.
- (2) This mounting concept is easily transferable to any other retrofit or new construction because it is not load coupled and essentially independent of the Bates building.
- (3) The mounting concept uses open web joists as spanning members, a result of a trade-off study of different members.
- (4) A compilation and assessment of the best available wind trading data for collector arrays has been made and a useful subset has been called.
- (5) The work is proceeding in the area of span length and stiffness of the entire structure. There is promise of further 10% savings in the cost of the roof structure and piers by using deeper members to span longer distances. This would obviate the need for about 25% of interior piers with corresponding savings. Also, savings in the roof joists would result because costs are not proportional to depth. Also, the proposed being based on a statics analysis with a deflection limit rather than stress limit to drive the design toward a stiff (high frequency) structure for dynamic stability/be overly conservative based on stress criteria. Further study will be pursued to develop an optimum design as regards structural frequency, deflection, and working stress levels.

D. Collector Subsystem

1. Collector Requirements

The function of the solar collectors is to provide thermal energy to a corrugation machine which requires 5000 pounds of 175 psi steam per hour. From meteorological data from the Dallas - Ft. Worth area, calculations predict that about 35,000 ft² of aperture are required. The steam generator is designed for heat transfer fluid provided in the 500°F range.

The collectors should be resistant to severe weather conditions including high winds, hail stones, moisture and dust. The reflective surface should be of a high specular reflectance and withstand frequent cleaning of dust and water spots. Other requirements are a 20 year system lifetime and ease of maintenance. An automatic tracking system for solar operation and automatic stow for inoperative hours is also required.

2. Concentrator Selection

The collector selected for the baseline design is the Solar Kinetics (SKI) linear parabolic trough with a 7-foot aperture, designated the T-700 (figure III-42). The current Solar Kinetics troughs have been evaluated by Sandia Laboratories and are considered one of the best systems available today. In order to insure a cost-effective industrial process steam application, competitive bids will be solicited from other linear parabolic trough manufacturers before the final system is selected.

The T-700 is manufactured in 20-foot long sections and constructed with aluminum components using a monocoque design with an aircraft-grade aluminum skin stretched over precision-machined cast aluminum bulkheads. The T-700 is also a low-cost collector system with a history of performance and has been fielded in a variety of solar energy applications. There are currently 7,000 square feet of T-700 collectors operating at the Willard, New Mexico, solar irrigation installation and a total of 67,000 square feet scheduled to be installed a number of other locations.

The reflector surface on the baseline trough is an acrylic film made by 3M, FEK-244, with an average specular reflectivity of 0.84. This surface is bonded to the excellent substrate provided by the collector skin. Weather testing has shown less than 4 percent specular loss over 3 years and no other unsatisfactory degradation. The T-700 has a single axis, hydraulically actuated tracking system. The unique tracking system provides adjustable tracking speeds, a rapid stow capability, and high tracking accuracy. The hydraulic system eliminates backlash found in mechanical systems from wind buffeting and cushions sudden loads, lessening greatly wear and degradation of tracking accuracy. The system is weather resistant, without exposed parts.

Solar Kinetics' rigid monocoque* aluminum mirror and no-lash hydraulic tracking* along with proven engineering concepts provide long life and low cost. Features of the system are:

- ① The black chrome plated steel receiver tube is surrounded by a dry air/argon annulus protected by Pyrex® glass tubing. Focus is adjustable during installation.
- ② A precisely constructed mirror surface is covered with metallized acrylic film, combining weather resistance and high reflectivity.
- ③ The parabolic contour of the cast aluminum ribs is N/C machine generated for an accurate focus.
- ④ The thermal expansion bellows allows for expansion of the receiver assembly and maintains a sealed, dry environment in the annulus.
- ⑤ An insulated stainless steel flex hose allows rotation of the collector with unrestricted flow.
- ⑥ Self aligning sealed ball bearings absorb structural loads maintaining collector motion without binding.
- ⑦ A forged steel flange carries torsional loads into the collector structure. Allows mirror installation with eight bolts.
- ⑧ The steel support pylon is galvanized for corrosion protection.
- ⑨ Mounting studs are a standard pattern for each collector.
- ⑩ This load bearing joint* protects the collector structure from strains induced by misalignment from foundation shifts.

*PAT PENDING

SPECIFICATIONS

T-700

MODULE WIDTH	95.0 IN
MODULE LENGTH	10/20 FT
MIRROR WIDTH	84.5 IN
SOLAR AREA (SQ FT)	70/140
REFLECTANCE	0.84
MAX VERT HEIGHT	105 IN
ROTATION AXIS HT	57 IN
TRACKING ANGLE	270°
STOW ANGLE	45°
SYSTEM WEIGHT	4.0 LB/FT ² (ALUMINUM) 7.0 LB/FT ² (STEEL)
RECEIVER TUBE	1.63 OD
ANNULUS MEDIUM	ARGON OR DRY AIR
SELECTIVE SURFACE	BLACK CHROME
ABSORPTIVITY	0.94-0.97
EMISSIONIVITY	0.18 @ 500° F
RECEIVER COVER	PYREX GLASS
MAX OPER TEMP	800° F
MAX OPER PRESS	600 PSI

Figure III-42. Description of Solar Kinetics T-700 Concentrating Collector

The collector structure is extremely resistant to deflection and damage because of its monocoque design and high grade aluminum skin. Natural hailstones up to 3/4-inch diameter have not caused damage to the aluminum skin in the Solar Kinetics test stand in Dallas. Extrapolation of wind tunnel test shows the T-700 able to withstand 90 miles per hour winds in the stowed position and steady 40 miles per hour winds at any focal position.

The performance of the T-700 collector system to date is based on manufacturer's data and collector performance models. The manufacturer's data shown in figure III-11 and section III-A are based on a combination of measured and extrapolated data from similar but smaller SKI collectors. BDM and Sandia Laboratories are currently evaluating the T-700 and will thus provide the certified data required by the PON. Additionally, through a nonlinear BDM has simulated circuit analog model the collector performance and has found excellent agreement with the SKI data. The full-sun efficiency of the T-700 in the Bates application at a bulk temperature of 450°F is about 62 percent.

The collectors will be mounted directly to the super structure without the collector pylons used on ground mounted systems. This method of installation reduces the cost of the collector field and also lowers the collector with respect to the super structure thus reducing the wind induced moment load. Two drives will be used per collector bank one on each side of the pitch of the roof. This reduces the turning moment on the drive and makes for an easy flex connection between the collectors on each side of the pitch. The actual mounting in place of the collectors is simply the bolting down of pillow blocks located on each end of the module. Each module is then coupled by a load bearing joint which protects the collector structure from strains induced by misalignment of structure shifts.

The collector field layout is treated in detail in sections III-A, and III-E.

E. HEAT TRANSFER FLUID (HTF) SELECTION

1. HTF Requirements and Candidate Fluids

In the broadest sense, thermal working fluid is any material capable of picking up or discharging heat. It can be a liquid, gas or even suspended solid particles. For the solar application, the fluid is most often a liquid (with gases used occasionally). The solar heat transfer is usually by simple heating or cooling of the fluid, without a change of phase (sensible heat). In the solar system, the thermal working fluid is used to transport energy gained in the collector field to the boiler.

The thermal working fluid needs to display several different physical properties and economic characteristics to be used in a larger solar collector system. These characteristics are summarized in figure III-43 for candidate fluids. The fluid must have good flow properties over the entire working temperature range of the system. That is, it must be easily contained in piping systems and capable of being transported from one area to another with a reasonably low amount of pumping energy required. Also, there should be as small a change as possible in physical properties such as viscosity and density over this same range of temperatures. Further, it would be highly desirable if the fluid did not become extremely viscous or freeze at the low temperatures encountered in the process. This would primarily be of concern during low ambient temperatures when the solar collectors were stored. Likewise, at the high end of the operating temperature range the vapor pressure of the fluid should remain reasonably low, such that the fluid would not boil at the operating pressure.

It is extremely important that the fluid have a high degree of chemical stability from both operational cost and maintenance considerations. It should not produce products with low molecular weights (lights) which might tend to either form gas bubbles or would vaporize in an open area such as an expansion tank. These effects can cause difficulties such as vapor lock in the system and loss of the fluids through atmospheric vents. Likewise, the fluid over a period of time at the working temperatures should not tend to form heavy molecular weight compounds which result in sludges which tend to settle out in lines or deposit on the walls of heat transfer surfaces such as in the collectors and heat exchanger. A low degradation rate implies lower replenishment costs.

With a distributed collector and receiver field, large quantities of fluid are required; therefore, one of the most important fluid parameters is cost. Many fluids were considered and a subset of these materials was quickly identified, and are listed in figure III-43.

FLUID	MAXIMUM OPERATING TEMPERATURE		POUR POINT		LOWEST PUMPING TEMPERATURE		VAPOR PRESSURE @ MAX. TEMP.		FLUID COST		BASIC COMPOSITION	COMMENTS
	°C	°F	°C	°F	°C	°F	mm Hg	K Pascals	\$/Gal.	\$/Ltr.		
Caloria NI-43	316	600	-9	15	-6	21	570	76	1.01	0.27 (3) @550	Cut from distillation of crude oil	Petroleum based fluid manufactured by Exxon. Inexpensive with low degradation up to 316°C (600°F). Selected as low temperature backup because of less desirable low temperature fluidic properties.
Therminol 55	316	600	-40	-40	-21	-5	352	47	2.01	0.27	Alkylated benzene	Therminol 55 - One of the petroleum based fluids produced by Monsanto Chemical, has an operating range of -18 to 316°C (0 to 650°F). This fluid is inexpensive with low degradation temperatures.
Therminol 66	343	650	-28	-18	3	38	512	68	7.00 to 8.51	1.85 to 2.25	Diphenyls	Therminol 66 - Another Monsanto Chemical Company product that is a synthetic petroleum based derivative. This fluid costs \$1.85 litre (\$7.00/gallon) and has an operating range of -18 to 343°C (0 to 650°F). It, like T-55 can not be used at the maximum expected LFPP temperatures. Has been eliminated by high cost as compared to T-55.
Therminol 88	399	750	145	293	145	293	1100	147	~9.00	~2.38	Terphenyls	Therminol 88 - The high temperature petroleum based derivative produced by Monsanto Chemical. The operating range is 140 to 399°C (300 to 750°F) which is more acceptable on the high side but requires special consideration for low temperatures. At temperatures below 145°C (293°F) T-88 is a solid. Eliminated on basis of cost.
MCS2067	399	750	144	290	144	290	~760	101	5.50	1.45	Polyphenyls	MCS-2067 - A product of Monsanto Chemical has good high temperature stability but solidifies at 144°C (290°F). Costs about \$1.45/litre (\$5.50/gallon). Exhibits good heat transfer characteristics; because of relatively low cost may be used as the high temperature fluid.
Syltherm 800	399	750	-48	-54	-46	-50	ND (1)		16.00	4.22	Polydimethyl-Siloxanes	Syltherm 800 - A silicone based product by Dow Corning. Has most of the properties needed for LFPP up to 399°C (750°F) but is very costly \$4.22 litre (\$16.90/gallon). This fluid is considered as a likely fluid to be used in the high temperature field.

Figure III-43. Summary of Heat Transfer Fluid Characteristics

Organic fluids encompass an extremely wide range of properties, from very low boilers to very high boiling compounds, but in general this family of fluids has been one of the principal heat transfer materials used throughout the years in many commercial areas such as the chemical process industry. The organic fluids considered met most of the requirements for a desirable heat transfer fluid, but none was completely free from problems. One of the main problem areas was the inability of the fluids to remain unaffected at the upper end of the operating temperature range and still be in the low cost (<\$10/gallon) region. The major effects were extremely high fluid losses, formation of sludges, or boiling of the fluid at ambient pressures. It can easily be noted from the figure that by the large number of organic fluids mentioned, that these were considered quite extensively in the study because of their good overall heat transfer fluid characteristics.

2. HTF Selection

The thermal working fluid selected to be circulated through the solar system is Therminol-55 made by the Monsanto Chemical Company. Reasons for its selection are its low cost, excellent fluidic properties and chemical stability in the operating range of -40 to 600°F. This is partly because it is a synthetic product so that its chemical composition is more controllable than crude oil cuts such as Caloria HT-43. A summary of its properties is shown in figure III-44.

Designed as a heat transfer medium, Therminol-55 has excellent stability at temperatures below 600°F with degradation of about 1 percent per year (2500-hour year at $T_{avg} = 500^{\circ}\text{F}$) and low vapor pressures (< 350mm) at elevated temperatures. Freezing is not a problem because of its -40°F pour point and the relatively high winter design (99% level) temperature of 20°F at Fort Worth, Texas, where Bates is located.

Alternative fluids such as Caloria HT43, Syltherm-800, VP-1, (vapor phase) etc., were considered, but not chosen because of degradation, high cost, and operational handling respectively. Salts were not candidates because of the low operating temperatures, freezing, and corrosion problems.

Therminol 55 (T-55) is a synthetic hydrocarbon mixture with an operating range of -5°F (-20.6°C) to 600°F (315°C) and a pour point of -40°F (-40°C). It is used extensively for moderate temperature non-pressurized thermal applications. It offers good viscosity characteristics (pumpable to -5°F (-20.6°C)) and a high specific heat and thermal conductivity. A tabulated summary of general properties is shown in figure III-44 with detailed temperature versus property relations in figures III-45 and III-46.

The following information is from the manufacturer's literature: Therminol 55 is not classified as a fire-resistant heat transfer fluid. Consequently, the use of protective devices may be required to

Composition	Synthetic Hydrocarbon Mixture
Appearance.	Clear Yellow Liquid
Specific Gravity, 60°/60°F. . .	.0.880-.910
Kinematic Viscosity @ 100°F . .	.20.5-34.1 cSt
Moisture Content.	.250 ppm, max.
Pour Point.	.-40°F.(-40°C.)
Flash Point, COC.	.350°F.(177°C.)
Fire Point, COC.	.410°F.(210°C.)
AIT (ASTM D-2155.	.675°F.(357°C.)
Coefficient of Thermal Expansion	.0.00049°F. ⁻¹ (0.00087°C. ⁻¹)
Boiling Range	
10%	.635°F.(335°C.)
90%	.734°F.(390°C.)
Heat of Vaporization (Calculated).	.84.4 BTU/LB.(46.9 cal/g.)
Average Molecular Weight. . .	.318

Figure III-44. Typical Properties - Therminol 55

Temperature		Density			Specific Heat		Thermal Conductivity		Viscosity		Vapor Pressure	
°F.	°C.	lb/gal	lb/ft ³	g/ml	BTU/lb. °F.	Cal/g °C.	BTU/hr-ft °F.	kcal/hr-m °C.	Absolute lb/hr-ft	Kinematic cSt	torr (mm Hg)	g/cm ²
0	-18	7.57	56.6	0.907	0.431	0.431	0.0764	0.1137	3070	1400		
50	10	7.41	55.5	0.888	0.453	0.453	0.0749	0.1115	263	122		
100	38	7.26	54.3	0.870	0.476	0.476	0.0733	0.1091	56.6	26.9		
150	66	7.10	53.1	0.851	0.498	0.498	0.0717	0.1067	20.3	9.86		
200	93	6.95	52.0	0.833	0.521	0.521	0.0701	0.1043	9.77	4.85	0.2	0.27
250	121	6.79	50.8	0.814	0.543	0.543	0.0684	0.1018	5.62	2.86	0.7	0.95
300	149	6.64	49.7	0.795	0.566	0.566	0.0666	0.0991	3.64	1.89	2.3	3.12
350	177	6.48	48.5	0.777	0.588	0.588	0.0647	0.0963	2.55	1.36	6.9	9.38
400	204	6.33	47.3	0.758	0.611	0.611	0.0627	0.0933	1.90	1.03	18.2	24.7
450	232	6.17	46.2	0.740	0.633	0.633	0.0606	0.0902	1.47	0.82	43	59
500	260	6.02	45.0	0.721	0.656	0.656	0.0583	0.0868	1.19	0.66	93	126
550	288	5.86	43.9	0.702	0.678	0.678	0.0559	0.0832	0.98	0.58	187	254
600†	316†	5.71	42.7	0.684	0.700	0.700	0.0533	0.0793	0.83	0.50	352	479
650	343	5.55	41.5	0.665	0.723	0.723	0.0505	0.0751	0.72	0.45	626	851

†Maximum recommended bulk temperature: 600°F. (316°C.)

a) Tabulation of Properties With Temperature-Therminol 55

b) Graph of Physical Property Variation With Temperature

Figure III-45. Therminol 55 Properties - I

a) Therminol 55 - Pressure Drop Turbulent Flow Inside Clean Round Piping and Tubing

b) Therminol 55 - Heat Transfer Coefficients Turbulent Flow Inside Clean Round Tubing and Piping

Figure III-46. Therminol 55 Properties - II

minimize fire risk. To minimize fluid oxidation, systems utilizing T-55 fluid should be blanketed with an inert atmosphere. Therminol 55 heat transfer fluid is practically non-toxic by ingestion in single doses and by single dermal applications. It is a slight eye irritant and produces only a trace of skin irritation on prolonged contact. No special handling precautions appear necessary other than good industrial practice.

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 should be used in a closed, non-pressurized system free from leaks and with the expansion tank vent trapped so as to condense any vapors.

The quoted price of T-55 is about \$2 per gallon.

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F. ULLAGE AND FLUID MAINTENANCE

The heat transfer fluid used will be operated at an elevated temperature and will expand correspondingly. Therminol 55 has a thermal coefficient of expansion of $0.00049/^{\circ}\text{F}$ which when multiplied by the system capacity of 1100 gallons and by a 500°F temperature gradient results in a 270-gallon increase in volume. This tank is sized so that it will be one-fourth full at ambient temperature and three-fourths full at operating temperature as recommended by the fluid manufacturer. Therefore storage of 540 gallons will be provided for expansion and overflow to protect the system from over-pressure.

Therminol 55 as well as other heat transfer fluids will eventually oxidize and degrade when exposed to the atmosphere; therefore the overflow tank will be pressurized with commercial-grade nitrogen to act as a blanket to the fluid preventing outside air from contacting it. Nitrogen is used because of its inert characteristics, low cost, and commercial availability. The pressure will be regulated at both the nitrogen supply and also on the tank as a gas bleedoff when the fluid is expanding. Pressure for the incoming nitrogen will be kept at 1-2 psi above ambient pressure to insure a positive pressure when the system is thermally at a minimum. A pressure relief valve will be used to vent the gas as the fluid expands. The suggested arrangement (figure III-47) is in parallel with the main piping system to prevent pumping losses and to insure maintenance without affecting the main supply.

The ullage system is also functional in removing contaminants from the fluid through condensation. Noncondensable vapors will be automatically vented to the atmosphere with the nitrogen each day as the fluid is heated and expanded.

A fluid maintenance unit composed of a filtration device will be placed in parallel with the main supply (cold) line. A continuous bleed-off of a small percentage of the flow will be filtered to remove sludge formation.

THE BDM CORPORATION

For startup or venting operations, valves B, C, D & F are opened and valves A & E are closed. All flow passes to expansion tank; degasses; vents; and maintains flooded pump suction.

For normal operation, valves B, C, & F are closed and valves A, D & E are open. This arrangement provides normal return flow to pump suction with open static head line from tank to pump. Bypass line through valve D eliminates thermal siphon to expansion tank.

Figure III-47. Suggested Inert Gas Arrangement for Ullage System

G. HEAT TRANSPORT AND DISTRIBUTION SUBSYSTEM (HTDS)

1. Heat Transfer Subsystem (HTS)

The purpose of the HTS is to transfer energy from the solar collectors to the heat exchanger. It comprises all piping, insulation, pumps, and related components.

In designing the heat transport and distribution subsystem several factors enhanced the system layout. The piping system was determined to be mild steel pipe because of its cost, weldability, availability and adaptability to valving and couplers. The insulation material, alumina-silica fiber, was selected for its high temperature characteristics, non-wicking properties, ease of installation, pricing, and its low thermal conductivity. The choice for insulation thickness was the result of extensive analysis comparing the levelized cost of energy lost due to conduction to the levelized capital investment for a 20 year life. Furthermore, a cost trade-off between pumping loss and heat loss was made to determine the optimum piping size for each flow rate. The resultant design has optimized economically the pumping costs, heat loss cost, capital investment, and should provide a 20 year lifetime with a minimum of maintenance.

The major component is the piping system shown in the single line drawing, figure III-48. A trade-off was made between schedule 40 steel tubing with compression type fittings and schedule mild steel pipe with welded butt joints. The convenience of having a take-apart system for maintenance is clouded by the fact that it is nearly three times as costly as the welded mild steel system. Also, experience shows that the need for piping system dismantling is minimal except at the collector level which is already equipped with compression fittings. Therefore, on the basis of cost the system will use welded mild steel piping for fluid transport. Pipe size in the main headers is tapered, the result of a cost analysis between pumping losses and heat transfer rates for different diameter pipes and to balance flow in the HTS. The collectors are directly manifolded into the main supply and return headers. The return (hot) header has its own mixing tank to assure uniform approach temperature to the boiler.

Valves have been located to permit control and isolation of individual collectors and sectors of the main header for repair. Each collector row has three valves: two automatic on/off valves with a hand jack at the inlet near the supply header, and at the return header and a temperature-control throttling valve at the outlet. Automatic on/off valves are located as shown in the supply and return headers to isolate sections for repair and minimize fluid loss in the unlikely event of a major break in the headers.

III-83

NOTES:

- ① MIXING TANK 75 GALLON @ 550°F 75 P.S.I.G.
- ② BLDG. HEIGHT = 27'
- ③ EXPANSION LOOPS WHERE NECESSARY.

BATES CONTAINER, INC.

DETAIL (A)
TYPICAL MANIFOLDING PER COLLECTOR ROW
(31 ROWS)

Figure II-27. Collector System Plumbing at Electrical Layout

A variety of commercial insulations for 500°-600°F outdoor applications are available. An essential requirement is that the insulator be nonwicking or could be installed safely in such a way as to be nonwicking for fire safety. Weatherability and minimal degradation of thermal and physical characteristics from humidity are needed. An aluminum-jacketed installation is preferred for its greater safety in the event of fluid loss.

A high temperature, variable speed pump will be located at the mixing tank discharge, and sized to provide 200 gal/min at 100 psia of head. Additional components comprising a fluid maintenance unit and ullage atmosphere are included.

2. System Study Approach

The approach used to determine the size and insulation thickness of the piping system was based on economic factors for initial installation costs and operating cost both in heat loss and pumping costs. Manufacturing data, independent tests, and technical papers on thermal conductivities and costs for various insulations were used to determine installed cost per linear foot for varying pipe diameters and insulation thicknesses. Lifetime, wicking, temperature stand-off ability, thermal conductivity, and price were considered in the final selection of the insulation most desirable for this project.

To determine the economics of the system, a computer model of heat transfer analysis was developed in which the pipe diameter and insulation thickness were varied and results tabulated for comparisons. The cost of energy lost was then calculated using the DOE economic model for determining fuel costs. The results were then plotted against the installed insulation cost to determine a minimum system cost for a 20-year lifetime. This gives the optimum economic insulation thickness for each pipe diameter considered.

To determine the optimum pipe diameter for each stepped flow rate, a pumping loss model was developed to calculate the head loss for different diameter pipes and varying flow rates. Again the DOE economic model for fuel cost was used and the cost for pumping losses was tabulated. The yearly cost of pumping losses was then compared to the installed piping yearly investment cost to finalize the optimum piping system layout.

To calculate the effect that pipe diameter and insulation thickness has on thermal energy dissipation, a steady state heat transfer equation for an oil carrying cylinder with variable conduction sheathing immersed in air (figure III-49) was programmed and the values for pipe diameter and insulation thickness were varied. For yearly losses, an average ambient temperature T_a was assumed using meteorological data from the Dallas-Ft. Worth area. The values for thermal conductivity were determined from manufacturing data and test studies for the operating temperature of the system. It is obvious from the calculations that the major contributor to impeding heat loss is the insulation material chosen. The results demonstrate an exponential characteristic as the insulation thickness increases and a linear dependency on ΔT and the thermal conductivity of the insulating material. Figure III-50 is the graphical representation of results compiled from the computer program using a thermal conductivity of 0.4 Btu/hr/ft² and a ΔT of 400°F. The plot of heat loss per foot versus pipe diameter is essentially linear for the various insulation thickness for pipe diameters of 1½ inches or greater. Below a 1½-inch diameter the values curve to no heat loss as the diameter goes to zero. It is apparent that although there is an energy savings as the thickness increases the change becomes decreasingly significant when the thickness goes above 4 inches.

To determine the economics of the operating heat loss a cost model was arrived at using the DOE Economic Analysis of Solar Industrial Process Heat Systems manual. The operating life of the system was set at a 20-year value, the internal rate of return at 10 percent a year, and a yearly fuel escalation value of 8 percent. A complete analysis of the levelizing procedure and system energy cost is covered in the following section. The yearly cost of heat loss was then the computed levelized cost factor for an escalating stream times the number of operating hours per year times the hourly system energy cost. These results will be compared to other operating costs in order to optimize sizes for the heat transfer system.

$$q = \frac{1}{2\pi h_i r_1} + \frac{\ln(r_2/r_1)}{2\pi k_a} + \frac{\ln(r_3/r_2)}{2\pi k_b} + \frac{\ln(r_4/r_3)}{2\pi k_c} + \frac{\ln(r_5/r_4)}{2\pi k_d} + \frac{1}{2\pi h_a r_5}$$

where:

T_i = fluid temp.

T_a = ambient temp.

r_1 = inside pipe radius

r_2 = outside pipe radius

r_3 = r_2 + insulation thickness

r_4 = r_3 + .002" for air gap

r_5 = r_4 + .016" for aluminum covering

h_i = surface coefficient of heat transfer for fluid

h_a = surface coefficient of heat transfer for fluid

k_a = thermal conductivity of black steel pipe

k_b = thermal conductivity of insulation

k_c = thermal conductivity of air

k_d = thermal conductivity of aluminum

Figure III-49. Heat Loss Analytical Model

Figure III-50. Thermal Losses for Insulated Pipe

3. Start Up Losses and Cost Model

Start-up costs of the system are the result of heat loss attributed to inoperative hours. The equation in figure III-50 can be used to calculate the steady state losses; however, for the period of non-operation of the plant, normally night time, the values of T_a and T_i are changing. To calculate the temperature T_i at time n hours the following equations were used in a marching fashion:

$$@ t = 0, MC_p (T_i - T_1) = q'_1 = f(T_i - T_{a_1})$$

$$@ t = n, MC_p (T_{n-1} - T_n) = q'_n = f(T_{n-1} - T_{a_n})$$

where MC_p is the effective thermal mass of the system = $(M_{\text{pipe}} C_{p\text{pipe}})$

$(M_{\text{oil}} C_{p\text{oil}}) + (M_{\text{insul}} C_{p\text{insul}})$ and T_1 = system temperature of time of

shutdown $\sim 480^\circ\text{F}$, and T_{a_i} is the ambient temperature.

From meteorological data obtained from the Dallas-Ft. Worth area, T_{a_i} can be determined for each hour.

Solving for T_i will then give the final temperature before start-up the following morning. Start-up costs will therefore equal to the energy required to raise the thermal mass of the system to operating temperature, namely $q = MC_p (T_i - T_1)$. These results apply only for the insulated piping, which includes the main supply and return line. The rest of the system is mounted in the receiver tube assembly and is exposed without insulation. Approximately 5000 feet of 1½-inch diameter pipe is uninsulated as opposed to approximately 900 feet of up to 4-inch diameter pipe. For preliminary purposes, the start-up penalty for the collector tubes assumes cooling over the contained fluid to ambient. Another concern is in prevention of thermosyphoning. With a system of manual valves, a thermal gradient between the receiver tube and insulated pipe causing density variations will allow a pumping action between the lighter hotter oil and the colder heavier oil. This action will eventually nullify any benefit that the insulation may have. Preliminary calculations indicate that valving or piping arrangements be provided to prevent thermosyphoning.

For the purposes of the PDR daily average start-up losses have been determined to be about 5 percent. Clearly these would be less or more seasonally.

4. Insulation Thickness Optimization

To determine the optimum insulation thickness for a given pipe diameter, an economic analysis was made comparing the levelized cost of capital investment for installation.

The capital investment is the sum of the material and installation costs. These values have been obtained from manufacturers and construction sources. The levelizing procedure was adopted from the Dickenson and Brown document with the DOE-recommended parameters.

In the previous section the relation between heat loss and insulation thickness for different size pipes was presented. It was apparent that although there are energy savings as insulation thickness is increased, the change becomes decreasingly significant when the thickness goes above 4 inches.

Figure 51 represents the yearly levelized costs of installed insulation and fuel cost per foot of pipe for pipe diameters from 1 to 4 inches. The insulation costs are dependent on D^2 , with D being the diameter of the pipe plus twice the insulation thickness. However for the relatively small thicknesses considered these curves appear almost linear. The fuel cost due to heat loss is exponentially decaying as the insulation thickness increases. The resultant total cost curve represents the sum of fuel costs plus the insulation costs and from it the minimum cost per foot of pipe per year can be determined. It is apparent from the total cost curves that yearly cost value is insensitive for several inches of insulation thicknesses with the minimum value centering on 6-inch thickness value.

Figure III-51. Insulation Optimization Trade Off

Figure III-51. Insulation Optimization Trade Off
(Concluded)

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5. Pumping Loss and Cost Estimate

To determine the energy required to transport the heat transfer fluid through the various piping systems, a steady state head loss equation was used, namely

$$h_L = f \frac{V^2}{2} \frac{L}{D}$$

where h_L = head loss per foot
 f = friction factor
 V = flow velocity
 L = length of pipe considered
 D = inside diameter of pipe

The friction factor f was determined to be fairly constant for the varying pipe sizes and flow rates considered and for the calculations was set at a value of 0.030. The flow velocity changes in the main headers with each additional step in the collector rows as the receiver tubes entered the header. The flow rate was varied from a minimum of about 7 gal/min for one receiver row to a maximum of 31 x 6.78 gal/min when the entire system would be collected. Once the head loss was determined the results were then used to determine the pumping requirements for each pipe diameter and flow rate considered. From the equation

$$P = h_L(m) (ME) \left(\frac{1}{1714}\right)$$

where P = power required
 h_L = head loss lbs/in²
 ME = Mechanical efficiency of pump ~ 47%
 m = flow rate in gal/min

the pumping power requirements were determined for an oil temperature of 500°F varying the different diameter of mild steel pipe and increasing the fluid requirements. The findings are summarized in figure III-52 which is a plot of pumping power versus flow rate for different diameter pipes.

The cost of pumping this fluid is derived by multiplying the pumping requirement by the levelizing function for an escalating stream and then by the cost of electrical energy at present value times the number of hours operated a year. These pumping costs can now be compared to other system costs for optimizing the system.

Figure III-52. Pumping Requirements

6. Pumping Losses Versus Piping Costs Optimization

The total cost per foot of the piping system can now be optimized for the various flow rates along the collector rows. Each row uses approximately 7 gpm at operating temperature and will be expanding correspondingly for 31 rows until 210 gal/min are collected for the pumping station. By adding the yearly levelized capital investment value for the pipe, insulation and installation costs to the levelized cost values of pumping and heat lost costs, a decision can be made as to what size pipe to use for each stage. Figure III-53 represents the yearly levelized cost per foot of pipe for the 31 stages of flow rates. For various pipe diameters, the asterixed values represent the pipe diameter at which the total cost is a minimum for that stage of flow. From these values an economically optimized piping system can be designed. In the final layout of the piping system both 1½" and 2½" diameter pipes were excluded and replaced with the next economic choice since only one stage was optimized by each. This has the benefit of reducing the number of connections and reduces needed and reduces the cost of installation.

Stage	1"	1¼"	1½"	2"	2½"	3"	3½"	4"
1	*3.39	3.70						
2	*3.50	3.75						
3	4.16	*3.90	4.00					
4		4.18	*4.13	4.50				
5			*4.35	4.56				
6			4.68	*4.66	5.13			
7				*4.79	5.19			
8				*4.97	5.26			
9				*5.20	5.35			
10				5.48	*5.47	5.49		
11					5.61	*5.55		
12						*5.61	5.93	
13						*5.68	5.96	
14						*5.76	6.00	
15						*5.86	6.04	
16						*5.97	6.09	
17						*6.10	6.14	
18						6.24	*6.21	6.48
19							*6.29	6.52
20							*6.35	6.56
21							*6.44	6.61
22							*6.53	6.66
23							*6.64	6.72
24							*6.75	6.78
25							6.87	*6.84
26								
27								
28								
29								
30								
31								

* Minimum Cost for Flow Stage

Figure III-53. System Piping Cost/Fit

7. Proposed Layout

The heat transport fluid has been determined to be most economically transported by mild steel pipe in a tapered configuration. mild steel pipe is easily welded in place and pipe adaptors, reducers, and fittings are readily available. Welded joints are recommended because organic heat transfer fluids at high temperatures have very low viscosities and a tendency to leak through joints and fittings. The control of piping leaks is especially important since fluid soaked insulation can slowly oxidize and cause temperature build up. This temperature build up can result in ignition when exposed to air for repair or inspection. The alumina silicate insulation chosen has nonwicking characteristics which isolate any leaks to the local area.

The proposed fluid control schematic figure III-54 was determined to be the most economically feasible for a 20 year life. Figure III-52 represented the yearly levelized cost of piping, insulation and fuel cost per foot for the various piping sizes considered. The results were then applied to the collector array and the design finalized. Both 1½-inch and 2½-inch were excluded in the schematic because only one section between collector rows could be optimized by their use and the additional joints needed for their installation add to the cost and leak probability of the system. As seen from the schematic the tapered pipe collects the heated fluid and is transported down the side of the building through 4-inch pipes to the pumping pad at the base of the building. From the pad the fluid is piped underground to the heat exchanger and then back underground to the pump. Then 4-inch pipe routes the fluid back up and across the field to the supply end of the collectors. The placement of the pumping pad has several advantages.

- (1) It is in line with the heat exchanger thus minimizing the amount of pipe required.
- (2) It reduces the amount of 4-inch pipe by splitting the collector bank into two sections.
- (3) The sound level inside the building is reduced.

The supply and return for the heat exchanger has underground placement for personnel safety in case of leakage. Both the supply and return manifold have their own mixing tank to assure uniform approach temperature to the boiler and to serve as a sump for the pump.

8. Balance of Subsystem Design and Fabrication

The balance of the subsystem includes the steam generators, pump, filter and related components. The steam generator will be a high temperature fluid to steam generator producing steam at 375°F, 175 psi at 5500 pounds per hour. This is equivalent to 5½ million BTU/hr and calculations show that 210 gal/min of 480° fluid with a temperature drop of approximately 95°F will be required. Figure III-55 is a schematic of the proposed steam generator that will be required in the thermal system. It is constructed with welded helical copper coils to transfer thermal energy from the heat transfer fluid to the water, and to prevent contamination from seeping into the make-up water from the heat source. The generator will be designed to be a closed system, i.e. all welded or brazed connections between tube sheets and risers. The generator will have a self-contained pressure regulator, check valves, feed water supply, water level control, pressure gauge, safety relief valve, condensate tank and necessary valving to control and isolate the generator.

The calculated head loss for the pumping system is 75 psi. This figure is for the heat transfer fluid at a temperature of 500°F which is the expected operating temperature. To handle the temperatures the pump will be of a magnetically driven centrifugal configuration with a 15 hp motor. This combination results in a 47 percent pump efficiency. These pumps are commercially available.

The fluid filter will be a commercially available unit and will be placed in parallel with a continuous fractional bleed through from the main return line and will be equipped with valves for isolating it for periodic cleaning. Also, a strainer for larger particles will be installed in line with the pump suction to prevent damage.

Figure III-56 is typical of fabrication procedures to be used in the construction of the heat transfer subsystem. Valving, pipe joints, reducers and any connections except to the flux hose will be either butt or socketed joint welded. Mild steel is easily weldable and is the surest way to prevent leaks. On the flex hose connections from the collectors, a Swagelok fitting will be used for easy disconnect in case of maintenance.

A 6-inch thickness of insulation will be used on all pipe diameters. Included in the installation will be a vapor barrier which precludes any moisture due to humidity or precipitation to penetrate causing degradation of insulating characteristics. This vapor barrier is commercially available from such companies as Kraft. In addition, pipes exposed to the weather are finished with a 0.016 inch smooth aluminum jacket which are pop-riveted in place. All piping is rigidly supported by pipe stands or hangers where necessary with provision for expansion through pipe loops.

Valves have been located to permit control and isolation of individual collectors and sections of the main header for repair. Ball valves are recommended for most operations as shown typically in figure III-57.

Figure III-55. Nonfired Steam Generator Schematic

• TYPICAL MANIFOLD CONNECTION •
(INSULATION OMITTED FOR CLARITY)

• TYPICAL INSULATION CONFIGURATION •

• TYPICAL GLOBE VALVE CONNECTIONS •
(INSULATION OMITTED FOR CLARITY)

Figure III-56. Piping System Details

Figure III-57. Typical Valve

9. Mechanical and Control Rooms

The layout of the mechanical room, figure III-58, is such that accessibility to each component for maintenance and service is easier. Housed in the mechanical room is the non-fired steam generator which is a double tank system. The heat transfer fluid to be used by the generator is fed and returned from a pump outside the building through 4" schedule 40 mild steel pipe. The double tank arrangement has the advantage of contributing to the energy requirements of the system with one generator if the other unit is down or being serviced. The non-fired generator is in parallel with the fossil fuel boiler also housed in the mechanical room. All control valving and plumbing will be housed in the mechanical room to isolate it from the main plant.

For steam generation water treatment is necessary to prevent tube fouling. Therefore a water conditioning unit that can handle the 5000 pounds of water needed to produce the steam required for plant operation will be installed. Also to conserve energy and water, unused steam will be returned to a condensate tank and then pumped to the boilers at a temperature higher than the feed water.

The control room figure III-59 will be isolated from the corrugator to reduce noise and prevent contamination to the instrumentation. The control room will house the data acquisition hardware which includes a Hewlett-Packard 9825-series programmable calculator, signal conditioner, cassette tape storage, and I/O display. Also in the room will be a Hewlett-Packard 9815 programmable calculator which will be used for system control. A panel will be used as a patchboard for signals from the collector array and heat transfer system to the HP9825 calculator. For visual observation of the system operating conditions, Bailey meters will be mounted for flow measurements of both the heat transfer fluid and steam. Pressure meters will also be installed to gauge fluid and steam conditions at the appropriate locations. The control panel will house all warning lights and controls to stop the system in case of over pressure, under pressure, over temperature, no flow and inclement weather conditions. An area will be set aside for storage of operating manuals, printout paper, data storage and miscellaneous materials.

Figure III-58. Mechanical Room

Figure III-59. Control Room

H. MASTER CONTROL SYSTEM (MCS) DATA ACQUISITION SYSTEM (DAS)

The major components and a functional diagram of the MCS and DAS are shown in figure III-60. They are:

- (1) The data acquisition hardware and software
- (2) The collector tracking, stow control, and safety circuit
- (3) The heat transfer fluid loop, pump flow, and safety circuit
- (4) The steam control circuit

The data acquisition hardware will consist of a Hewlett-Packard 9825-series programmable calculator with components to provide multiplexing, signal conditioning, cassette tape storage, and I/O display capabilities. The HP-IB interface will be incorporated. All sensors will be hard-wired to the DAS and will be continuously scanned, averaged and stored for retrieval if necessary, thus providing a record of system performance. Since the main computer is both programmable and able to initiate control functions, the sensor inputs are compared to acceptable and alarm levels. Corrective actions such as valve adjustments, closures and pump speed changes can be initiated if needed. Quantities to be measured are temperatures, flow rates, and on/off pressure indicators in the system. Other items include weather data, e.g., direct normal insolation, wind speed, rainfall, outdoor temperature, and derived performance figures such as collector efficiency, cumulative steam production, etc. A second Hewlett-Packard programmable calculator, Model-9815, will be used for data acquisition and storage and will have its own set of separate tape units. This is in line with a philosophy of separating the control from the data acquisition functions.

The collector tracking, flow and safety circuits are duplicated on each of 31 rows of collectors. Tracking control consists of a shadow band tracker mounted on the collector which aligns itself with respect to the sun until the shadow it casts is equal on two light sensitive cells. Tracking is initiated when unequal shadows electrically activate solenoid valves in the hydraulic tracking system and cause fluid to flow, thus moving the collector toward equal shadowing. Collector stow can be initiated by signal indicating low insolation, under pressure or over temperature. Low pressure detector and thermistors will be located on each row for flow control. These signals are input to the MCS which interprets them. If they are beyond alarm thresholds, collector stow and flow stoppage can be automatically initiated for each row or systemwide. Additionally, three valves make up the CS temperature control and safety controls. The first is located at the inlet and is an automatic of/off valve that can be closed from MCS signals arising through a noflow low pressure condition. It also can be manually operated. Its function is to stop flow into the collector in case of a break. The second valve is used for positive shut-off of the row outlet since the flow control valve is not designed for the function. The third valve is for flow control to obtain the proper outlet temperature from the row. This senses the row output temperature and fixes flow to meet the required temperature. In the event of a break this valve can be closed, thus isolating the collector row.

The heat transfer fluid loop, and pump flow, and safety circuit consist of pump speed controls, a series of automatic shut-off valves to isolate sections of the heat transfer loop and flow meters to detect leaks in the circuit. The flow meters are located on either side of the pump and insure that integrate fluid flows are equal.

The steam control circuit consists of a 3-way steam valve and an automatic stoker for the fossil boiler. Its function is to insure acceptable steam productions from solar steam by monitoring steam conditions and controlling flow and temperatures of the heat transfer fluid through the liquid/liquid steam generator. In the event of inadequate solar supply to meet the corrugator demand, the fossil boiler is activated sufficiently to produce makeup. A secondary function is to control condensate and makeup flow. Safety controls regulating the solar and fossil steam generator liquid levels, pressure relief valves, makeup water levels will also be installed.

Figure III-60. Schematic of Solar System and Controls

I. SUBSYSTEM TESTING

Prior solar industrial process heating applications have experienced component degradation due to various environmental effects and pollutants. In order to determine the causes and extent of environmentally induced component degradation, Sandia Corporation will establish test rigs at each application. These test rigs will contain coupons of the receiver tube coating and reflective surface material. Sandia will periodically collect and analyze these coupons to measure the extent and determine the causes of environmental degradation.

Sandia has prepared plans for the construction of test rigs for solar mirror weathering tests and a test chamber for black chrome weathering. Sandia will solicit competitive bids for the construction of the test rigs and chambers in January 1980. Procedures have also been established for periodic sample removal and return to Sandia for analysis.

Bates agrees with the procedures established for environmental testing and will provide the required electrical power connections for the tests. A subsidiary of Bates Container Machinery Corporation expects to submit a bid for the construction of the test racks when the solicitation is announced.

CHAPTER IV

PRELIMINARY PHASE II COSTS

A. COST BREAKDOWN STRUCTURE

The economic analysis of the Bates solar industrial process steam system is being conducted using the annual required revenue methodology developed by W.C. Dickinson and K.C. Brown (Economic Analysis of Solar Industrial Process Heat Systems: A Methodology to Determine Annual Required Revenue and Internal Rate of Return, UCRL 52814, August 17, 1979.) The Contractor Guidelines for Performing an Economic Analysis of DOE-sponsored Solar IPH System (October 4, 1979) are the required parameters which will be used for the complete economic analysis. For the purpose of the PDR, only the initial estimates of capital and recurring costs will be presented. These initial estimates will be updated as design decisions are made, and the economic analysis will be completed when the design is finalized.

The preliminary capital cost breakdown structure is shown in figure IV-1. These estimates are based on vendor quotes for installed equipment, which were obtained at the beginning of the program and will be revised. The estimates for indirect and other costs have been obtained from R.S. Means Building Construction Cost Data, 1979, 37th Annual Edition.

The present system preliminary capital costs approximately \$1,250,000 indicate a cost per million Btu of \$157 per year, slightly above the DOE guidelines. It is anticipated that as the final design is refined, this cost will drop to a level well within the DOE \$150 per million Btu guideline.

B. OPERATION AND MAINTENANCE EXPENSES

The estimates of operating, maintenance, property tax, and insurance costs are shown in figure IV-2. These estimates were developed from the following sources.

- (1) Collector - Solar Kinetics, the collector manufacturer, estimate of 1.5 percent of collector cost. This is based on SKI experience for systems already fielded.
- (2) Fluid Replacement - Based on experimental data for fluid degradation. Computed at total dollars in fluid times the fluid degradation rate.
- (3) Heat Transport System, Steam Generating System, Master Control System - Based on EPRI estimates of 0.5 percent of capital costs for power plant systems.
- (4) Property Tax - Based on the rate for Dallas/Fort Worth.
- (5) Insurance - Estimated at 0.25 percent of capital costs.

Bates Solar Industrial Process Steam System

Direct Costs	Amount
A100 - Capital Equipment	
A110 - Collector/Receiver	\$775,000
A120 - Fluid/Heat Transport System	
A121 - Fluid	2,000
A122 - Piping and Insulation	125,000
A123 - Pumps	7,300
A124 - Valves	10,300
A130 - Steam Generation Subsystem	
Boiler/Preheater/Feedwater Heaters	18,000
A140 - Master Control Subsystem	
A141 - Data Acquisition System	6,000
A142 - Instrumentation DAS	25,000
A143 - Steam Control	15,000
A144 - Electrical	8,300
A150 - Collector Mounting Structure	<u>254,000</u>
Total Capital Costs	\$1,245,900
Indirect Costs	
B100 - Construction Overhead	
@ 5% of Capital Costs	\$ 62,500
B200 - Design and Engineering	
@ 2.5% of A120-150	<u>11,900</u>
Total Indirect Costs	\$ 74,400
Total Direct & Indirect	\$1,324,400
Other Costs	
C100 - Contingency	
@ 2% of Capital Costs	\$ 25,000
C200 - Fee	
@ 5% of Total Direct Costs	<u>66,200</u>
Total Cost	\$1,415,600

Figure IV-1: Preliminary Cost Breakdown Structure

ITEM	AMOUNT
1. Collector	\$11,600
2. Fluid Replacement	20
3. HTS, SGS, MCS, CMS	2,400
4. Insurance	3,100
5. Property Tax	<u>1,500</u>
TOTAL OMPI	\$18,620

Figure IV-2. Annual Operating, Maintenance, Insurance and Property Taxes .

C. COST ANALYSIS

The preliminary system capital costs were developed for a number of configurations to select the most cost-effective design. Figure IV-3 compares the preliminary capital costs of three collector mounting alternatives for the Bates Solar Industrial Process Heat array. Configuration A represents the completely roof-mounted structure that has evolved after substantial trade-offs and design refinements which are fully documented in section III-C of this report. Option B is a mounting scheme with one-half the array above a parking and loading area that is necessary for the Bates facility with the balance ground-mounted on presently vacant land adjacent to the plant. Option C is a completely ground-mounted facility which would require acquisition of additional adjacent land for sufficient area to contain the collectors. As the preliminary capital cost figures indicate, the roof-mounted integral structure is slightly (about 10%) less expensive and clearly competitive. This is primarily because of the high land cost and the elimination of the collector pylon and ground pier costs. Land costs were estimated conservatively at \$ 2 per square foot. The innovative mounting design for the roof uses the joint support members to support the collectors directly without the use of pylons. It is clear that in a non-retrofit situation the lower part of the support structure could be the superstructure for a roof and ceiling so that a substantial offset in collector mounting costs could be realized by the cost sharing with a roof frame. Another advantage of a roof-mounted structure is that its costs are a depreciable quantity.

The above ground-mounted collector system concept A is also more cost-effective on the basis of the levelized annual required revenue by approximately 4 percent. Table IV-1 shows the levelized annual required revenue calculated using the Dickinson Brown methodology and DOE guidelines for a 10 percent rate of return. The salvage value of land for configurations B and C is assumed to be the price of land when originally purchased. Also, the entire solar investment is assumed to be provided by Bates with no financing.

		CONFIGURATION		
	ROOF STRUCTURE INTEGRAL OPTION (A)	PARKING LOT ROOF (1/2) GROUND MOUNTED (1/2) OPTION (B)B		GROUND MOUNTED OPTION (C)
		PARKING LOT	GROUND	
JOISTS	\$101,000	\$ 50,500	0	0
COLUMNS	90,000	59,400	0	0
PIERS	12,000	8,000	0	0
ROOFING	0	98,000	0	0
LAND	0	0	77,000	153,000
SITE PREP	0	0	38,000	75,000
COLLECTOR	775,000	388,600	437,000	874,000
BALANCE OF SYSTEM	<u>268,000</u>	<u>780,000</u>	<u>7,000</u>	<u>231,000</u>
TOTAL	1,250,000	1,440,000		1,333,000

Figure IV-3. System Capital Cost Trade-off Analysis

TABLE IV-1. LEVELIZED ANNUAL REVENUE REQUIRED
IN THOUSANDS OF DOLLARS

Configuration A	Configuration B	Configuration C
Integral Roof-Mounted	Parking Lot 1/2 Ground-Mounted 1/2	Ground-Mounted
182	202	.190

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