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Proceedings of the Distributed Solar Collector Summary Conference — Technology and Applications

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Albuquerque, New Mexico

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ABSTRACT

This report is the Proceedings for a meeting on distributed solar collector systems technology held at Albuquerque, NM in March 1983. The meeting covered research on development of components and subsystems, systems engineering and analysis, the results of the MISR project, including system design descriptions and test results, and finally, operating experiences and performance data from distributed collector experimental field projects.

DISTRIBUTED SOLAR COLLECTOR SUMMARY CONFERENCE --
TECHNOLOGY AND APPLICATIONS

Conference Objectives:

- To provide for the dissemination of subsystem technology that has been developed within the past years by both government and industry.
- To present the results of the Modular Industrial Solar Retrofit Project (MISR) and present the four MISR test systems located at Sandia National Laboratories to the attendees.
- To provide up-to-date operational experiences on most of the DOE sponsored Industrial Process Heat (IPH) experiments.
- To provide an opportunity for potential solar system users, solar system manufacturers and marketers, and solar system technical investigators to meet and exchange technical viewpoints.

SANDIA SOLAR THERMAL PROJECTS

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Project Divisions:			
Solar Research & Evaluation Division		9721	
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SESSION I

DISTRIBUTED COLLECTOR TECHNOLOGY UPDATE

Session Chairman: J. F. Banas

ACUREX LINE-FOCUS COLLECTOR DEVELOPMENT

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Introduction

The Acurex Solar Model 3011-01 Concentrating Collector and related tracker and controls were developed under cooperative agreements between the Department of Energy and Acurex Corporation. The line-focus collector system was developed to a fully operational prototype with complete performance characterization under these agreements. Sandia National Laboratories in Albuquerque (SNLA) provided the technical overview for these product developments.

This fourth-generation Acurex collector is a significant advancement in the state of the art of medium-temperature solar thermal collectors. Major improvements were made to increase collector performance and reliability, and decrease manufacturing and installation costs.

All of the elements of the Model 3011-01 collector system were incorporated into the Modular Industrial Solar Retrofit (MISR) program addressed in separate Acurex and SNLA papers.

Design Approach

The basic design goal for the development of the Model 3011 collector was to significantly improve performance and cost. An early evaluation of the third-generation Model 3001-03 collector and of alternate collector and component concepts indicated that the Model 3011 development goal would best be achieved through our Model 3001 experience, by "evolution, not revolution." The specific design improvement goals were to:

- Improve total efficiency by optimizing optical efficiency and minimizing thermal losses
- Reduce manufacturing cost by designing for automated high-production approaches
- Reduce field alignment cost by designing self-aligning subassembly mating interfaces
- Reduce field installation cost by factory assembly and checkout of subassembly components in single shippable units
- Reduce shipping cost by increasing module packing density
- Reduce operation and maintenance cost by specifying long-life, maintenance-free components and finishes

The collector system design was based on the following operating conditions:

- 25-mph operating wind speed
- 80-mph survival wind speed in stowed position
- Withstand 3/4-in. diameter maximum hail size at 55 ft/sec maximum speed
- -20° to 120°F (-29° to 49°C) ambient temperature operating range
- Perimeter wind fence required with 50 percent maximum porosity

- 3- to 15-gpm flowrate operation range for water or heat transfer oils
- 40-psi maximum operating pressure
- 200° to 600°F (93° to 315°C) average bulk fluid temperature range at outlet
- 1/4-g lateral and 1-g vertical acceleration survival due to seismic loading with any collector orientation

Specific dimensional and component selections were based on trade-offs which considered:

- Material and component availability
- Handleability in the factory
- Shipping limitations and costs
- Collector manufacturing costs
- Installation costs
- Structural constraints
- Performance constraints

Collector System Description

Collector Group

The building block for large collector fields is a six-module group or drive string (figure 1). The six modules, connected to form a group of collectors, are driven by a single drive unit at the center of the group (figure 2). The collector subsystems and basic group dimensions are shown in this figure.

Reflector Module Subsystem

The reflector module aperture is 20 ft x 7 ft, with a rim angle of 90°. The reflector structure uses a galvanized torque tube with welded rib flanges to which the two rib halves are riveted to form an accurate parabolic contour. Each rib is stamped Galvalume with two angle stiffeners riveted to it.

The reflector panel is a thin glass laminate of two silvered glass mirrors bonded to a steel substrate. Six panels are installed in each module and are retained by edge clamps which force the panels into conformance with the ribs. The module with reflector panels installed is a very stiff structure requiring no additional bracing or back panels.

The crank at each end of the torque tube positions the tracking axis coincident with the module center of gravity. A unique key perpendicular to the crank pivot centerline allows accurate module-to-module alignment and quick, single-bolt module installation.

Thermal Subsystem

The primary receiver components are:

- Black-chrome-plated carbon steel receiver tubes, 1.25-in. outside diameter and nominally 20 ft long

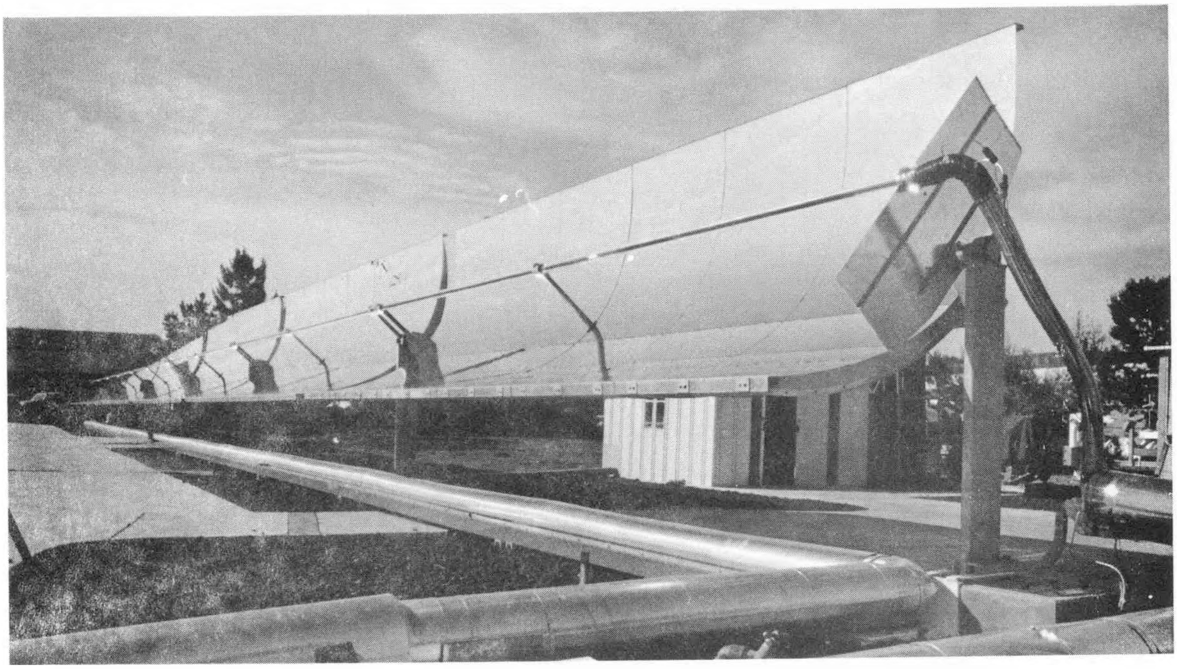

Figure 1. Model 3011 Collector, Acurex Solar Energy Test Facility Installation

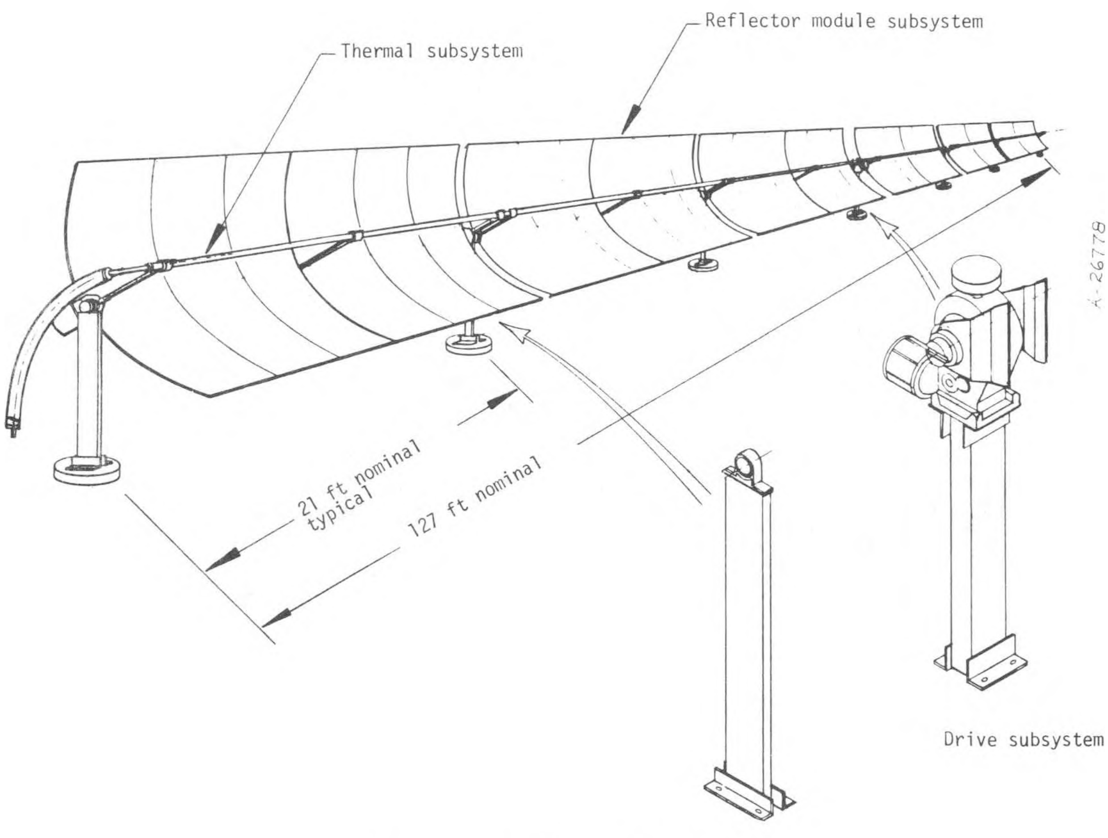

Figure 2. Collector Subsystems

- Pyrex receiver glazings, 2.125-in. outside diameter and nominally 10 ft long
- Split ring receiver tube supports and environmental barriers
- Glazing seals
- Split collars which form the support assembly

The receiver assembly is mounted on fixed supports at the ends and middle of each module. The split collars provide self-alignment of the assembled receiver so that no field alignment is required. The receiver tube is fixed at the drive and is free to thermally expand in each direction along the half-length of each group. Module-to-module connections of the receiver tubes are accomplished with swage-type tube fittings. This intermodule region is enclosed by a split glazing to minimize thermal losses.

A flexhose at each end of the drive string provides the connection between the receiver tube and the near-grade piping.

Drive Subsystem

A custom-designed sealed gear drive with 1,000:1 speed reduction provides the collector string tracking. The gearbox is driven by a permanent magnet AC stepping motor which provides quick, accurate, and reliable start/stop capability. The gear box incorporates a slip clutch and a stop arm to minimize structural loads and damage during severe wind conditions.

The drive and nondrive support posts are rectangular steel tubes with angle foundation footings for low-cost manufacture and quick installation. The intermodule bearings are self-lubricating and require no maintenance.

Tracker and Controls

Collector group control is accomplished through:

- Master controller
- Solar Tracking Angle Reference (STAR)
- Tracker controller
- Alarm sensors

This control set provides completely automatic operation of a collector field and industrial process heat system. The STAR serves a complete collector field and senses the insolation level and approximate sun angle through a series of photodetectors. The STAR insolation level and angle signals provide the go/no-go and approximate sun acquisition commands to the tracker controllers which are mounted at and control each drive unit. The tracker controller has an inclinometer for approximate sun acquisition and a light-band, single-chip, multi-element, photodiode for precise acquisition and continuous tracking. Position updates are made at approximately every 0.2°. The necessary tracking control logic to maximize thermal output and to minimize thermal losses and system parasitics under intermittent cloud and low insolation conditions is built into the control system.

The master controller provides a complete display of system status and also allows manual system operation. Manual collector group operation is also allowed by a control at each drive unit. Alarms, such as overtemperature, high wind speed, or low flow, are indicated at and acted upon by the master controller which automatically commands the proper collector field or system safety and survival actions.

Prototype Performance

A detailed series of tests were conducted in the Acurex solar test facility to characterize the optical, thermal, and operating performance of the collector system. These tests were performed on the six-module prototype group (figure 1) and on a complete single module installed on our two-axis tracking platform. These tests are identified in table 1.

The collector efficiency, the fraction of incident solar energy converted to thermal energy, is shown in figure 3. Comparison of this performance with the earlier Model 3001-03 collector is presented in a later section. The efficiency of figure 3 is for incident solar energy normal to the collector axis (0° incident angle). The incident angle modifier, the multiplier for normal incident performance due to incident angle, was measured to be unity to incident angles of about 40°.

Accelerated mechanical cycling tests, which included warmup, at-temperature, and cooldown, were equivalent to over 10 years of operation. The only problem encountered was intermodule pivot bearing retention; a minor design change eliminated this problem.

Additional details of the full set of performance and operation tests (table 1) are presented in reference 1.

Manufacturing Approach

Manufacturing techniques, factory requirements, plant layout and work flow, and collector costs were also developed for the Model 3011 collector. Delivery of the lowest cost product to the collector field site was the primary criterion in defining the above manufacturing elements.

High value-added processes specific to Model 3011 manufacturing are performed in the manufacturing plant. Automated techniques are employed whenever cost effective (e.g., torque tube and rib flange welding). Conventional manufacturing processes which require high capital investment (e.g., rib stamping, receiver glazing fabrication) are done by local or specialty vendors.

The plant site is defined by the key considerations of labor cost, availability, and stability; shipping costs and methods; and plant costs and availability.

The overall plant layout and production flow through the factory are shown in figure 4. The five stations identified are:

- Station 1 -- Automated robotic welder for rib flange and pivot crank welding to the torque tube
- Station 2 -- Automated punch for punching rib attachment holes in the rib flanges
- Station 3 -- Semi-automated fixture for rib and edge retainer assembly
- Station 4 -- Semi-automated mandrel and fixture for assembling the glass panels into the module structure
- Station 5 -- Loading station for packing modules and other hardware into an integrated shipping crate

The shipping crate also serves the field installation process, eliminating any intermediate transfer of hardware at the collector field site. An overhead crane system facilitates the transfer of parts and assemblies through the production process. The production capacity of the plant (figure 4) is over 2 million ft^2 of aperture per year of Model 3011 collectors in a two-shift operation.

Table 1. Performance and Operation Tests

Number	Test	Fluid/ Temperature Range (°C)	Purpose
Six-Module Drive String			
6-1	Near normal energy conversion efficiency	Water/ambient; oil/ 212° to 640°F	Measure the energy conversion efficiency of the drive string as a function of temperature for water and heat transfer oil at normal incident angle
6-2	Incident angle modifier determination	Water/ambient	Measure energy conversion efficiency as a function of incident angle
6-3	Receiver heat loss	Oil/212° to 570°F	Measure receiver heat loss as a function of fluid temperature
6-4	Response time determination	Water/ambient	Establish length of test periods for thermal testing
6-5	Receiver fluid pressure drop	Water/ambient; oil/212° to 640°F	Measure the pressure drop of the fluid across the drive string including flexhoses
6-6	Thermal and mechanical cycling	Oil/212° to 640°F	Establish baseline thermal and mechanical product lifetimes
6-7	Receiver thermal expansion	Oil/640°F	Verify proper receiver expansion
6-8	Mechanical fit and function	--	Verify proper component assembly and operation
Single Module, Two-Axis Tracking			
1-1	Normal incident energy conversion efficiency	Water/ambient; oil/212° to 570°F	Measure the energy conversion efficiency of a single module as a function of temperature for water and heat transfer oil at normal incindent angle
1-2	Incident angle modifier determination	Water/ambient	Measure energy conversion efficiency as a function of incident angle
1-3	Receiver heat loss	Oil/212° to 390°F	Measure receiver heat loss as a function of fluid temperature
1-4	Response time determination	Water/ambient	Establish length of test periods for thermal testing
1-5	Optical efficiency	Water/ambient	Determine the optical efficiency ($\Delta T \approx 0$)

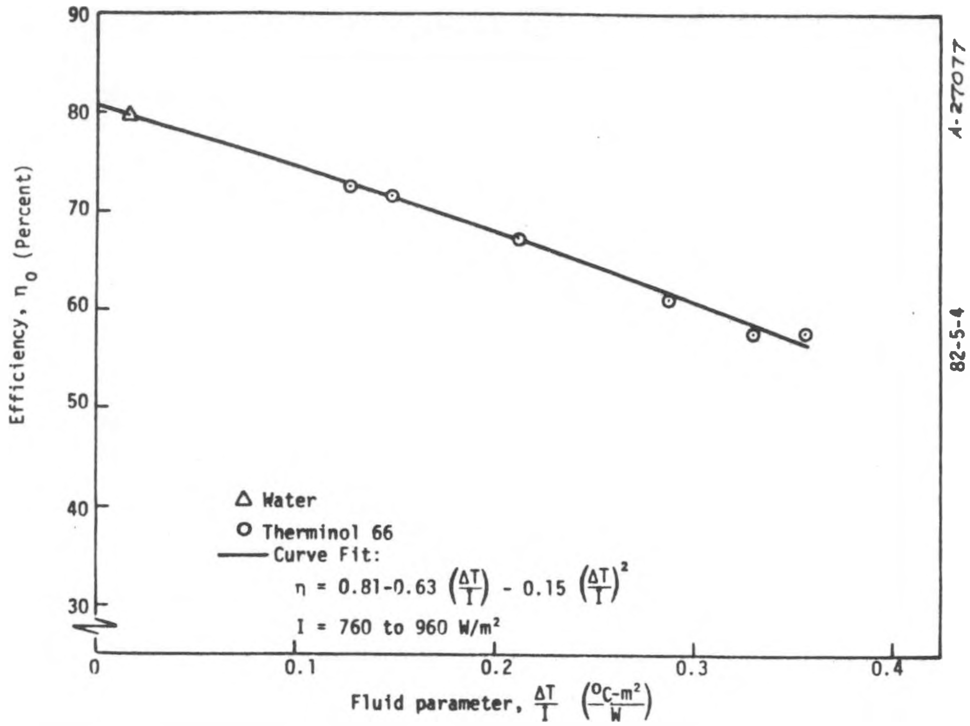

Figure 3. Preliminary Model 3011 Near Normal Thermal Performance

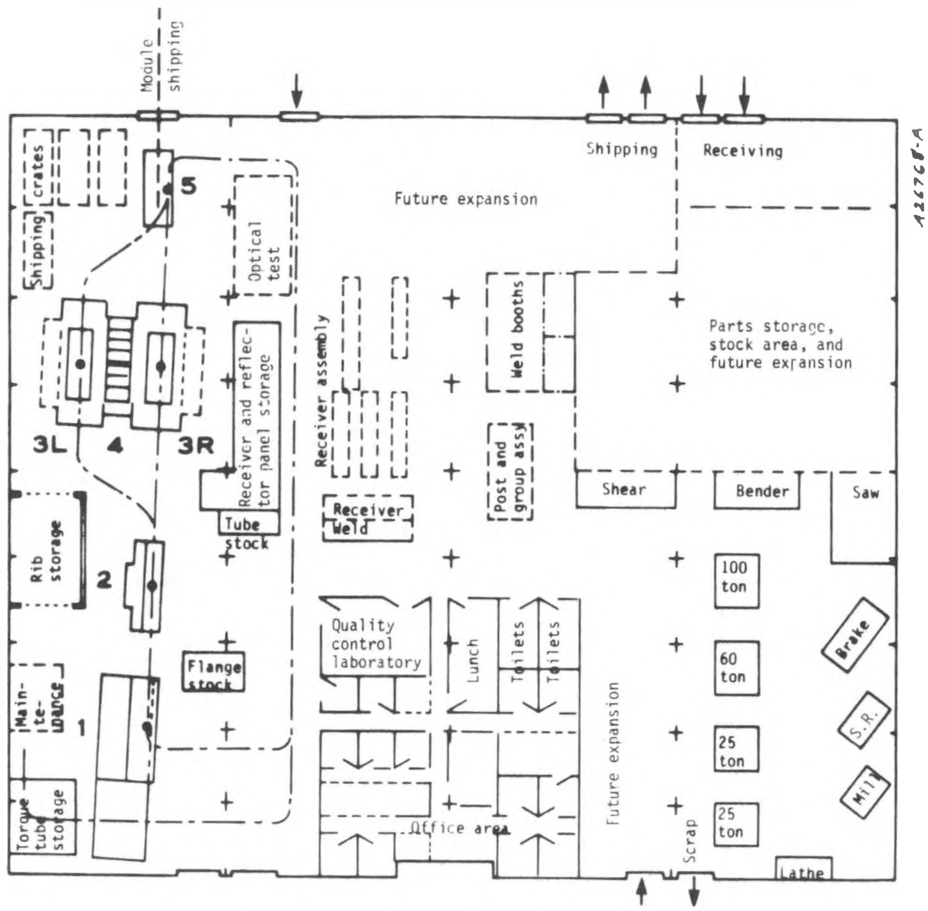

Figure 4. Overall Plant Layout

Comparative Results

Performance improvements and cost reductions for the Model 3011-01 collector as compared to its Model 3001-03 predecessor are shown in table 2. Improvements in all categories were significant. In every case our internally set goals were exceeded as was the Department of Energy cost goal for high-volume production.

Product Enhancements

The presentation above describes the prototype Model 3011-01 collector system developed under the referenced cooperative agreements. This is the same collector installed in our MISR system and discussed in two other papers. We have now essentially completed the process of product development beyond this prototype to a commercial product. This product now incorporates some significant performance and cost enhancements over the prototype and more are in development as shown in table 3.

Conclusion

A high-performance, cost-effective collector system, the Acurex Solar Model 3011-01 Concentrating Collector, was developed through prototype. This prototype exhibits major performance and cost improvements over its predecessor and is in successful operation in the Acurex MISR system discussed in other Acurex and SNLA papers.

Collector design stressed performance improvement and manufacturing, shipping, and installation cost reduction. Performance increased 34 percent and manufacturing cost decreased 32 percent over the predecessor Model 3001-03 collector.

The manufacturing facility and production flow for minimum collector cost were defined through consideration of value added, automated and conventional production, and specialty-vendor capabilities. Significant enhancements beyond the prototype have resulted in further performance and cost improvements in the production collector system.

Reference

1. Reese, J. J., Jr., V. W. Wong, G. W. Sutton, and H. Gumbel, "Development of Mass-Producible Line-Focus Tracking Concentrating Solar Collectors -- Category 1: Collectors", DOE Contract DE-FC04-80CS30264, Acurex Final Report FR-82-26/AE, to be published.

Table 2. Comparative Performance and Costs

Parameter	Collector 3001-03	Collector 3011-03	Percent Change
Module size	6 ft x 10 ft	7 ft x 20 ft	--
Group length	120 ft	120 ft	--
Row spacing	20 ft	20 ft	--
Reflective surface	FEK	Mirror glass	--
Normal efficiency			
• Optical intercept	0.64	0.81	27
• T_{ave} = 372°F (189°C)	0.57	0.68	20
• T_{ave} = 572°F (300°C)	0.46	0.59	29
Gross output[a] (million Btu/ft^2-yr)	0.323	0.433	34
System losses	10 percent	10 percent	--
Net output[a] (million Btu/ft^2-yr)	0.291	0.390	34
Collector system cost	--	--	32
Shipping cost	--	--	71
Installation cost	--	--	76

[a]Phoenix, Arizona; T_{ave} = 372°F

Table 3. Product Enhancements

<u>3011-02 Production Collector -- Changes from 3011-01 Prototype</u>

- Antireflective receiver glazing[a]
- Eight modules per group (six)[b]
  - -- Recent wind data allow extension
- One piece rib (three)
- Three glass sheets per panel (two)
  - -- Sheet interfaces are no longer at the maximum stress location
- Welded end cranks on both ends of torque tube (one bolted)
  - -- Deformation in production processes found to be insignificant
- Receiver plane tracker mount
  - -- Improved daily performance
- Stainless-steel receiver tube (carbon steel)
  - -- Improved black chrome processes and life
- Five rib-to-flange rivets (nine)

<u>Under Development</u>

- Evacuated receiver
- Improved receiver selective coatings
- Improved reflective systems
- More flexible master control
  - -- Interact with process load
  - -- Integration of energy output

[a]Incorporated into MISR system
[b]Parentheses refer to 3011-01

MASS PRODUCTION DESIGN
OF THE SOLAR KINETICS T-800
PARABOLIC TROUGH SOLAR COLLECTOR

by

John Witt

Director of Engineering

Solar Kinetics, Inc.

February 23, 1983

INTRODUCTION:

The T-800 collector is a direct descendant of the well-known T-700 parabolic trough system. The T-800 shares much of the same design philosophy of high-structural efficiency, and simple, reliable approaches to the problems of design and production.

The design criteria for the T-800 were:

1. Lower cost.
2. High performance.
3. High structural efficiency.
4. High torsional rigidity in the mirrors.
5. Simple installation procedures.
6. Production possible at several levels of automation.
7. High reliability.

In the following description of the T-800 component parts, these criteria were constantly present during the design trade-off process.

Mirror Structure

The collector mirror structure continues the development of the monocoque structure pioneered by Solar Kinetics in the T-500 series of collectors.

Steel was the material of choice for the primary structure. As in other mass production articles, the ease of fabrication and the low cost of steel are significant advantages.

Building a precisely curved mirror from imprecise parts was the primary design problem. This objectiv and low cost both require parts to be of the broadest possible dimensional tolerance. As in other industries, precise tooling which located parts only on one surface provided a solution.

The T-800 is fabricated by spot-welding repeatable segments of the mirror structure. All of the components comprising these segments are made to ordinary commercial tolerances. Parts are either roll formed or stamped. The resulting structure is a pure monocoque with all loads borne by the surface sheet metal. A series of local reinforcements are provided to allow mounting the mirror and to distribute localized load inputs from receiver supports, drive connections and other components.

The spot-welding of the prototype mirrors was accomplished by a manually controlled industrial spot welder. This device is positioned by hand for each of the welds. The mirror assembly may also be produced by any of several highly automated techniques in use by the automobile industry. The part assembly sequence allows access by a robot arm device, a multiple spot gang welder or a dedicated, automatic welder. Most of the structure could be assembled either by spot or seam welding.

Conventional peel and tension test specimens were used to qualify the welding parameters.

A method of making structural and configuration trade-offs is a necessary design tool for a structure of this nature. Computer modeling was chosen using an SKI-originated program which uses aircraft type buckling shell theory to predict the failure of the monocouque structure. The accuracy of the computer model was eventually borne out by actual destructive tests of the mirror structure which showed torsional rigidity to be within 5% of predicted values. Individual mirrors have withstood torques of 4000 ft-lbs. before buckling occurred. Deflection at failure was about one inch out of plane at the mirror corners.

A finite element analysis was also performed in the early phases of design, but this approach was very expensive. A single iteration approached the cost of actually building and testing a mirror segment.

Athough steel offers many fabrication advantages, a major drawback is its susceptibility to corrosion. An extensive investigation of the properties of commercially available finishes and plating was undertaken. The final surface finish is an epoxy primed, 2 coat acrylic finish which is applied over a galvanized steel base.

Sheared edges of the sheet metal are protected by a corrosion inhibiting potting enclosed by a vinyl envelope. This edge trim also provides a finished appearance to the mirror module.

The net result of the mirror design was a structure of exceptional torsional rigidity. A positive result of this stiffness is the extension of the length of a tracking row to include eight mirrors. This one factor reduces the number of drives required in a given array by one fourth.

A number of reflective surfaces are available to the T-800, allowing a high degree of flexibility in the selection of the most cost effective. This was considered to be important in the design since this area of the technology is in a state of flux.

Any of several types of plastic films may be applied to the mirror surface. FEK-244 film has been applied to the mirrors currently under test at the MISR QTS site. A bonded steel/glass sandwich with a reflectivity of 96% has also been constructed for use on the T-800. This composite mirror is designed to provide a compressive load into the glass mirror, making it more resistant to crack propagation.

The laminate is fabricated from .030 in. (.8mm) thick glass bonded to an .035 (.9mm) steel substrate. This structure is edge loaded and forced into the parabolic curvature of the mirror by a formed steel spring.

Drive Pylon

The drive pylon structure is composed of roll-formable sections which are welded in a rotating fixture. Since the quantity of drives required is small compared to other system components, a fixture of this type is usable up to fairly high production rates. The drive mechanism is similar to the originally patented T-700 system, but the prime mover is an electrically driven jackscrew in a place of the hydraulic system originally used by the T-700.

The prime mover is a 1/4 horsepower D.C. motor with current supplied by an AC-DC convertor-controller unit. This unit is included on each drive pylon. Electric power in the array is 120 VAC. The controller limits starting inrush current which in turn reduces the size of the field wiring and other related components. The motor controller also provides two-speeds: A low tracking speed and a higher stow/out of stow traverse speed.

Tracking Control System

The control system developed under the PRDA is a synthetic, microprocessor driven system which utilizes an incremental shaft encoder for position feedback. Communication of the calculated sun position information is via a frequency modulated signal which is superimposed on the control power lines. No separate control wiring is required.

The Central Control System (CCU) is supplied with a push button control panel for entry of the required operating parameters. An alpha-numeric display is provided for data and system status.

The complete instruction set for the CCU is contained in programmable read-only memory. This information is maintained by a gelled electrolyte battery which is charged by an integral float type charger.

The CCU instruction set, programmed in assembly language, includes the sequence of actions required to accommodate the collector array to the real world. The instruction set is easily altered to accommodate new information or changes in the process the array serves.

The control system can be adapted to two-axis tracking requirements and also accommodates collector rows of varying azimuth angles. Up to 100 such variations can be accommodated.

The Row Control Unit (RCU) includes a receiver for decoding the FM control signal and its own ROM-based microprocessor. The RCU program includes data verification routines and control outputs required for fail-safe operation of the individual row. Two local hazard inputs are also included.

Intermediate Pylons

The intermediate collector support pylon consists of roll-formable sections with a stamped and welded base.

The pylon is assembled with self-threading screws and may be shipped knocked down. The upper bearing is a self-aligning bronze casting. The bearing is retained by a pair of stampings which are bolted into the top of the pylon with self-threading screws. The protective finish is galvanizing.

Modular Receiver Assembly

The receiver assembly is the subject of ongoing development to enhance operational qualities. One of the main objectives of SKI's original (pre-PRDA) development program was a modular, factory assembled receiver which offered easy, fast, field installation.

Before the design of a modular receiver, the tube was assembled full length and the individual glass covers, 10 ft. long, were then slid into place over the tube. The procedure was time consuming and a great deal of glass was broken. The annulus interior was often contaminated by the handling, even when great care was exercised.

With the modular receiver, assembly is simple enough that non-factory trained workmen can successfully do it.

The crux of the design is a vee-clamp connection that also includes the support bracket. The clamp itself is a stamped stainless steel part. One half of the clamp includes a shield which protects the glass cover seal from incident flux. Several sealing ring types are available, all of which have survived rigorous testing. The assembled connection is very short, so a minimum of receiver length is obscured from the concentrated flux. Even though the clamps and connections are uninsulated, thermal loss from a six mirror string or receivers connectors is estimated to be less than 1 BTU/FT /HR compared to an insulated connection.

Sealing for the glass annulus was investigated at some length. The classic goal for this area has been an evacuated annulus, but this is still not cost effective with present materials. A wide variety of seal types were designed and tested, with the current producible system supporting the glass cover with a filled-teflon, spring loaded seal. This seal is located by a metal retainer which is designed to have a high resistance thermal path to the receiver tube resulting in seal temperatures appropriate to the seal material.

The black chrome coating for the receiver selective surface has been the subject of much concern by everyone connected with parabolic trough development. Although not a direct part of the PRDA work, some design effort was expended toward developing plating fixtures. This allowed more rapid handling of the receiver tubes which enhanced the plating consistency.

Array Installation

Solar Kinetics' experience in the installation of large collector systems has lent special concern to the area of equipment installation. The T-800 system may be assembled by the same level of personnel currently available to a mechanical contractor.

As an aid to the correct relationship of the various pieces of the system, parts are designed to fit in only one position or are reversible. As many of the components as possible are factory assembled, resulting in only seven major assemblies. There is a minimum of fasteners and no fasteners smaller than 5/16 inch diameter. There are no field adjustments to be made by the installing workers. All field wiring connections are to screw terminals as are ordinarily found in industrial systems. All of these features contribute to a lower total system cost.

ACKNOWLEDGMENTS

The entire staff at Solar Kinetics contributed in many ways to this successful design effort. Special acknowledgment is accorded to Mr. David White for his exceptional design work on the mirror structure and to Mr. Larry Stephens for his persistent investigation of the many drive alternatives.

Field Layout Studies

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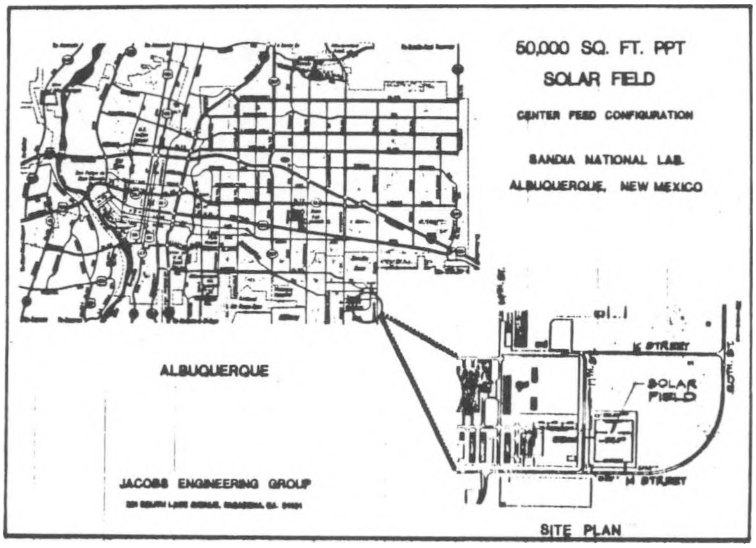
Introduction

This report presents the results of a detailed cost study of two parabolic trough collector field piping arrangements. Presented in this writing are sketches of the detailed designs of these layouts and the estimated costs to construct each of them. The cost results are thought to be accurate to within ±5 percent as they are based on a materials takeoff from detailed drawings and recent costs of similar size projects. The costs are expressed in terms of 1981 dollars.

FIGURE 1



Each of the two arrangements presented in this document are thought to be in their optimum cost configuration, within the design constraints and ground rules established by Sandia National Laboratories, Albuquerque (SNLA). This is because the designs are based on trade-off analyses which were made to determine the most cost-effective way to design and construct each of the field layouts. A great amount of time and effort was expended to determine cost differentials between such things as alternative methods of supporting pipes; pipe support spacing; accommodating and relieving induced pipe stresses due to thermal expansion; orientation of expansion loops; expansion joints vs. expansion loops; type of pipe support piers; providing field access to edge feed fields; thermal insulation type and thickness; pipe header diameter; piping materials; pump driver and pump arrangement; control valve selection and emergency generator selection. Due to the extended time period of the study, all cost studies and value engineering were performed on the basis of constant 1979 dollars. Once a detailed design concept was developed and engineered for each of the two layouts, the capital and construction costs were then reestimated and expressed in current dollars.

Summary of Results

BASIC ASSUMPTIONS AND GROUND RULES

Certain basic assumptions and design ground rules were fixed by SNLA at the beginning of the study. These design criteria were established on the basis of the previous research and development, a need to maintain consistency of results between the various organizations participating in the line focus solar thermal development program, future goals for IPH solar fields, and SNLA-generated parametric studies. The basic assumptions are listed below:

- Location is Albuquerque, New Mexico; at location shown on Figure 1.
- Collector type is Sandia Performance Prototype Trough (PPT).
- Collector efficiency is 68 percent at 600°F, which corresponds to Sandia goal for PPT fields.
- Collector orientation is East-West.
- Thermal energy is valued at $10 per million Btu.
- Electric power is valued at 10¢ per kwh.
- Annualized capital cost (annual capital charge) is 15 percent of total capital investment.
- All final design costs to be based on wage rates and materials costs which prevailed in 1981 in Albuquerque.
- All designs to consider first cost over increased maintenance cost, where appropriate.
- Aesthetic qualities can be sacrificed in favor of lowering first cost, where appropriate.
- PPT collector to be in 20-foot modules.
- PPT Aperture is 2 meters.
- Collector row spacing is set at 15 feet.
- Collector foundations per Sandia Report, Sand 78-7048.
- Collector manufacturer to provide receiver tubes, flexhoses, trough, drive and support pylons as complete unit ready to be placed on concrete foundations.
- All trackers and controls by others.
- Every collector row has a control valve.
- All controllers are to be electrically actuated.
- All valve steams to be oriented below the horizontal plane.
- All power and communications cabling along collector row to be provided by collector manufacturer.
- Piping is to be of all welded construction.
- Jacobs Engineering to consider center feed and edge feed flow configurations in final design.

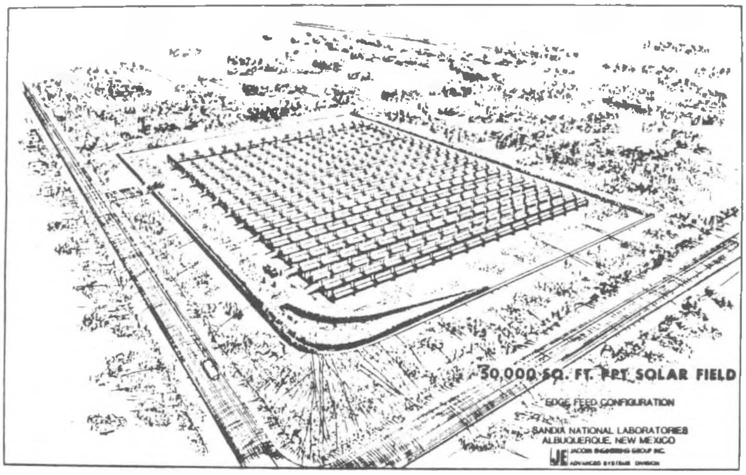
TRADEOFF STUDIES

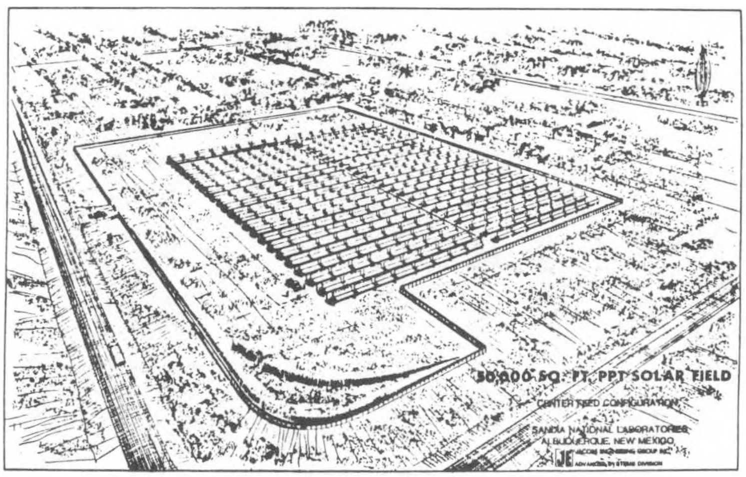
Soon after project initiation it became apparent that there was a need to know more about relative costs of the available design options before it was possible to establish a cost-effective basic layout. Some of the questions which arose regarded row spacing, Delta-T string length, receiver tube diameter, compensation of thermal stresses and others. The results of the tradeoff studies and cost analysis were used to answer our questions and determined our overall design. The topics covered in the tradeoff studies were:

- Field shadowing and row spacing.
- Delta-T string length.
- Thermal insulation specification.
- Piping materials selection.
- Control valve and valve operator selection.
- Process pump driver selection.
- Method of thermal expansion compensation.
- Piping header profile.
- Electric power and communications cabling.

Results and Discussion

A perspective view of the optimized Edgefeed and Centerfeed field layouts is presented in the sketches below. The design drawings for each of the field layouts are provided in Field Layout Studies, final report (1). Capital costs to design and construct each layout were developed for each of the arrangements. Each of the collector fields was priced on the basis of Open shop and Union labor. These costs are presented in Table I, broken down by category. The same costs are presented in Table II on a dollars-per-square-foot basis. Excluded from the costs are the collectors receiver tube; collector support and drive pylons; drive motors; trackers and controls; flexhoses; all wiring between branch piping junction boxes; steam generator and piping, and heat transfer fluid.





The capital cost includes:

- o All collector supports including excavation, rebar, concrete and anchor bolts.
- o All heat transfer fluid (HTF) supply and return header piping which extends from the pump discharge to the last collector row.
- o Branch piping which extends from supply header up to, but not including, flexhoses.
- o Electric actuated control valve, two block valves and check valve in the branch piping for the Delta-T string.
- o HTF circulation pump, pad, DC motor and SCR controls.
- o Chain link fence and access gate.
- o Oil collection sump.
- o All miscellaneous process piping and valves shown within battery limits fencing except steam line.
- o Electrical cabling for power and communications. All cabling terminates at junction boxes placed at every row.

<u>Offsites</u>

The offsites, or items in the design which are specific to the jobsite are listed below:

- o Steam line and insulation from steam main to steam generator location shown on the plot plan in Reference 1.
- o Equipment located outside of the wind fencing to bring power to the array.
- o Modification to existing power poles.

CAPITAL COST ESTIMATE

Overall, the major goal of the project has been to develop accurate cost data for the systems integration of a large parabolic trough solar thermal collector field. Every effort has been made to design the field with minimum frills, within

TABLE I

SOLAR ARRAY COST SUMMARY

	Materials, M$				Labor, M$				Total, M$			
	Open Shop		Union		Open Shop		Union		Open Shop		Union	
Description	Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center
Pump	4.0	4.0	4.0	4.0	3.0	3.0	3.0	3.0	7.0	7.0	7.0	7.0
Sitework	---	---	---	---	---	---	---	---	44.0	25.0	45.0	25.0
Concrete	42.0	43.0	42.0	43.0	23.0	24.0	25.0	27.0	65.0	67.0	67.0	70.0
Piping	113.0	116.0	113.0	116.0	75.0	93.0	80.0	99.0	188.0	209.0	193.0	215.0
Electrical	97.0	97.0	97.0	97.0	38.0	38.0	43.0	43.0	135.0	135.0	140.0	140.0
Offsites	34.0	34.0	34.0	34.0	44.0	44.0	44.0	44.0	78.0	78.0	78.0	78.0
Construction Services Labor	---	---	---	---	12.0	14.0	13.0	15.0	12.0	14.0	13.0	15.0
Temp. Const. Facilities	8.0	9.0	9.0	10.0	---	---	---	---	8.0	9.0	9.0	10.0
Nonpayroll Taxes & Ins.	---	---	---	---	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Construction Equip.	8.0	9.0	9.0	10.0	---	---	---	---	8.0	9.0	9.0	10.0
Field Staff & Clerical	---	---	---	---	14.0	16.0	15.0	17.0	14.0	16.0	15.0	17.0
Premium Time	---	---	---	---	1.0	2.0	2.0	2.0	1.0	2.0	2.0	2.0
New Mexico Tax	11.0	12.0	12.0	12.0	11.0	11.0	12.0	12.0	22.0	23.0	24.0	24.0
TOTAL, M$	317.0	324.0	320.0	326.0	222.0	246.0	238.0	263.0	583.0	595.0	603.0	614.0

the ground rules established by SNLA. Extensive tradeoff studies were performed which enabled the informed selection of design alternatives.

We have prepared capital cost estimates for the two alternative collector field arrangements. The cost estimates are based on direct materials takeoff from the design drawings. Two separate estimates were prepared for each arrangement, one based on the use of Open Shop labor and a second using Union labor rates. The rates are for Albuquerque, New Mexico and are for 1981.

Table I presents a summary of the total estimated capital costs for the Edgefeed and Centerfeed field layouts. The total cost for each arrangement is broken down into its materials and labor components. The labor category shows labor costs for an array constructed using Open Shop labor and separate costs for Union labor.

Total estimated cost of integrating a solar array system using an Edgefeed configuration with Union labor is $603,000. The Centerfeed arrangement would be $614,000. Cost difference is $11,000.

Total estimated cost of the Edgefeed configuration is $583,000 using Open Shop labor. The Centerfeed configuration on the same basis is estimated to cost $595,000. Cost difference is $12,000.

Table II presents these costs on a dollars-per-square-foot basis. The array field layout costs range from $12.06 to $12.28 using Union labor and from $11.66 to $11.90 using Open Shop labor.

TABLE II

SOLAR ARRAY COST SUMMARY

	Dollars Per Square Foot of Collector Aperture Basis											
	Materials, $/Ft²				Labor, $/Ft²				Total, $/Ft²			
	Open Shop		Union		Open Shop		Union		Open Shop		Union	
Description	Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center
Pump	0.08	0.08	0.08	0.08	0.06	0.06	0.06	0.06	0.14	0.14	0.14	0.14
Sitework	---	---	---	---	---	---	---	---	0.88	0.50	0.90	0.50
Concrete	0.84	0.86	0.84	0.86	0.46	0.48	0.50	0.54	1.30	1.34	1.34	1.40
Piping	2.26	2.32	2.26	2.32	1.50	1.86	1.60	1.98	3.76	4.18	3.86	4.30
Electrical	1.94	1.94	1.94	1.94	0.76	0.76	0.86	0.86	2.70	2.70	2.80	2.80
Offsites	0.68	0.68	0.68	0.68	0.88	0.88	0.88	0.88	1.56	1.56	1.56	1.56
Construction Services Labor	---	---	---	---	0.24	0.28	0.26	0.30	0.24	0.28	0.26	0.30
Temp. Const. Facilities	0.16	0.18	0.18	0.20	---	---	---	---	0.16	0.18	0.18	0.20
Nonpayroll Taxes & Ins.	---	---	---	---	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Construction Equip.	0.16	0.18	0.18	0.20	---	---	---	---	0.16	0.18	0.18	0.20
Field Staff & Clerical	---	---	---	---	0.28	0.32	0.30	0.34	0.28	0.32	0.30	0.34
Premium Time	---	---	---	---	0.02	0.04	0.04	0.04	0.02	0.04	0.04	0.04
New Mexico Tax	0.22	0.24	0.24	0.24	0.22	0.22	0.24	0.24	0.44	0.46	0.48	0.48
TOTAL, $/Ft²	6.34	6.48	6.40	6.52	4.44	4.92	4.76	5.26	11.66	11.90	12.06	12.28

Further details of the piping subsystem cost estimates are presented in Tables III and IV, on the basis of Union Shop and Open Shop labor.

The dollar amounts shown in each of the cost accounts has been derived from vendor quotes, direct materials takeoff and estimates of manhours required for installation. A brief discussion of the origin of the numbers for each account is presented below. Details of the cost estimate and vendor quotations are included in Reference 1.

Piping, Pump and Concrete. The materials costs for pipe, welds, weld fittings, valves, concrete, insulation, anchors, guide and supports are derived from direct materials takeoff. The labor costs associated with these items is based on individual estimates of the manhours required to install the item. The basis of the estimate is actual field construction data. The materials and amount of labor required for testing, piping modifications, general foreman, freight, s/c handling, overhead and profit are estimated based on factors derived from previous projects of similar size and scope.

Electrical. The materials costs for the transformer, generator, emergency lighting, conduit, wire trending, power and communications cabling are derived from a direct materials takeoff from the design drawings. The labor costs are based on an estimate of manhours required to install the individual equipment item or lay the conduit and cables.

TABLE III

UNION SHOP COST DETAILS

Description	Materials, $		Labor, $		Total, $	
	Edge	Center	Edge	Center	Edge	Center
PUMP						
Pump	3,300	3,300	1,500	1,500	4,800	4,800
Insulation subcont.	—	—	1,200	1,200	1,200	1,200
Productivity	—	—	300	300	300	300
Freight	200	200	—	—	200	200
s/c Markup	500	500	—	—	500	500
SUBTOTAL, $	4,000	4,000	3,000	3,000	7,000	7,000
SITE WORK						
Oil & Silt Basin	—	—	—	—	1,600	1,600
Construct 450' of berm	—	—	—	—	1,900	1,900
Construct 320' of Drainage	—	—	—	—	2,500	2,500
Chain Link Fence w/B.W.	—	—	—	—	18,500	18,500
12" CMP w/tee	—	ALL SUBCONTRACT		—	500	500
Steel Frame	—	—	—	—	3,000	—
Culvert	—	—	—	—	5,900	—
Truck Ramp	—	—	—	—	11,100	—
SUBTOTAL, $	—	—	—	—	45,000	25,000
CONCRETE						
Pipe Supports	3,750	5,100	2,500	4,000	6,250	9,100
Collector Supports	31,950	31,700	18,700	18,700	50,650	50,400
Slab & R.V. Pit	600	600	700	700	1,300	1,300
Transformer Pads	700	700	600	600	1,300	1,300
s/c Markup @ 15%	4,500	4,700	—	—	4,500	4,700
Productivity	—	—	3,000	3,200	3,000	3,200
SUBTOTAL, $	41,500	42,800	25,500	27,200	67,000	70,000
PIPING						
Pipe	20,000	14,900	11,500	12,500	31,500	27,400
Weld Fittings	1,700	1,600	100	100	1,800	1,700
s/w Fittings	1,500	4,100	—	—	1,500	4,100
Valves	29,200	29,200	10,700	10,700	39,900	39,900
Welds, Field & Shop	4,900	5,100	25,700	35,600	30,600	40,700
Pipe Insulation	30,000	34,000	—	—	30,000	34,000
Anchors, Guides, Supp.	5,800	7,600	5,300	7,100	11,100	14,700
Flush & Drain, Misc.	1,100	1,100	2,400	3,000	3,500	4,100
Piping Modifications	2,900	2,700	4,900	5,900	7,800	8,600
Testing	1,100	1,100	4,900	5,900	6,000	7,000
General Foreman	—	—	6,500	8,100	6,500	8,100
Freight	4,000	4,300	—	—	4,000	4,300
s/c handling, O/H&P	10,800	10,300	—	—	10,800	10,300
Productivity	—	—	8,000	10,100	8,000	10,100
SUBTOTAL, $	113,000	116,000	80,000	99,000	193,000	215,000
ELECTRICAL						
Transformer & Generator	49,000	49,000	11,500	11,500	60,500	60,500
Lighting	1,100	1,100	2,200	2,200	3,300	3,300
Conduit and Wire	1,400	1,400	1,500	1,500	2,900	2,900
Array Power	32,100	32,100	21,200	21,200	53,300	53,300
Array Communication	700	700	2,200	2,200	2,900	2,900
s/c Markup @ 15%	12,700	12,700	—	—	12,700	12,700
Productivity	—	—	4,400	4,400	4,400	4,400
SUBTOTAL, $	97,000	97,000	43,000	43,000	140,000	140,000
SITE SPECIFIC COSTS						
Road Crossing	5,000	5,000	5,000	5,000	10,000	10,000
Piping	15,000	15,000	27,000	27,000	42,000	42,000
Electrical	8,200	8,200	8,300	8,300	16,500	16,500
*Construction Services Labor	2,400	2,400	—	—	2,400	2,400
Temporary Const. Facilities	1,900	1,900	—	—	1,900	1,900
Nonpayroll Tax & Insurance	—	—	500	500	500	500
Construction Equipment	1,600	1,600	—	—	1,600	1,600
Field Staff and Clerical	—	—	2,700	2,700	2,700	2,700
Premium Time	—	—	300	300	300	300
New Mexico Tax	1,700	1,700	1,700	1,700	3,400	3,400
SUBTOTAL, $	35,800	35,800	45,500	45,500	81,300	81,300
MISCELLANEOUS						
Construction Services Labor	—	—	13,000	15,000	13,000	15,000
Temporary Const. Facil.	9,000	10,000	—	—	9,000	10,000
Nonpayroll Taxes & Insur.	—	—	1,000	1,000	1,000	1,000
Construction Equipment	9,000	10,000	—	—	9,000	10,000
Field Staff and Clerical	—	—	15,000	17,000	15,000	17,.000
Premium Time	—	—	2,000	2,000	2,000	2,000
New Mexico Tax	10,000	10,500	10,000	10,000	20,000	20,500
SUBTOTAL, $	28,000	30,500	41,000	45,000	69,000	75,500
GRAND TOTAL, $	319,300	325,100	238,000	262,700	602,300	613,800

*These costs are those which are properly allocated to this specific site. They are not included in the "miscellaneous" costs shown above.

TABLE IV

OPEN SHOP COST DETAILS

Description	Materials, $ Edge	Materials, $ Center	Labor, $ Edge	Labor, $ Center	Total, $ Edge	Total, $ Center
PUMP						
Pump	3,300	3,300	1,500	1,500	4,800	4,800
Insulation subcont.	—	—	1,200	1,200	1,200	1,200
Productivity & Adjust.	—	—	300	300	300	300
Freight	200	200	—	—	200	200
s/c Markup	500	500	—	—	500	500
SUBTOTAL, $	4,000	4,000	3,000	3,000	7,000	7,000
SITE WORK						
Oil & Silt Basin	—	—	—	—	1,600	1,600
Construct 450' of berm	—	—	—	—	1,900	1,900
Construct 320' of Drainage	—	—	—	—	2,500	2,500
Chain Link Fence w/L.W.	—	—	—	—	18,500	18,500
12" CMP w/tee	—	ALL SUBCONTRACT		—	500	500
Steel Frame	—	—	—	—	3,000	—
Culvert	—	—	—	—	5,500	—
Truck Ramp	—	—	—	—	10,500	—
SUBTOTAL, $	—	—	—	—	44,000	25,000
CONCRETE						
Pipe Supports	3,750	5,100	2,200	3,400	5,950	8,500
Collector Supports	31,950	31,700	16,100	16,100	48,050	47,800
Pump Pad & R.V. Pit	600	600	600	600	1,200	1,200
Transformer Pads	700	700	500	500	1,200	1,200
s/c Markup @ 15%	4,500	4,700	—	—	4,500	4,700
Productivity & Adjust.	—	—	4,100	3,600	4,100	3,600
SUBTOTAL, $	41,500	42,800	23,500	24,200	65,000	67,000
PIPING						
Pipe	20,000	14,900	10,200	11,100	30,200	26,000
Weld Fittings	1,700	1,600	100	100	1,800	1,700
s/w Fittings	1,500	4,100	—	—	1,500	4,100
Valves	29,200	29,200	9,500	9,500	38,700	38,700
Welds, Field & Shop	4,900	5,100	22,800	32,000	27,700	37,100
Pipe Insulation	29,500	34,000	—	—	29,500	34,000
Anchors, Guides, Supports	5,800	7,600	4,700	6,300	10,500	13,900
Flush, Drain, & Misc.	1,100	1,100	2,100	2,600	3,200	3,700
Piping Modifications	2,900	2,700	4,300	5,300	7,200	8,000
Testing	1,100	1,100	4,300	5,300	5,400	6,400
General Foreman	—	—	5,800	7,200	5,800	7,200
Freight	4,100	4,000	—	—	4,100	4,000
s/c Handling, O/H&P	10,800	10,100	—	—	10,800	10,100
Productivity and Adjust.	400	500	11,200	13,600	11,600	14,100
SUBTOTAL, $	113,000	116,000	75,000	93,000	188,000	209,000
ELECTRICAL						
Transformer & Generator	49,400	49,400	9,700	9,700	59,100	59,100
Lighting	1,100	1,100	1,900	1,900	3,000	3,000
Conduit and Wire	1,400	1,400	1,200	1,200	2,600	2,600
Array Power	32,100	31,400	17,800	17,800	49,900	49,200
Array Communication	700	600	1,800	1,300	2,500	1,900
s/c Markup @ 15%	12,700	12,600	—	—	12,700	12,600
Productivity & Adjust.	(400)	500	5,600	6,100	5,200	6,600
SUBTOTAL, $	97,000	97,000	38,000	38,000	135,000	135,000
OFFSITES						
Road Crossing	5,000	5,000	5,000	5,000	10,000	10,000
Piping	15,000	15,000	27,000	27,000	42,000	42,000
Electrical	8,200	8,200	8,300	8,300	16,500	16,500
*Construction Services Labor	2,400	2,400	—	—	2,400	2,400
Temporary Const. Facilities	1,900	1,900	—	—	1,900	1,900
Nonpayroll Tax & Insurance	—	—	500	500	500	500
Construction Equipment	1,600	1,600	—	—	1,600	1,600
Field Staff and Clerical	—	—	2,700	2,700	2,700	2,700
Premium Time	—	—	300	300	300	300
New Mexico Tax	1,600	1,600	1,500	1,500	3,100	3,100
SUBTOTAL, $	35,700	35,700	45,300	45,300	81,000	81,000
MISCELLANEOUS						
Construction Services Labor	—	—	12,000	14,000	12,000	14,000
Temporary Const. Facil.	8,000	9,000	—	—	8,000	9,000
Nonpayroll Taxes & Insur.	—	—	1,000	1,000	1,000	1,000
Construction Equipment	8,000	9,000	—	—	8,000	9,000
Field Staff and Clerical	—	—	14,000	16,000	14,000	16,000
Premium Time	—	—	1,000	2,000	1,000	2,000
Contractor Markup	—	—	—	—	—	—
New Mexico Tax	9,700	9,900	9,600	9,900	19,300	19,800
SUBTOTAL, $	25,700	27,900	37,600	42,900	63,300	70,800
GRAND TOTAL, $	316,900	323,400	222,400	246,400	583,300	594,800

*These costs are those which are properly allocated to this specific site. They are not included in the "miscellaneous" costs shown above.

Site Work. The costs shown for sitework have been estimated on the assumption that the work would be bid lump sum by a subcontractor. The design drawings were used as the basis for estimating earthwork volumes, fencing and civil materials.

Miscellaneous. Certain costs and expenses are incurred during construction which are not direct costs of materials and labor. These costs are the temporary construction facilities, etc.

Discussion of Results

The overall objective of this work has been to develop cost-effective solar array piping subsystems. Results of the design effort, when complete, would be the identification and quantification of the cost-intensive design variables and information about cost differences between alternative field layouts.

Table V summarizes the total capital costs for both of the piping subsystems. Costs are shown for both Union and Open Shop labor, along with cost differentials.

TABLE V

PIPING SUBSYSTEM COST SUMMARY

Labor Basis	Centerfeed	Edgefeed	Δ Cost
Union, $	614,000	603,000	11,000
Open Shop, $	595,000	583,000	12,000
Δ Cost, $	19,000	20,000	--

In the initial stages of the project it was believed that the Edgefeed alternative would provide cost savings over the more conventional Centerfeed arrangement. A design consideration such as impaired field access would be traded off for the gain of less piping, heat loss, pumping parasitics and a simpler appearing layout. Although this assumption turned out to be true, the cost difference between the two arrangements either on a Union Shop or Open Shop basis is only eleven or twelve thousand dollars, or three to four percent of the total cost. Therefore, there is no significant cost driver for the selection of one configuration over the other.

In fact, close inspection of Tables III or IV will show that there are no obvious cost elements in either alternative which clearly control the design.

REFERENCE

1. R. E. Morton. "Preliminary Design of Two 50,000-Square-Foot Solar Collector Fields, Final Report". To be published, 1983.

SITING TRADEOFFS FOR PARABOLIC TROUGH FIELDS

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Abstract

This paper presents siting tradeoffs for parabolic trough fields. The net energy from the collector field depends on siting tradeoffs that include: collector spacing, location, and orientation. An optimum collector field design for a specific site and site load requires that these tradeoffs be understood. Individual variations of the spacing, location and orientation show the leverage associated with each type of siting tradeoff. A computer model simulates the performance of the system.

SITING TRADEOFFS FOR PARABOLIC TROUGH FIELDS

INTRODUCTION

Energy systems considered in this study use linear parabolic mirrors tracking about one axis to concentrate sunlight on a receiver containing a heat-transfer fluid. These systems can provide thermal energy over a wide range of temperatures for a variety of applications. For a given collector design, the net energy supplied depends on collector spacing, location, and orientation. Optimum system design requires an understanding of the dependence of net collected energy on these variables.

This study describes the effect of spacing, location, and orientation on net energy collected for both daily and annual operation. In the study, packing factor provides a measure of collector spacing and latitude represents location. A clear-sky insolation model [1] generates insolation values, thereby eliminating the effect of local weather conditions. Packing factor ranges from .2 to 1.0 with a baseline value of .4. Latitude ranges from 25. degrees to 45. degrees north with a baseline value of 35. degrees. Field orientations from 0. (N/S) degrees to $\pm$ 90. (E/W) degrees are considered with baselines being N/S and E/W. In order to illustrate the effect of these site-specific variables, a typical generic collector design is used in all cases. Descriptions of the generic system and the computer model follow. Simulation results are then presented.

GENERIC COLLECTOR SYSTEM

The baseline design described in Table 1 is typical of the MISR project designs and is used for analysis purposes only.[2] The design uses 2304 m^2 of collectors arranged in 8 rows, 144 meters in length. The field is center fed with the manifold being 10 cm (4 in.) in diameter.

Table 1

Baseline Design

Collector module:	90 degree run angle 2 m aperture 6 m length
Drive string:	6 modules
Field:	2 drive strings/row 2 rows/ T string (center feed) 8 T strings 2304 m^2 aperture 10 cm center-feed manifold
Receiver:	2.5 cm diameter
Error distribution:	7 milliradians
Average reflectivity:	.89
Fluid temperature:	200° C inlet 288° C outlet

COMPUTER MODEL

The program calculates total available energy, individual energy losses, and net energy collected. Interpolating between precalculated values, rather than repeated calculations, minimizes execution time.

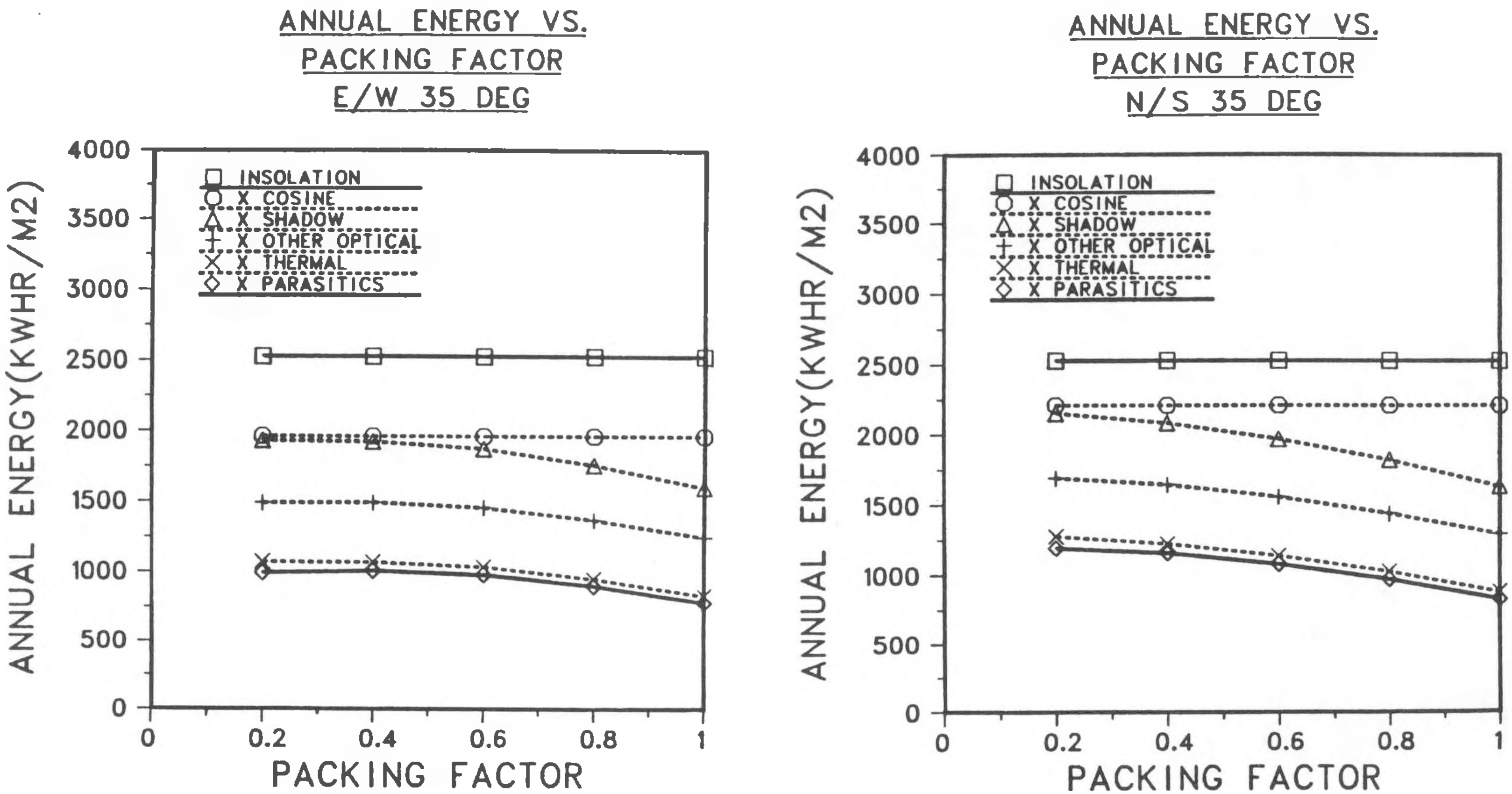
Optical performance includes cosine, shadowing, reflectance, end, gap, spillage, transmission, and absorption losses. Cosine losses are inherent in systems tracking about one axis only. At certain times one collector may cast a shadow over another. End losses occur whenever sunlight is not normal to the axis of the collectors. Non-reflective areas of the collector and non-absorptive regions of the receivers cause gap losses. Reflected light that misses the envelope or the absorber tube is spilled. Of the light striking the envelope of the receiver, only a fraction is transmitted by the envelope and absorbed by the receiver tube.

The model calculates receiver thermal losses using experimental correlations [3] and [4] or an analytical calculation based on a one-dimensional heat-transfer model [5]. Heat losses from the manifold during operation, heat losses due to overnight cooling, and electrical energy for pumping fluid are called parasitic losses and comprise the remainder of the energy losses calculated by the program.

SIMULATION RESULTS

Figures 1A for an east/west field orientation and 1B for a north/south orientation illustrate the dependence of net energy collected annually on packing factor. In each plot, the bottom curve represents the net energy added to the heat-transfer fluid, and the top curve represents the total available insolation as seen by an aperture tracking about two axes. The vertical distance between adjacent curves represents the magnitude of an energy loss corresponding to the symbol denoting the lower curve. Thus, other optical losses, including end losses and gap losses, are represented by the space between the curve denoted by the triangles and the curve denoted by the addition (+) signs. Latitude is constant at 35 degrees. Annual cosine losses are greater for the east/west orientation and do not vary with the packing factors analyzed. Shading losses are greater for the north/south orientation and increase rather markedly with packing factor. While the fractional loss attributed to other optical lo--e- does not depend on packing factor, the actual magnitude of the other optical losses decreases with packing factor. The magnitude of receiver thermal losses does not depend on either orientation or packing factor. As packing factor increases, the field uses less manifold piping and less fluid. Consequently, parasitic losses decrease with increasing packing factor for both orientations.

Figure 2 compares the net energy collected by fields oriented in east/west and north/south directions at a latitude of 35. degrees. Over the range of packing factors considered the north/south field collects more energy than the east/west field. The difference is caused by the higher cosine losses of the east/west field. As the collectors become more closely packed, the shadowing losses of the north/south field increase more rapidly than the shadowing losses of the east/west field and the annual energy outputs converge.



A. East/West

B. North/South

Figure 1. Annual Energy vs. Packing Factor
Latitude 35 degrees

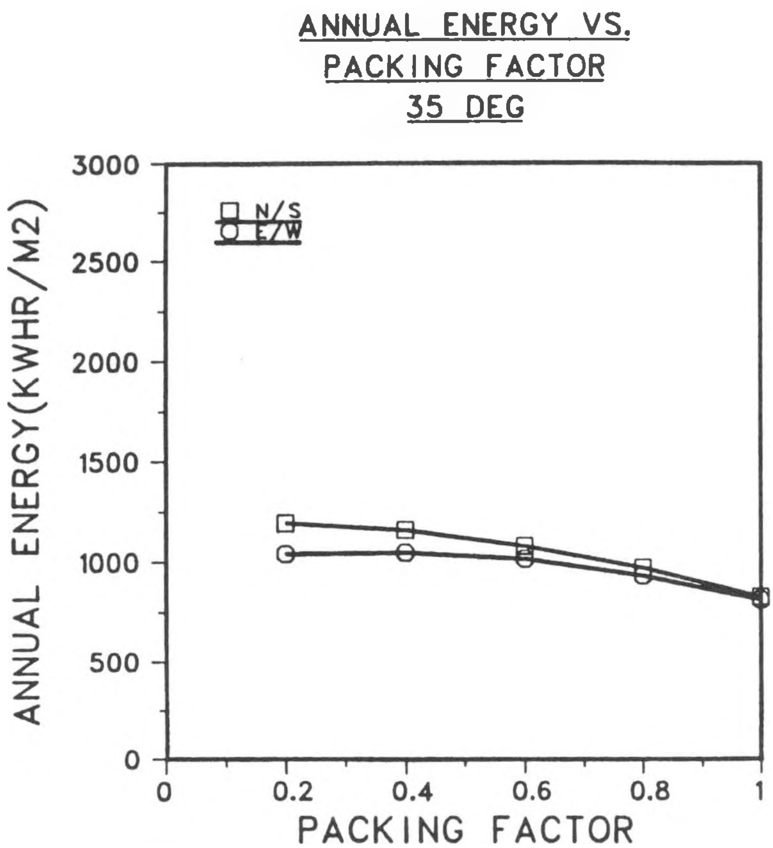
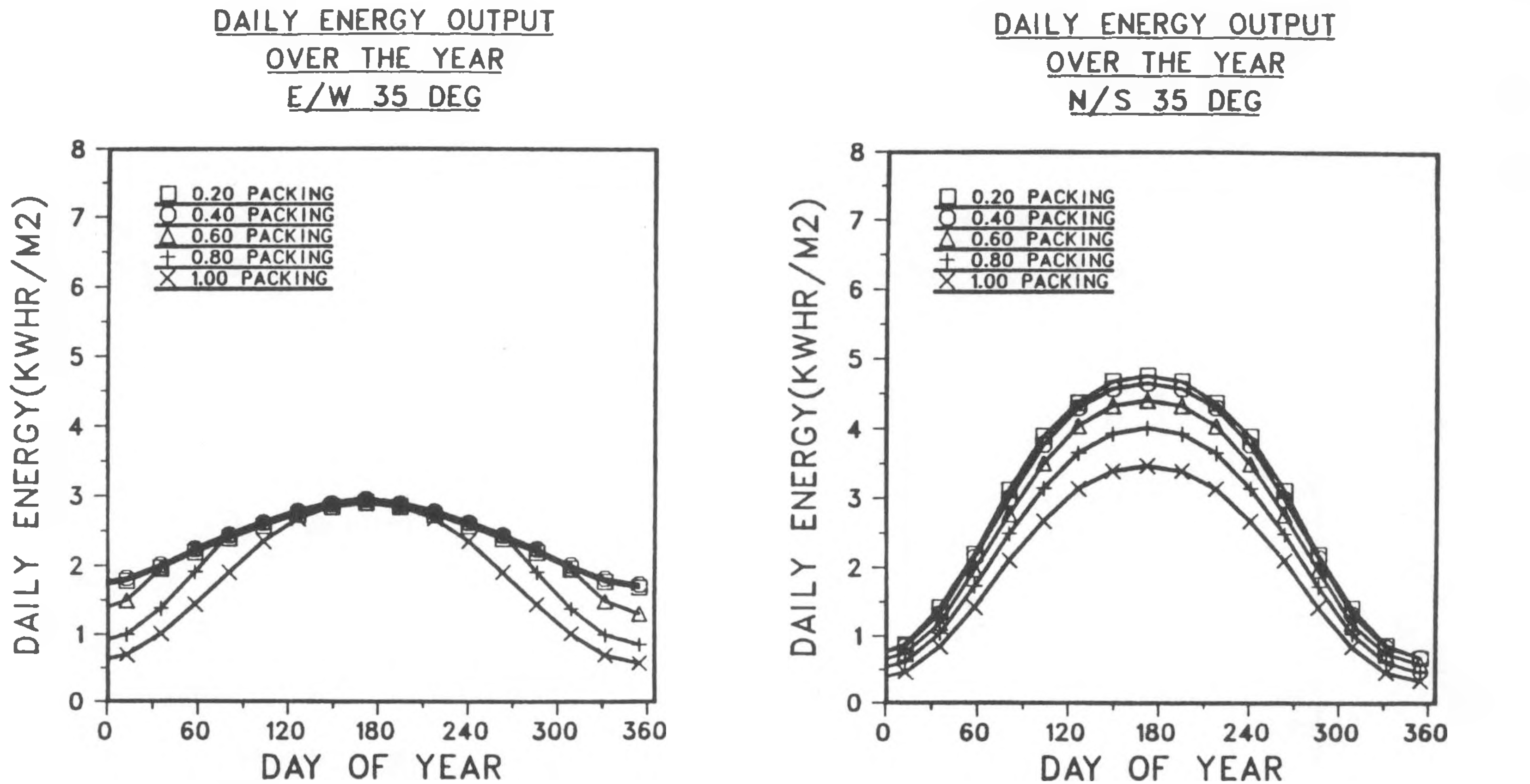


Figure 2. Annual Energy vs. Packing Factor
Latitude 35 degrees

Figures 3A for an east/west orientation and 3B for a north/south orientation illustrate the dependence of net energy collected daily on time during the year for five collector spacings. For the east/west field, no shadowing occurs for packing factors less than .4. In the winter, the sun elevation is low so shadowing losses reach a maximum. For the north/south field, shadowing occurs throughout the year for all packing factors considered. In the summer, a considerable amount of energy arrives at large azimuth angles so shadowing losses reach a maximum. For the range of packing factors considered, the east/west field collects more energy during the winter and the north/south field collects more energy during the summer.



A. East/West

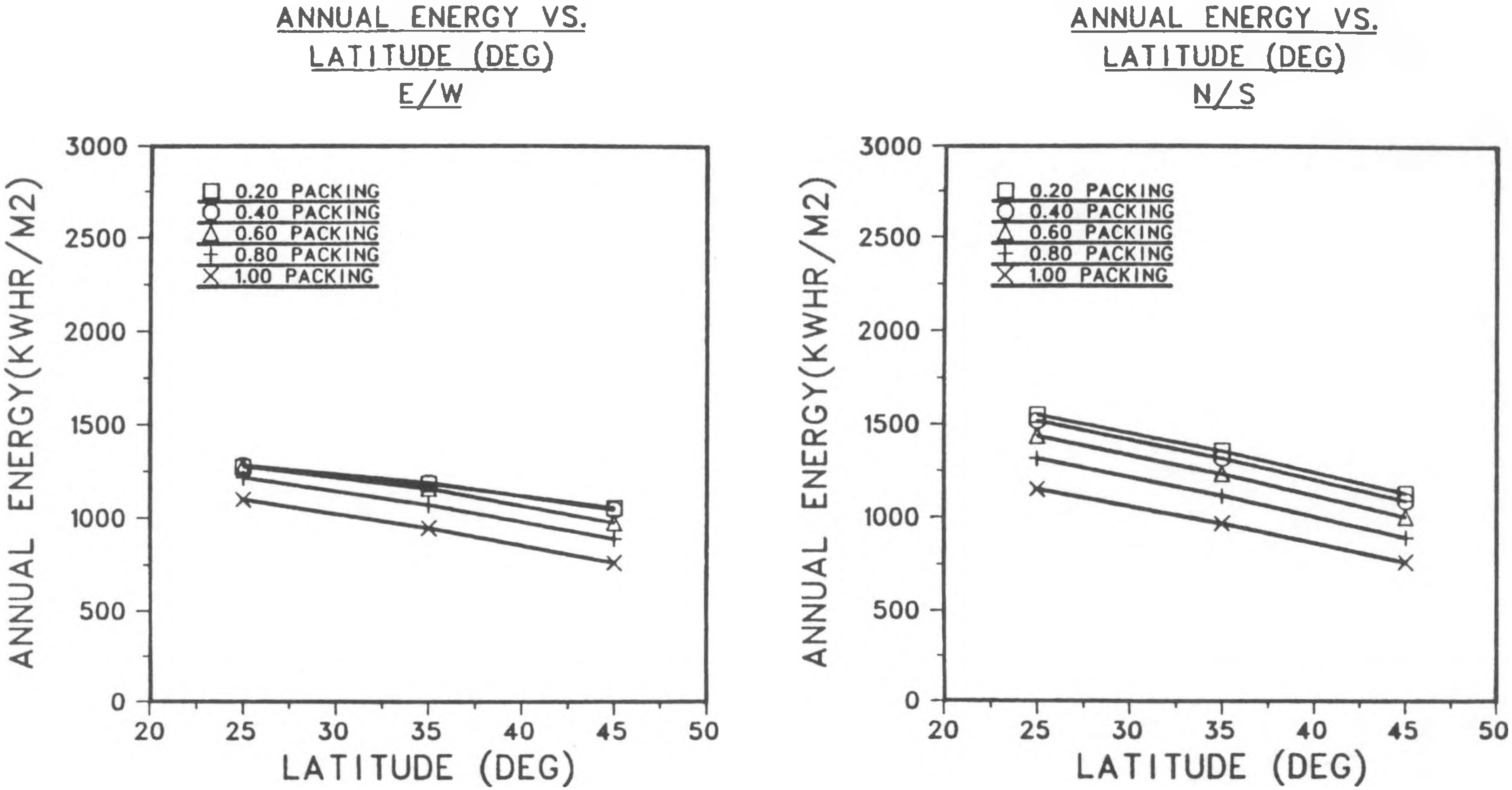
B. North/South

Figure 3. Net Energy Collected Daily vs. Day of Year
Latitude 35 degrees

Figures 4A for an east/west orientation and 4B for a north/south orientation illustrate the dependence of net energy collected annually on latitude for five collector spacings. For the east/west field, at latitudes less than 45 degrees, no shadowing occurs for packing factors less than .4. For packing factors less than .6, no shadowing occurs for latitudes less than 35 degrees. At higher latitudes, shadowing losses increase more rapidly with packing factor than at lower latitudes. For the north/south field, Figure 4B, the increase in shadowing losses due to increasing packing factor is nearly independent of latitude. Thus the difference in annual energy output at a latitude of 25 degrees between minimally and maximally packed fields is approximately equal to the difference in annual energy output at a latitude of 45 degrees between minimally and maximally packed fields. Annual energy output decreases with increasing latitude more rapidly for the north/south field due to all day cosine losses than for the short time cosine losses of an east/west field. However, over the range of packing factors considered and for latitudes less than 45. degrees, annually the north/south field collects more energy than the east/west field.

Figure 5 plots insolation (dashed lines) and net energy collected annually (solid lines) as a function of field rotation for three latitudes. A north/south orientation corresponds to a rotation angle of 0. degrees and an east/west orientation corresponds to a rotation angle of ± 90 degrees. The packing factor is .4. At lower latitudes the net energy varies more strongly with field orientation and reaches a maximum for a north/south orientation. At a latitude of 45 degrees, net energy is nearly independent of field orientation.

Figure 6 plots insolation (dashed line) and net energy collected daily (solid lines) as a function of time of year for three field orientations at a latitude of 45. degrees and a packing factor of .4. Energy supplied by the east/west field is more uniformly available throughout the year, whereas energy supplied by the north/south field peaks in the summer and is at a minimum during the winter.



A. East/West

B. North/South

Figure 4. Net Energy Collected Annually vs. Latitude

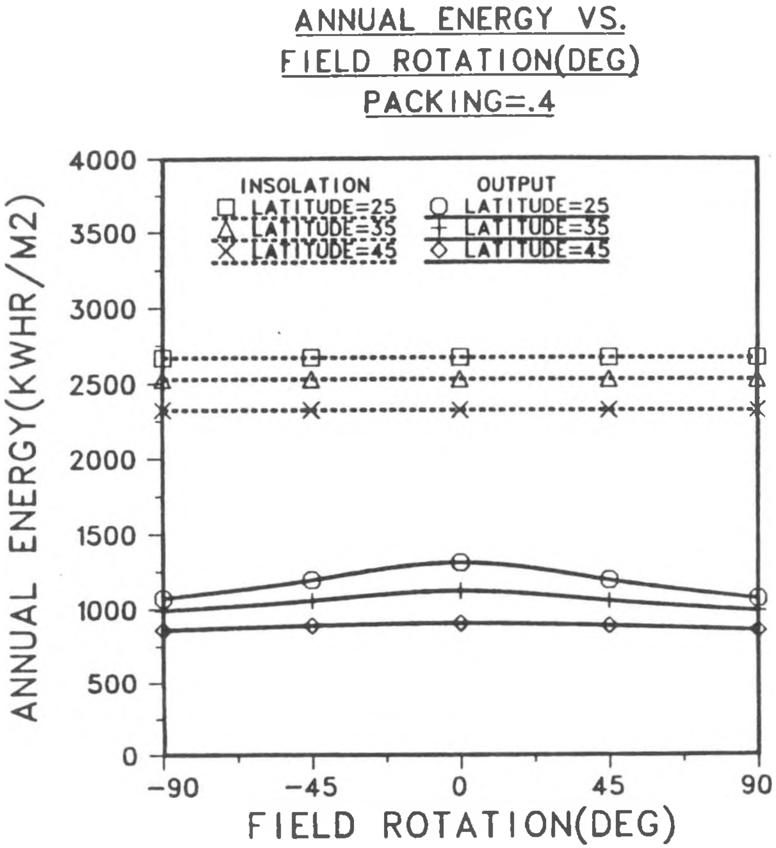


Figure 5. Annual Energy vs. Field Orientation

Packing Factor .4

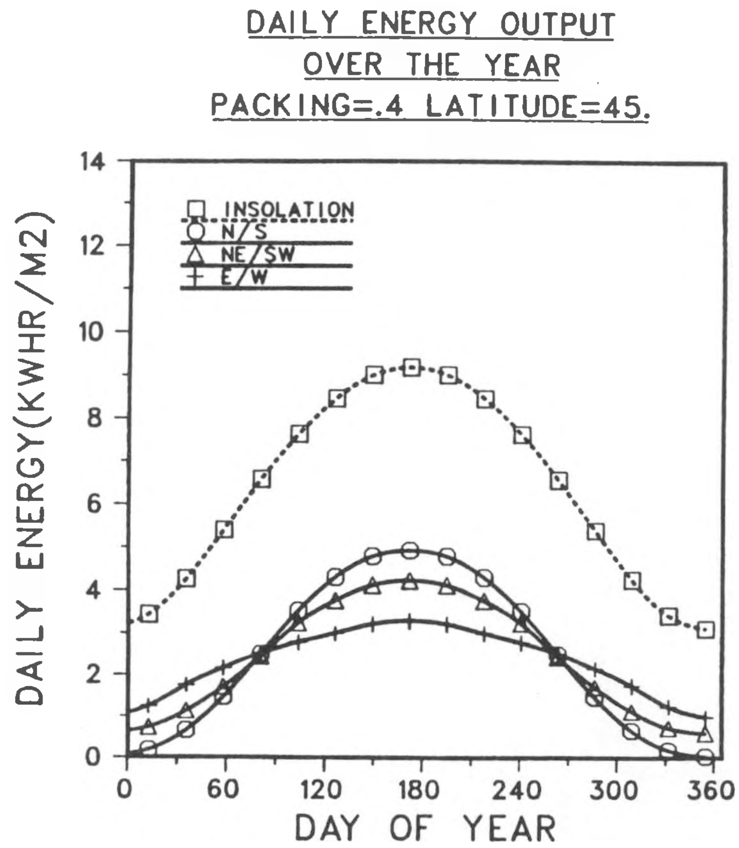


Figure 6. Daily Energy vs. Day of Year
Latitude 45 degrees

Packing Factor .4

CONCLUSION

The results discussed in this paper show the effect of collector spacing, location, and orientation on the net energy output of parabolic trough collector fields. Decreasing the collector spacing (increasing the packing factor) reduces the net energy available from a fixed amount of collector field primarily due to increased shadowing. The shadowing penalty is more severe for north/south field orientations but the annual energy delivered is always greater for a north/south field than for an east/west field for the latitudes considered. Moving the field location further north (increasing the latitude) decreases the annual energy available. The decrease is more a function of latitude than collector spacing. Changes in annual energy output for different collector orientations (field rotations) are reduced when the latitude is increased until they are approximately equal at 45 degrees; but the variations in daily output still exist.

REFERENCES

1. H. C. Hottel, Solar Energy, 18, 129 (1976).

2. K. Wally, Ed., "Modular Industrial Solar Retrofit: System Constraints, Specifications and Guidelines," SAND81-1300, August 1981.

3. J. K. Sharp, "Designing the manifold Piping for Parabolic Trough Collector Fields," SAND 81-1780, April 1982.

4. L. L. Lukens, "Experimental Parabolic Trough Collector Performance Characterization," SAND81-0313, May 1981

5. A. C. Ratzel and C. E. Sisson, "Annular Solar Receiver Thermal Characteristics," SAND79-1010, October 1980.

COLLECTOR DRIVE DEVELOPMENT

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INTRODUCTION

Standard industrial speed reducers are designed for a variety of end uses. This requires each component to be sufficiently strong for the worst combination of loads that a customer is expected to impose. In addition, industrial type gear drives typically operate continuously for many hours per day and require consideration of thermal limits.

For use on a solar collector with well defined operational and maximum load conditions, a special design has significant cost advantages since all components can be sized to meet known loads and large safety margins are not required. Also since total horsepower transmitted is low, thermal limits need not be considered. Since little operational experience with solar collector drives is available, many design parameters have to be determined through a program of testing and design refinement. Such a program is well worth the initial effort, since solar reflector drives are expected to be produced in large quantities.

DESIGN STUDY

In September, 1980 Winsmith received a contract from D.O.E. to design and develop an improved gear drive for line focus solar collectors. The most important performance requirements were:

1. Operate at 25 mph average, 37.5 mph peak gust conditions.

2. Support loads generated by 80 mph wind.

3. Operate with a .5 HP drive motor.

4. Positional accuracy of .25° total.

5. Self-locking under backdriving conditions.

6. 20 year life under outdoor conditions.

7. Expected cost of less than $20 per meter^2 of collector area.

Several wind data revisions resulted in final torque loads of 18,000 in. lbs. as a maximum continuous operating and 57,000 in. lbs. as a static survival torque for a 120 ft. long collector. Time to stow was to be less than 5 minutes, which determined a maximum gear ratio of 14,000:1 for a 1,750 RPM drive motor speed. The minimum gear ratio possible was determined by the requirement of 31,700 in. lbs. maximum momentary operating torque, a maximum motor torque of 80 in. lbs. and a minimum starting efficiency of 13%. These requirements result in a minimum gear ratio of 3000:1.

These performance requirements can be met with a variety of gear drive configurations. Spur or helical gearing would require 5 or 6 stages for the overall reduction of 4,000 to 14,000. Efficiency of such a drive system is high, in the 80% range. However, this high efficiency would make it impossible to meet the self-locking requirement under backdriving conditions. The drive motor would mount parallel to the output shaft unless a bevel gear stage were included causing the drive unit to be wider than necessary, separating adjacent collector sections more than required.

Another possible drive configuration is a differential planetary as shown on Fig. I. Such a drive can be designed with very high gear ratios, up to 25,000:1, by altering the internal gearing. However, efficiency is rather low at high gear reduction which limits the available output torque to a constant value irrespective of the gear ratio if the input torque is constant. This torque multiplication factor is about 350:1 which would require an input torque higher than that available. In addition, the in-line configuration of input and output shafts require mounting at the end of the reflector structure with resultant problems in strength and deflection of the mirror support structure.

Multi-stage worm gears can be designed to fit in the center of a reflector structure driving 1/2 of the total length from each side of a double extended output shaft. For a two stage worm gear drive, the maximum practical overall gear ratio is 3600:1 which is very close to the required minimum of 3000:1. The output/input torque ratio is about 1,000 at 3600:1 gear ratio and 1,800 RPM input speed. For 100 RPM input speed, the output/input torque ratio reaches an upper limit of about 550 due to lower worm gear efficiency at low surface sliding velocities.

Triple reduction worm gear speed reducers show output/input torque ratios much higher than either planetary or double stage worm gearing. Also, the available range of reduction ratios covers the range required, and the configuration allows installation in the center of the mirror structure. The disadvantage is that a triple reduction unit would require complex machining if a single housing is used, and the total number of parts is larger.

Previous experience with drives for heliostats suggested that a two stage gear drive using a differential planetary as a first stage and a worm gear as a second stage would be a compact and cost effective configuration for the intended use. Fig. 2 schematically shows the internal gearing arrangement of this proposed configuration. The output stage is a worm and gear set with 40:1 gear ratio. The top practical limit of this stage is 60:1 without change in size of either the worm or worm gear. 40:1 was selected for several reasons:

1. At very low speeds or at static conditions, this gear ratio is self-locking under backdriving conditions. (Backdriving means torque input into the slow speed shaft).

2. 40:1 is very close to the maximum torque capacity of any worm gear ratio for a given center distance.

3. A single thread worm could be made by thread rolling to minimize manufacturing cost.

4. Efficiency of this worm and gear ratio is within acceptable limits.

The worm gear stage is driven by the output ring gear of the first stage differential planetary gear set. This first stage is designed with simplified gearing, whereby two ring gears which have different numbers of teeth, but of identical inside diameters, engage planet gears of double width. (Differential planetaries are normally designed with planet gear clusters having two gears of different diameters on a common axis and interconnected.) The primary ring gear engages one set of planet gears, and the secondary ring gear engages the other set of planet gears. The primary ring gear is stationary while the secondary ring gear is the rotating output member. The input is the sun gear which engages the primary planet gear set.

The overall gear ratio of a differential planetary is determined by the difference in operating pitch diameter between primary and secondary ring gear. If this difference is zero, or if the primary and secondary ring gears are identical, the output speed becomes zero, that is the gear ratio is infinity. For small differences in the size of primary and secondary ring gear, it is possible to use the same gear cutting tool and machine different numbers of teeth while maintaining the same ring gear inside diameter. Such ring gears will properly mesh with the same planet gear even though the operating center distance remains constant. The only other requirement for proper operation is selection of the correct numerical difference in the number of teeth. For an arrangement of two equally spaced planets, the difference in the number of teeth between primary and secondary ring gear must be any multiple of 2, that is 0 x 2, 1 x 2, 2 x 2, etc. For three equally spaced planets this difference must be any multiple of three. Since there is a practical limit of how many different number of teeth can be generated by the same tool on a constant ring gear inside diameter, the difference in number of teeth between primary and secondary ring gears is limited to the number of planet gears. By altering the diametral pitch and the number of teeth of all planetary gear members, a large gear ratio range can be obtained without any changes to the primary gear housing. This is an advantage because a variety of gear ratios can be obtained in the same space envelope using many common components.

In the example shown in Fig. 2, the overall gear ratio is 40 x 85.705 = 3428.2. The efficiency is above 30% at 1200 RPM input speed and high output torque resulting in a torque multiplication factor of over 1,000. This value is of the same magnitude as that which can be expected from a double reduction worm gear drive without the gear ratio limitation of that gear drive.

Fig. 3 shows a drive schematic using a 40:1 worm gear set and a 250:1 planetary for an overall reduction ratio of 10,000:1 which is outside the practical ratio range of a double reduction worm gear drive and would require at least five or possibly six helical or spur stages.

Fig. 4 shows a cross section of the design as manufactured in prototype quantities. The drive motor is directly mounted on the motor adapter and drives the sun gear through a shear pin coupling. Gravity forces, wind forces, and wind moment are supported by the double extended output shaft through tapered roller bearings, the housing, and finally the mounting pedestal.

DEVELOPMENT

During component development, a number of changes were required relative to each component in order to achieve a balanced design. Our initial aim was to design deliberately on the light side and to increase component strength and durability only when testing indicated a need for it. Experience has shown that components that have excess strength will not normally be decreased in size as a result of testing.

All static loads that feed back into the gear box are absorbed by the worm gear set. The ratio of survival torque to maximum operating torque is 3.16 which is within the capability of worm gearing. Stress analysis of the worm indicated the need for a root diameter greater than the optimum for high efficiency. This causes a potential problem with the overall efficiency of the gear drive since all worm gear drives, regardless of the method of manufacturing, must run in for a period of time in order to achieve their rated torque capacity and efficiency. Initial values may be as much as 20% below that which a well run-in gear drive is able to achieve. After about 100 - 200 hrs. operation, all sliding surfaces will have polished each other and the gear drive will deliver expected efficiency and output torque, without requiring higher than normal input torque.

We tested a number of different worm gear materials and surface treatments in order to overcome the run-in problems. In all cases, a carburized, hardened, and ground worm was used. For reasons of strength and cost cast iron was used for the worm gear, even though cast bronze is the more common choice. In order to overcome the problem of initial lower efficiency, we tried plating the cast iron worm gear.

Endurance testing for 722 hours of the plated gear showed a well polished surface with very little wear. Additional investigations are underway to determine if plating can be eliminated through use of additives in the lubricating oil.

The present configuration as shown on Fig. 4 has many features considered important from a cost and performance point of view.

- Tapered roller bearings for worm shaft and output shaft support. (Tapered roller bearings have the lowest cost per unit capacity).

- Needle, rather than sleeve bearings, for planetary shaft support.

- Provisions for a pin type shear member on the input shaft.

- Dual shaft seals on the input shaft.

- Differential planetary of simplified construction that can easily be modified to accommodate different gear ratio requirements.

- Carburized, hardened, and ground worm. We are presently experimenting with rolled worms and have had very encouraging results.

- Worm gear made of high strength cast iron, plated to improve efficiency.

- Hardened and tempered output shaft with dual shaft seals, dust shield, and dust seal on each end.

- Provision for mounting a position encoder driven by low backlash gearing. This gearing can provide 1:1 or any other desired gear ratio between output shaft and encoder.

- Use of an expansion chamber to prevent breathing and thus eliminate water condensation inside the gear box.

- Synthetic lubricant (Mobil SHC 626) which is suitable for the entire anticipated temperature range, and does not require regular oil changes. We plan to experiment with various greases and additives to 1) eliminate the need for shaft seal replacement if small cracks should develop after long term exposure, 2) eliminate plating of the worm gear.

- Suitable protection from corrosion through plating and painting as appropriate.

- Compact design of a configuration that integrates easily with the structure of line focus collectors.

- Sufficient and balanced component strength and durability.

There are still areas where improvements in cost can be made without sacrifice in performance. The main housing and cover are presently only available in cast iron since anticipated production quantities are low in the near future. Should production orders improve significantly, the initially high tooling investment for die casting dies can be justified. In this case, we would make several components of zinc-aluminum alloy with resultant decreases in weight and cost. We have made several prototype housings and covers out of this material using a plaster cast process. Although elastic deformation of these housings were larger than that measured on cast iron housings, no detrimental effects which could negatively affect the performance of the gear drive have been detected.

We have progressed through several iterations during the design and development of this gear drive. Many hours of operation at rated load did not cause component wear which could cause operational problems during the expected life time. We are confident that the present design meets all objectives of cost and performance and we have identified several areas of potential cost reductions if production order quantities justify the initially high investment.

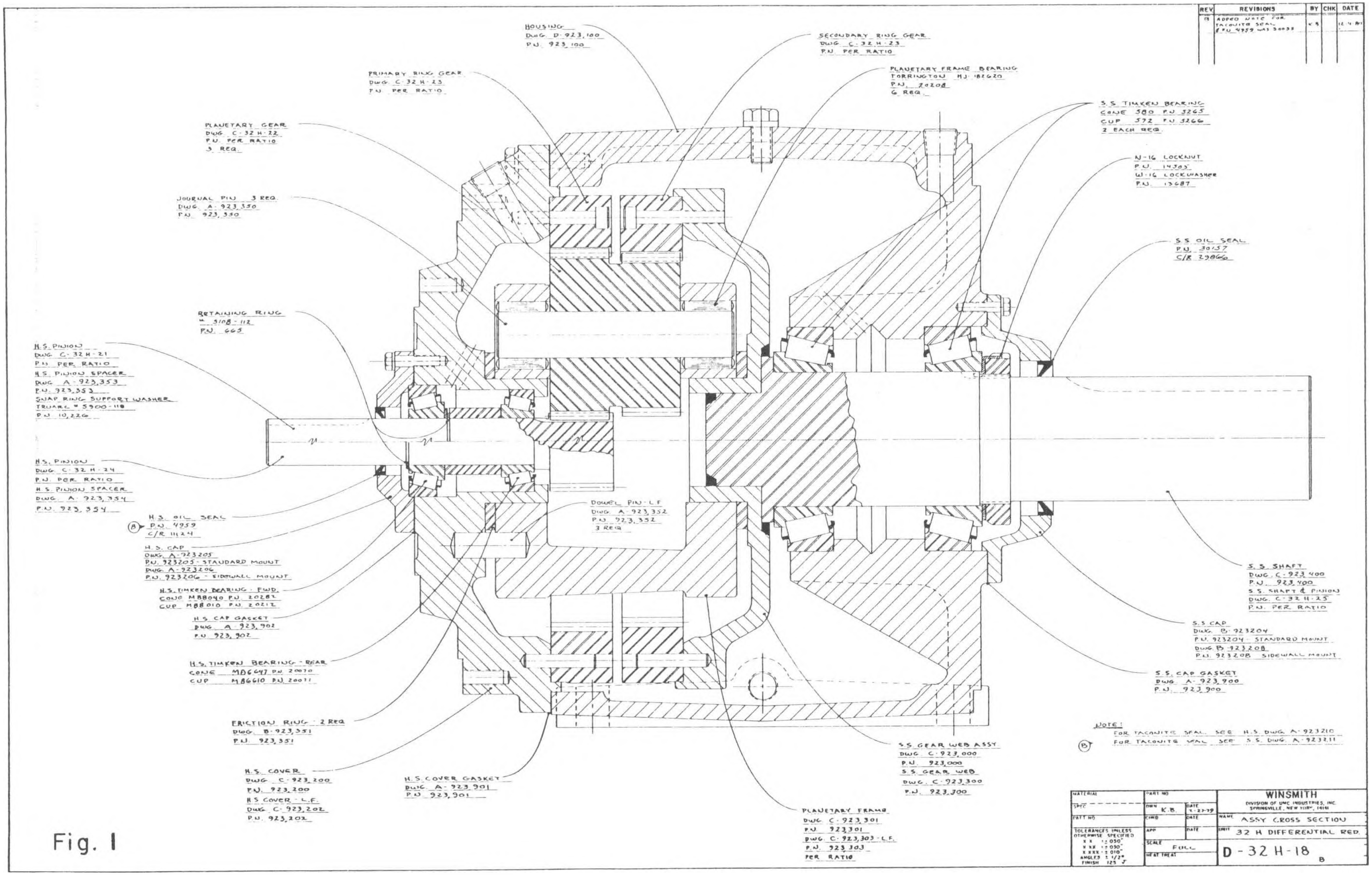
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Fig. 1

DRIVE ARRANGEMENT

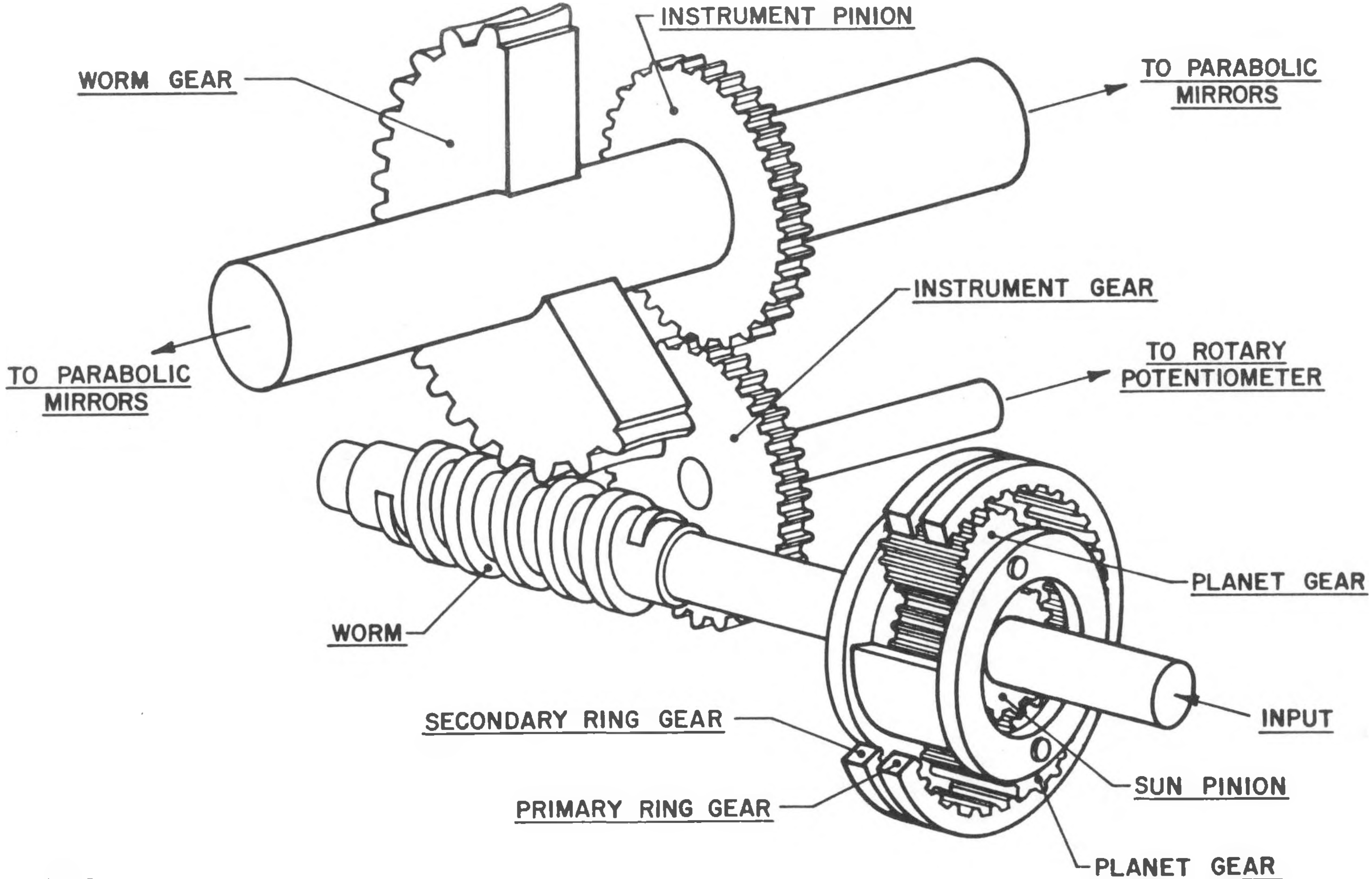
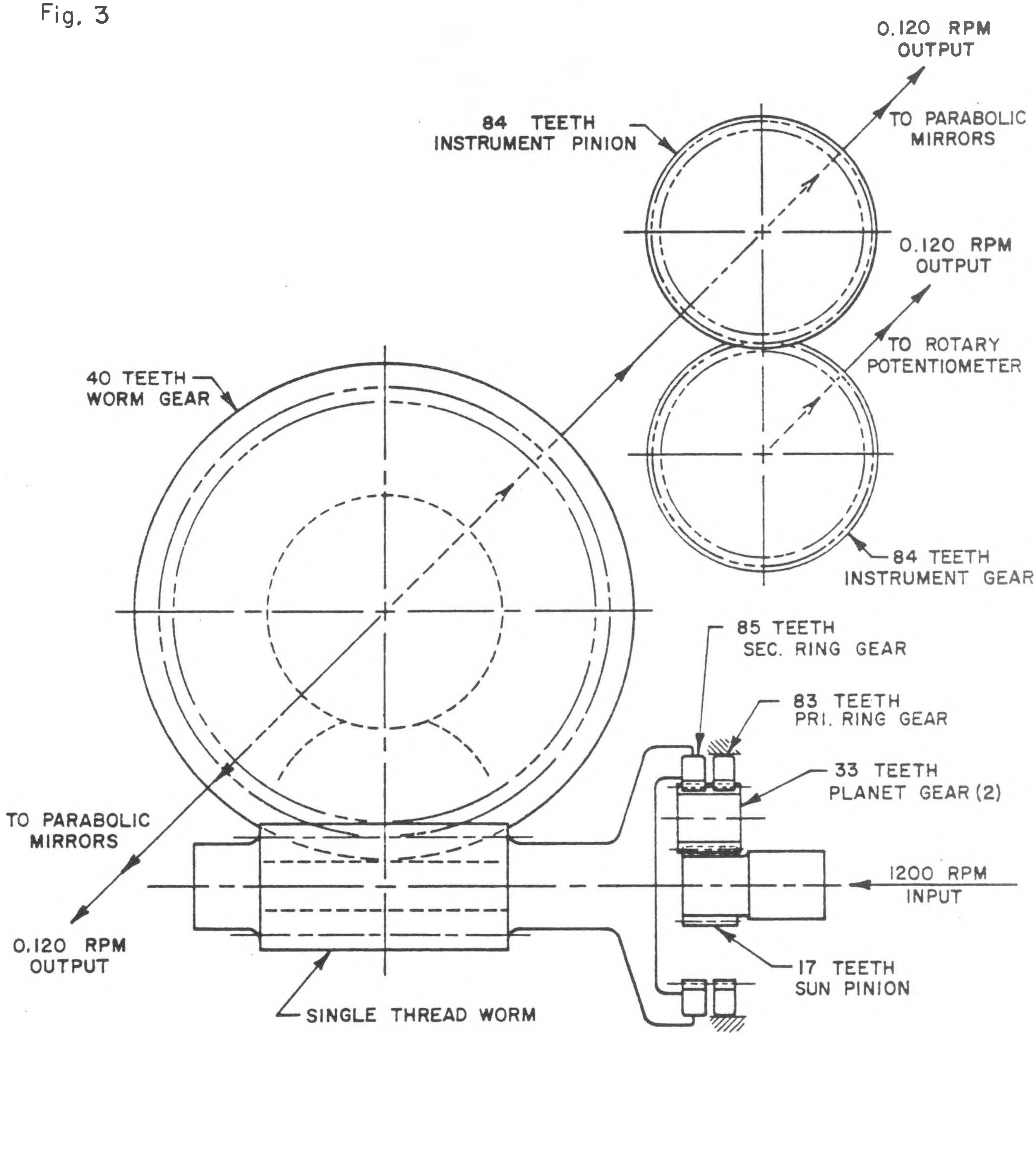


Fig. 2

DRIVE SCHEMATIC

Fig. 3



WORM GEAR RATIO	PLANETARY RATIO	OVERALL RATIO
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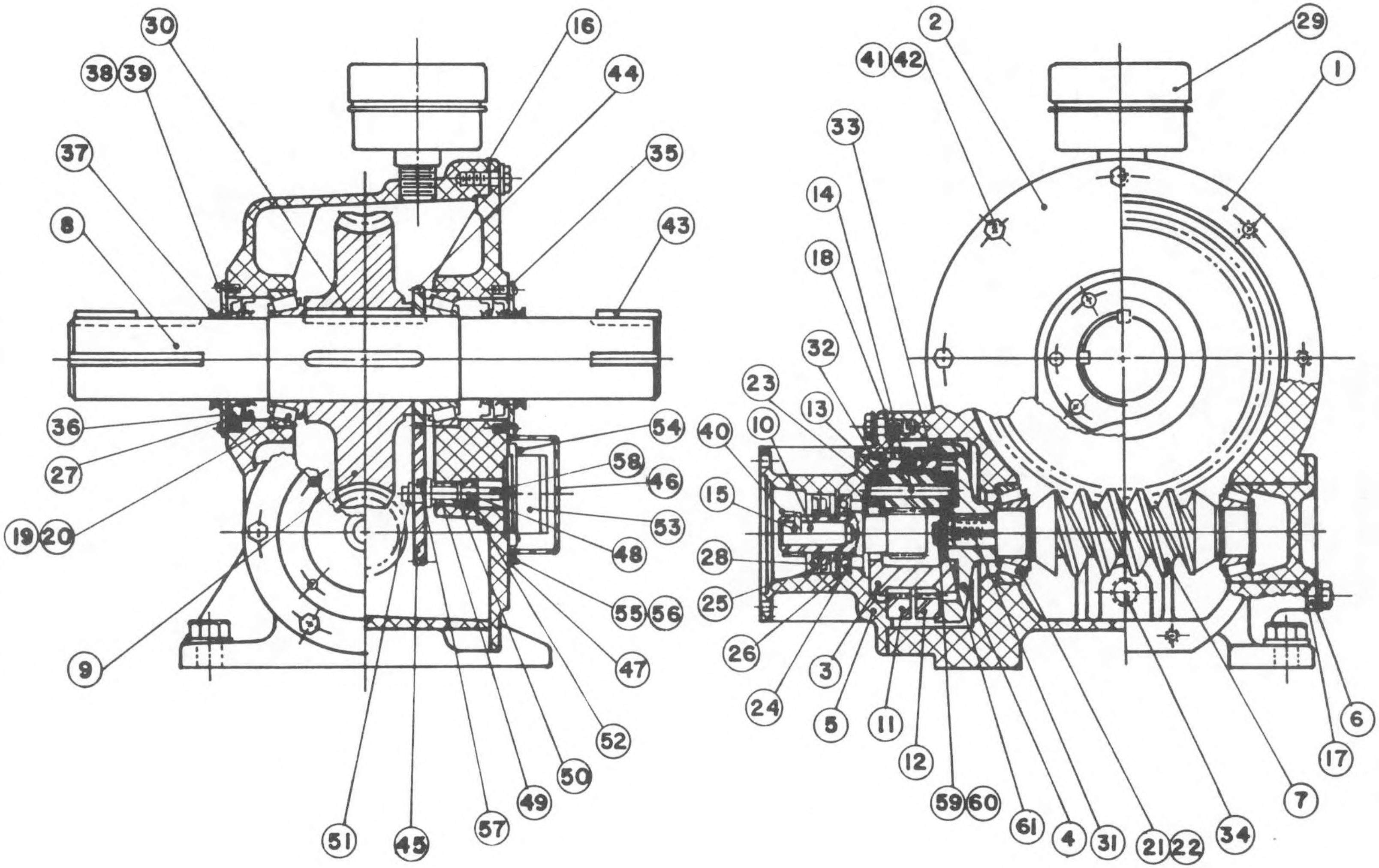

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Fig. 4

SHEET METAL, SAGGED GLASS AND SMC REFLECTOR/STRUCTURES

Albert W. Biester
The Budd Company Technical Center
Fort Washington, PA 19034

Introduction

In late 1979, the extensive experience and capability of The Budd Company in the development, prototype production, and mass production of automotive components was enlisted by Sandia National Laboratories to aid in the development of accurate, durable, and mass producible line focus parabolic trough solar reflector panels. Under contract to Sandia, The Budd Company Technical Center in Fort Washington, PA developed and produced prototypes of two (2) different mass producible panel designs--one design of sheet metal construction and the other of sheet molding compound (SMC). A torque tube assembly for mounting and positioning six one meter by two meter reflector panels was also developed and fabricated. The prototype units produced on these contracts were subjected to structural, laser ray tracing, and thermal cycling tests by Sandia.

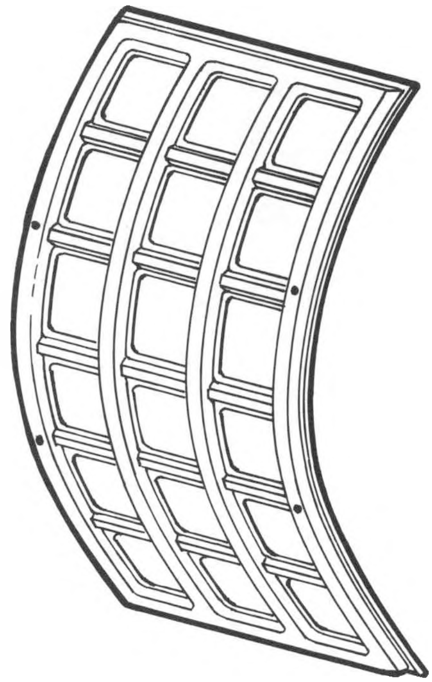
Subsequently, the sheet metal panels and the SMC panels were chosen by Sandia for performance testing on the Performance Prototype Trough (PPT) phase of the program. Also, Budd was awarded an additional contract to develop and fabricate a Sandia concept for a glass/space frame solar collector assembly for testing on the PPT Program.

This discussion will include a summary of the description of the parabolic reflector panels and the torque tube assembly, the fabrication and assembly procedures developed and utilized, the laser ray tracing inspection methods, and the shipment of the assemblies. More detailed information concerning the development and production efforts may be obtained from the Budd reports published by Sandia Laboratories. A listing of the publications will be furnished at the end of this paper.

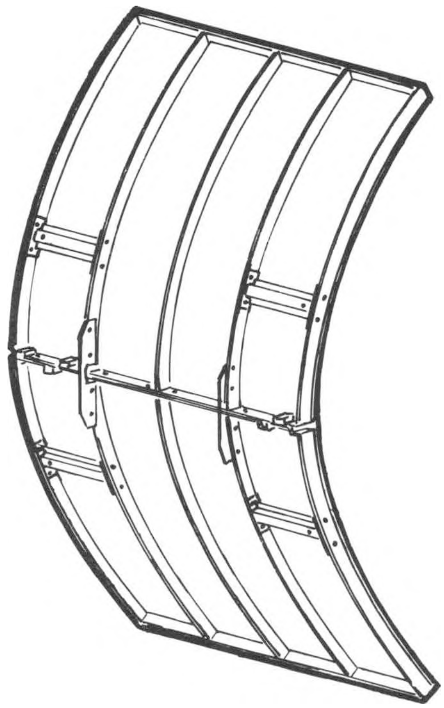
Sheet Metal Reflector Panels

All of the reflector panels included in this discussion were one

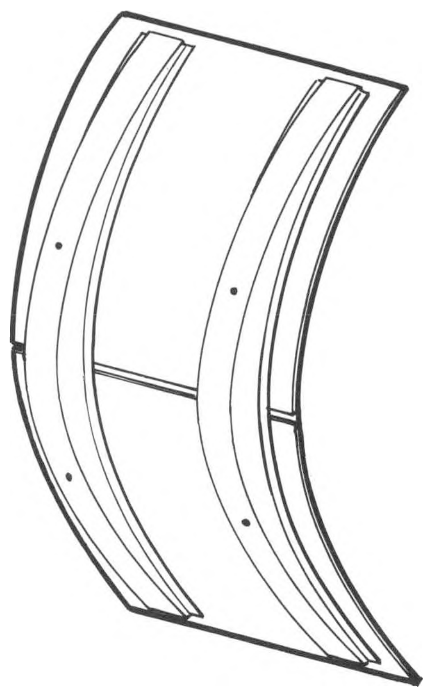
REFLECTOR PANELS



SHEET METAL REFLECTOR



SMC REFLECTOR



SAGGED GLASS REFLECTOR

meter by two meter panels with the two meter dimension being rim to rim. The sheet metal reflector panels consisted of two pieces of 0.050 inch thick chemically strengthened glass mirrors bonded to a 0.030 inch thick electrogalvanized stamped steel frame panel. Goodyear Pliogrip 6000 urethane adhesive was used for bonding. Since the steel frame panel incorporated a channel at the vertex and two pieces of glass mirror are used for each parabolic reflector, it was necessary to bond a bridging strip of electrogalvanized steel 0.030" x 4-1/4" x 39" to the frame panel at the vertex to provide rigidity and a substrate for the glass at that area. The bridging strip was bonded to the frame panel with Goodyear Pliogrip 6000 urethane adhesive prior to the glass bonding operation.

Automotive prototype part zinc alloy dies were used to produce the stamped steel frame panels. For low quantity production, this type of tooling saves the cost of hard steel production dies. After forming, the steel panels were manually trimmed to size and drilled using a template. For high production, a blank and pierce die would be used.

To bond the glass mirrors to the steel frame panel, it was necessary to prepare the surfaces for bonding. The back, or painted surface of the mirrors was wiped lightly with alcohol and a coating of Goodyear 6031/6032 epoxy primer was applied by spraying and air drying. The mating surface of the steel frame panel was lightly abraded with Scotchbrite and thoroughly cleaned with methylene chloride. A coating of Goodyear 6031/6032 epoxy primer was then applied to this surface by spraying and air drying.

Bonding of the glass mirrors to the steel frame panel was accomplished in a fixture with an accurately machined parabolic surface and provision for vacuum hold down of the glass. After the mating surfaces were prepared for bonding, the glass mirror sections were placed on the bonding fixture, elastically formed over the parabolic surface and held in place by vacuum. Adhesive was applied to the mating surfaces of the steel frame panel and the panel was placed over the glass on the fixture. Two datum holes on the vertex of the steel panel engaged locating pins on the fixture providing accurate orientation for the panel. Pressure was applied to the frame panel by four cargo type straps placed longitudinally over the panel and tightened by torque wrench actuated buckles. After approximately two and one half hours of adhesive curing, the panels were removed from the fixture.

After removal from the fixture, the remaining production processes were performed. The concave glass reflecting surface was masked and the entire back surface of the panel was cleaned with methylene chloride. The back surface was then spray painted with a two part epoxy primer and air dried for eight hours. The final coat of two part white urethane paint was then applied by spraying and was allowed to air dry.

SMC Reflector Panels

Each one meter by two meter SMC reflector panel consists of two one meter by one meter panels which are joined at the vertex to form the full panel. The panel was designed in half sections to reduce the cost of the mold. The panel mold was made of zinc alloy and incorporated provision for heating by hot oil or steam. Hot oil was used in producing the panels.

A feature of the SMC panel was that the chemically strengthened glass mirror was molded integrally with the SMC structure, thereby eliminating subsequent attachment operations. To provide proper adhesion of the glass to the molded structure, it was necessary to prepare the back surface of the glass with an adhesive coating. The painted surface on the back of the glass was cleaned by wiping with clean cloths moistened with methylene chloride. Three separate coats of an adhesive mixture consisting of Epon 828, Versamid 140, ATBN and MEK were applied to the glass by spraying. Each coat was applied at a ninety degree angle to the previous coat and provided a total nominal coating thickness of 0.009". The adhesive coating was cured in air for one hour and then cured on a rack in an oven for one hour at 240°F.

To form the one meter by one meter panel, the glass was preheated to 250°F for a minimum of fifteen minutes. The SMC charge pattern was prepared and the preheated glass was placed in the mold. The SMC charge was then placed in the mold and the mold was slowly closed. Forming was accomplished under a nine hundred ton force (1,000 psi on the panels) at a temperature of approximately 300°F and held for three minutes. The mold was then opened, the part ejected from the mold and placed on a cooling fixture. Some of the SMC panels were molded with a lip covering the periphery of the glass. This was accomplised by inserting a slightly undersized formed sheet of aluminum under the glass, allowing the SMC to flow around the edge.

Assembly of the two half panels into a one meter by two meter reflector panel was accomplished on a male parabolic fixture. The excess material and bosses were removed from the molded panels and the panels were placed on the fixture. The bosses had been included in the original design for a different mounting method. The panels were bonded and riveted together at the vertex. To provide additional strength at the vertex joint, two steel doubler plates were bonded and riveted to the ribs across the joint. To provide for mounting the SMC reflector panels to the same torque tube used for the sheet metal reflector panels, it was necessary to modify the original design by adding four steel hat sections with floating nuts for attachment. For production, the bosses could be eliminated and the attaching points added to the mold. With the panel on the fixture, the steel hat sections were positioned by a locating fixture and bonded and riveted to the SMC panels. All bonding operations were performed using Goodyear Pliogrip 6000 urethane adhesive with Goodyear 6031/6032 epoxy primer on the steel parts and Goodyear 6036 primer on the plastic areas.

To provide additional environmental protection, after removal of the SMC reflector panel from the fixture, the concave glass surface was masked and the entire back of the panel was spray painted with a two part epoxy primer and air dried for eight hours minimum. Finally, the back surface was spray painted with a two part white urethane paint and allowed to air dry.

Glass/Space Frame Solar Collector

The original concept for the glass/space frame solar collector was a six meter long steel structure which would be bonded to twelve half parabola one meter by one meter preformed laminated glass mirrors. Six pairs of formed sheet metal cross frames, formed to a modified parabolic contour to interface with the back surface of the preformed glass mirrors, were to be welded to a six meter long tube.

During the investigation and development by Budd, the initial concept was modified. Instead of laminated glass mirrors, six millimeter thick, solid glass, sagged or preformed, mirror panels were supplied by Sandia. The cross frames were removed from the design of the tube assembly and formed steel ribs were developed. By bonding two steel ribs to two half parabola glass mirror panels, a separate one meter by two meter reflector panel was produced. It was then possible to attach the individual reflector panels to the torque tube assembly by means of bolts in the same manner utilized for the sheet metal and SMC reflector panels. The individual panel configuration is more suitable to mass production techniques than is the original space frame concept.

The support rib which was developed to join the two half parabola glass mirrors was a formed steel hat section, with the depthof the part tapering from the mounting points to the ends. The parabolic curve of the flanges was developed to allow for the six millimeter thickness of the glass and the curve was held accurately in the finished stamping.

Standard automotive prototype parts procedures were used in producing the formed steel ribs. To eliminate the high cost of hard steel dies, the parts were formed using zinc alloy dies. After forming, the parts were manually trimmed to final configuration using a trim template. Weld nuts and doublers were located by a fixture and spot welded to the stamping for attachment. Since the ribs were formed from draw quality steel due to the relatively severe forming operation, it was necessary to provide corrosion protection on the inside surfaces prior to bonding to the glass. This was accomplished by masking the mating flange surfaces and coating the inside surface with a two part epoxy primer and a two part white urethane finish coat.

To bond the ribs to the glass panels, the fixture developed for the sheet metal reflectors was utilized. However, due to the thickness of the glass, the vacuum provision in the fixture was not used. Locators for the two half parabola glass mirrors were used instead.

The mating flange surfaces of the steel ribs were cleaned with methylene chloride and coated with Goodyear 6031/6032 epoxy primer. To provide for positioning the ribs on the glass and for application of bonding pressure, an additional fixture was designed and fabricated. The ribs were attached to the fixture at the mounting points. The fixture incorporated locating holes on the vertex which mated with datum pins on the fixture at the vertex and also incorporated stops to provide a nominal 0.030" adhesive bond thickness.

The painted back surface of the glass mirrors was cleaned with alcohol and a coating of Goodyear 6031/6032 epoxy primer was applied to the mating surface. Alcohol was used for cleaning to prevent damage to the mirror backing paint. The glass panels were placed on the fixture against the locators. Two steel ribs were attached to the locating fixture and Goodyear Pliogrip 6000 adhesive was applied to the mating flanges. The fixture, with the ribs attached, was then placed on top of the glass in the bonding fixture. The vertex datum pins engaged the holes in the locating fixture and straps were applied to provide the bonding pressure.

After curing of the adhesive in the fixture for approximately two and one half hours, the one meter by two meter reflector panel was removed from the fixture. The entire back surface was then spray painted with a two part epoxy primer and air dried for a minimum of eight hours. A finish coating of a two part white urethane paint was then applied by spraying and was air cured.

Torque Tube Assembly

The torque tube assembly which was initially developed for use with the sheet metal reflector panels was suitable for use with the SMC panels and, with a slight modification, was also used with the glass reflector panels. The torque tube assembly consists of seven stamped steel trough supports welded to a steel tube and flange assembly. For ease in handling, lifting eyes were provided on both sides of the tube at the quarter points. The center trough support on each assembly incorporated a mounting plate for the receiver tube support.

The trough supports were formed from 0.078" thick galvanized steel. Forming was accomplished on zinc alloy dies. After forming, the parts were trimmed to a template and mounting slots for the panel mounting were punched at the four corners. For attachment to the tube, tabs were formed in the part to provide for welding attachment to the sides of the tube. Since the welding was accomplished on opposite sides of the tube, distortion due to the heat of welding was minimized.

Due to the spacing of the steel ribs on the glass reflector panel and the depth of the stamping, it was necessary to modify the end trough supports by increasing the depth of the stamping at each end of the part. Since the number of pieces requiring modification was small, the change was performed manually. The modification did not interfere with the mounting of the sheet metal or SMC panels.

The torque tube assembly was produced on an assembly and welding fixture. Two pre-machined steel flanges, 1/2" thick by 9-3/4" diameter and a steel tube, 7" diameter with 0.188" wall thickness by approximately twenty feet long and the lifting eyes were loaded in the fixture, the flanges and lifting eyes were welded to the tube, and the datum holes in the flanges were drilled and reamed. The tube and flange assembly was removed from the fixture and the trough supports were positioned on their locators and clamped in place. The tube and flange assembly was then reloaded in the fixture, with pins through the datum holes. The trough supports were then welded to the tube and the receiver support mounting holes were drilled.

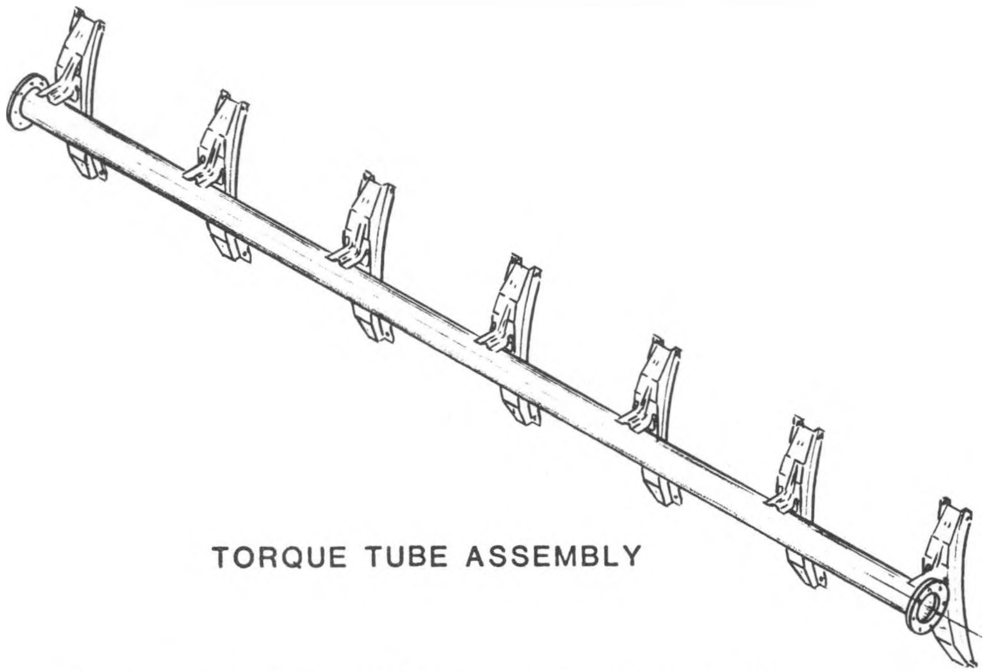
After removal from the fixture, the torque tube assembly was placed in a combination transport and painting fixture. While in this fixture, an additional operation was performed. Stainless steel shims were bonded between a bridging strip on the trough support and the tube, two holes were drilled, and the trough support was riveted through the shims to the tube. The requirement for this operation was disclosed by laser ray trace inspection, which indicated a sagging condition due to gravity. The weight of the panel caused relative movement between the trough support and the tube. The shimming and riveting operation eliminated the sagging condition.

The torque tube assembly was then cleaned thoroughly by solvent wiping and a coating of two part epoxy primer was sprayed over the entire assembly and air dried. A final coat of two part white urethane paint was then sprayed over the entire assembly and air dried.

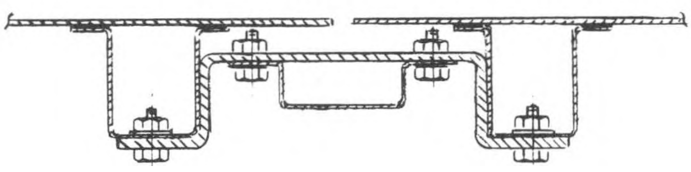
Solar Collector Assemblies

Assembly of the reflector panels to the torque tube assembly required that provisions by made to assure alignment accuracy of the panels and to maintain the required dimension between the centerline

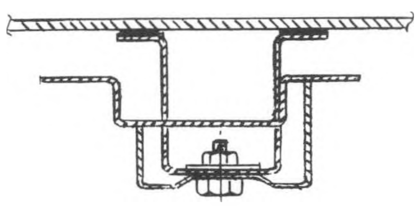
TORQUE TUBE & ATTACHMENTS



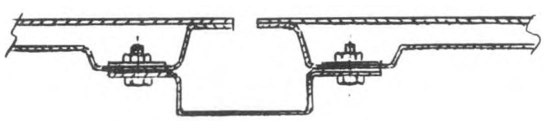
TORQUE TUBE ASSEMBLY



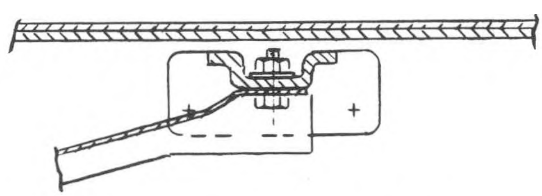
GLASS PANEL ATTACHMENT-INTERMEDIATE



GLASS PANEL ATTACHMENT-ENDS



SHT METAL PANEL ATTACH



SMC PANEL ATTACH

of the tube and the vertex of the panels. To accomplish this, a fixture was designed and fabricated. The design of the fixture enabled it to be used for assembly of the sheet metal, SMC, and glass reflectors. The design of the fixture was based on a six meter long aluminum honeycomb male parabolic mold furnished by Sandia. The mold was modified by installing spring loaded pins along the vertex to engage the datum holes in the sheet metal reflectors. For the SMC panels, locator blocks which fit into recesses in the panel engaged the same pins for locating the panels. Since the glass panels had a gap at the vertex between the glass half parabolas, a locating fixture which held the panel and engaged the same pins was provided. Supports were designed and fabricated for each end to position and hold the torque tube assembly in proper relationship to the aligned panels. The torque tube end supports were adjustable vertically to compensate for the different thicknesses of glass to assure maintaining the dimension between the centerline of the tube and the vertex of the panels.

To assemble the reflector panels to the torque tube assembly, the panels were placed on the parabolic mold with the pins engaging the locating holes. For the glass panels, the panels were first attached to the locating fixture. The panel was strapped down with cargo-type web straps and, for the glass panels, the fixture was removed. After six panels were properly positioned on the mold and strapped down, the torque tube assembly was placed on top and positioned by pins through the fixture end supports and the datum holes in the tube flanges. The panels were then bolted to the trough supports, shimming as necessary between the trough support and the mounting surface. For the glass panels, due to the spacing of the ribs, it was necessary to provide formed steel mounting straps at the intermediate mounting points. The ribs at each end were mounted directly to the modified trough supports at each end. The entire two meter by six meter assembly was then removed from the assembly fixture and placed in a combination transport and laser ray tracing fixture.

Laser Ray Trace Inspection

Essentially, the laser ray tracing operation is performed by positioning the laser inspection device accurately with respect to the panel or trough being inspected and scanning the reflective surface with the laser ray. The reflected ray's angle of reflection can be measured by detecting the position of the reflected ray as it strikes a detector surface. The comparison of the actual return position of the ray as indicated by the detector surface to the angle from the theoretical curve at that point can be translated to a measure of slope error, which is essentially the difference in angles between the actual and theoretical parabolas at a point. The readings are fed into a computer which calculates the statistical sum of the slope errors and provides a root mean square (RMS) slope error for the item being inspected.

The laser ray trace inspections performed on these projects were performed using portable laser tracing equipment loaned to Budd by Sandia Laboratories. The equipment provided capability for scanning the full two meter panel opening for a length of three and one half meters. To inspect a full six meter long assembly it was necessary to make two scans on the assembly to cover the full length by moving the laser equipment.

For inspecting the individual reflector panels, a relatively simple fixture was provided. The fixture held the panels with the rim to rim plane in a vertical position to allow laser scanning of the mirrored surfaces. Alignment of the panel with the laser equipment was accomplished by manual measurements.

For inspecting the two meter by six meter assemblies, a more elaborate combination transport and laser ray tracing fixture was provided. The collector assembly was mounted on pinions, similar to the mounting on pylons in the field. This arrangement permitted rotation of the assembly one hundred and eighty degrees so that each assembly could be fully inspected on one side, then rotated for full inspection on the other side. With the focal plane horizontal, laser ray inspection in the two positions indicates any effect due to gravity.

On each end of the fixture, accurately machined alignment arms extended from the vertex of the trough through the pivot center and beyond the receiver tube location. These arms incorporated sight holes and by shining an alignment laser beam through these holes and through holes mounted on the laser equipment, accurate alignment between the assembly and the laser equipment was provided. The fixture also incorporated casters, permitting easy transport of the full assembly between production and inspection areas.

Every two meter by six meter collector assembly was laser ray trace inspected by performing two scans on one side and then rotating the assembly one hundred and eighty degrees and performing two scans in that orientation. Of the individual reflector panels, the first six panels of each type were laser ray trace inspected and then one of each six subsequent panels produced were inspected. More information regarding the laser ray tracing inspection results is included in the Sandia publications. The average values of the inspections were as follows:

Type	Quantity Inspected	Average Slope Error (milliradians)	Average Focal Line (inches)
Sheet Metal:			
Indiv.Pnls	17	2.238	19.13
Assemblies	8	2.866	19.12
SMC:			
Indiv.Pnls	11	4.014	19.03
Assemblies	4	4.323	19.02
Glass:			
Indiv.Pnls	13	3.678	19.06
Assemblies	7	4.197	18.97

It should be noted that the laser ray trace inspection operation is not just a laboratory type exercise. It can be an effective in-process inspection method to assure that the production processes are kept within control limits and are consistently producing acceptable parts. It is an extremely valuable tool during development efforts.

Shipment of Assemblies

Shipment of fully assembled two meter by six meter collector assemblies from Fort Washington, PA to Albuquerque, NM, presented something of a challenge. To accomplish this task, special shipping fixtures were designed and fabricated. The fixtures consisted of aluminum stands in an inverted "T" configuration for each end of the assemblies. The stands were connected by wooden beams and two collector assemblies were attached to a set of stands. Attachment of the assemblies to the stands was made through the bolt holes in the end flanges of the torque tubes. The assemblies were mounted to the end stands in the stow (glass side down) orientation with the individual panels allowed to hang free. Neoprene vibration dampers, two located under one end stand and one located under the other end stand were incorporated in the shipping fixture.

After laser ray trace inspection, two collector assemblies were mounted in each shipping fixture. For shipment, forty-five feet long, air cushion suspension, flat bed trailers were utilized. Two fixtures containing a total of four assemblies were mounted on each trailer and covered with a wooden frame and tarpaulin for additional protection. Five separate shipments were successfully accomplished in this manner.

Problem Areas

The only significant problems encountered during the activities described herein were during the development of the glass reflector panels. The problems encountered were associated with the protective paint coating on the back surface of the six millimeter thick preformed glass panels furnished by Sandia. This coating was not the same as that furnished on the 0.050" thick chemically strengthened glass.

The first problem encountered involved bubbling of the final paint coatings along the adhesive bond line. Bubbling of the paint in this area propagated for periods up to three months. Investigation and analysis by both Budd and Sandia indicated that the bubbling condition was caused by unreacted isocyanate in the adhesive reacting with moisture in or under the backing paint on the glass panels, producing carbon dioxide.

During the same time period that the investigation of the bubbling problem was being conducted, thermal cycling of glass reflector panels in environmental chambers at Sandia disclosed delamination of the mirror backing paint at the interface between the copper plating and the backing paint. Later, the same problem was noted, to a lesser extent, on some of the panels mounted in the field.

To provide further investigation of these problems, additional experimental flat panels and parabolic panels were produced using various combinations of materials, adhesive and procedures. In all, six additional flat panels and nine additional parabolic reflector panels were produced and furnished to Sandia for testing. Since the results of the testing of the experimental panels are not known at this time, and the various combinations are extensive, further description of the experimental panels is not included here. Detailed descriptions of the panels involved are included in available Sandia publications listed at the end of this paper.

Conclusions

The development and production of the solar collectors discussed herein demonstrated that efficient and durable solar collectors can be produced using mass production techniques such as commonly used in the automotive industry. All of the items were produced using quasi-production tooling and techniques. However, since quasi-production type fabrication uses tooling and processes similar to mass production methods but not hard, production tooling or automated processes, the costs of production are relatively high since the operations are labor intensive. At the present time, market demands will not justify the investment in tooling and automation which would make the panels discussed here cost competitive. The quantities required at present lie between prototype production and mass production.

Until such time as production quantities would justify hard tooling and automated equipment to reduce labor content, further effort should be expended in the development of reflector panels and support structures which can be produced more economically at lower production quantities. These intermediate type products, as they might be called, may not necessarily be more economical to produce in high quantities than the parts which have been developed, but in the interim period they are necessary. Methods are available to produce such products. The intent of the efforts discussed here was to develop mass producible items and this was accomplished. But for the immediate future, further development is required.

The information obtained during this effort also emphasized the further development requirements for protective backing paint for mirrors. The backing paint used on the chemically strengthened mirrors is the same as that furnished on commercial mirrors. Experience has indicated that this paint does not adequately protect the silver on the mirrors, and in time the reflective properties deteriorate. The delamination problems encountered with the thick glass mirrors disclosed the requirement for better adhesion properties in the protective backing paint. Further effort should be expended in the development of more suitable protective coatings for the back of mirrored surfaces to provide longer-life mirrored glass reflector panels.

Additional Information

Additional information regarding the tasks discussed in this paper can be obtained from the following Sandia publications:

SAND 81-7037 Development Effort of SMC Parabolic Trough Panels (P. A. Kirsch)

SAND 81-7038 Development of Sheet Metal Parabolic Trough Reflector Panels (A. W. Biester)

SAND 82-7039 Glass/Space Frame Solar Collector Development (A. W. Biester)

SAND 82-7109 Development and Fabrication of Solar Collector SMC Reflector Assemblies (P. A. Kirsch)

SAND 82-7110 Sheet Metal Solar Collector Development and Production (A. W. Biester)

The above publications are the final reports on the projects completed by The Budd Company Technical Center, Fort Washington, PA and can be obtained from:

National Technical Information Services
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

ANTIREFLECTIVE COATING ON PHASE-SEPARATED PYREX*

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INTRODUCTION

Parabolic trough solar collectors operating at 300°C require a transparent envelope surrounding the receiver tube in order to reduce thermal losses.[1,2] Currently, these envelopes are fabricated from glass.[3] The solar transmittance of the envelope is reduced by as much as 0.07 transmittance units due to reflectance losses at the two air/glass interfaces. Antireflecting the glass surface can potentially increase the solar transmittance by 0.07 and thereby increase the collector operating efficiency. The present study optimized a phase separation/etching process to form an antireflection (AR) layer on Pyrex (Corning Code 7740 glass). The optimized process was then used to fabricate 3 m long x 6 cm diameter Pyrex envelopes that were tested in a parabolic trough collector.[2]

ANTIREFLECTIVE GLASS SURFACES

Several methods for producing antireflective glass surfaces for solar energy and high power laser applications have recently been reviewed by Milan.[4] As an alternative to forming AR coatings by conventional vacuum deposition of discrete dielectric films with different refractive indexes, several methods have been developed whereby bulk glass[5] or glass coatings deposited by the sol-gel process[6] are chemically etched to produce AR surfaces. In the case of bulk glass, broad band antireflective properties have been produced on Pyrex glasses that were thermally phase separated into two interconnecting glass phases with different acid solubilities.[5] Preferential leaching of one glass phase at a faster rate than the total dissolution (etching) of the surface layer produced AR films. The reduction

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in the reflectance properties over the complete solar spectral range from 350 to 2500 nm suggested that the surface AR layer was a gradient refractive index film.

Processing Pyrex to produce an AR surface includes the following steps:

1. Heat treatment below 649°C causes phase separation into a relatively insoluble silica-rich phase and a soluble low-silica content phase. Because of the high viscosity in this temperature range, it is expected that both the heat treatment time and temperature will affect the size, interconnectivity and composition of the resulting two-phase microstructure.[7] Therefore, the process parameters of interest are the temperature and time of the heat treatment.

2. Before the AR surface can be formed, a thin surface layer must be removed using a 10 wt % NH_4FHF acid bath in order to expose the underlying phase separated bulk glass. This thin surface layer most likely has a different composition as a result of the high temperatures used to process the glass during manufacture. The process parameter of interest is the immersion time in the acid.

3. The AR surface layer is then formed by immersion in a bath consisting of 0.26N H_2SiF_6 plus 0.15 wt% NH_4FHF. The two process parameters of interest are the bath temperature and the etching time.

EXPERIMENTAL PROCEDURES

Spectral transmittance (τ) and reflectance (ρ) properties were measured using a Beckman 5270 spectrophotometer[8] equipped with an integrating sphere accessory. Transmittance data are accurate to $\pm$ 0.005 transmittance units (100% transmittance = 1.00 transmittance units). All reflectance measurements were referenced to Halon powder[9] and should be accurate to $\pm$ 0.005 reflectance units. As a check on the accuracy of the reflectance measurements, the reflectance of 0.072 measured at 590 nm for Pyrex was within 0.001 reflectance units of the value calculated using the measured index refraction of Pyrex which is 1.474. The spectral data were averaged over the solar spectral distribution of Thekaekara[10] for an air mass of 1.5 to determine a solar-averaged transmittance value (τ_s).

In order to determine the solar transmittance properties of processed 3 m long tubes without cutting the tube into small sections, a portable solar reflectometer, model SSR, manufactured by Devices and Services Company, Dallas, Texas was used.[8] While this instrument is designed to measure the solar average reflectance (ρ_s(D&S)) of flat samples, a correlation equation for curved samples was developed such that

$$\tau_s = 0.987 - \rho_s(D\&S) \qquad (1)$$

where τ_s is the solar-averaged transmittance measured using the spectrophotometer. Using this equation, solar transmittance values calculated from the reflectance measurements were within $\pm$ 0.003 transmittance units of the values calculated from the spectrophotometer data.

DETERMINATION OF PROCESS PARAMETERS

Before the process parameters were optimized, the useful lifetime of both the pre-etch and film forming etch bath solutions was determined. When solutions were stored in polyvinylchloride (PVC) containers, an area of more than 15 m^2 of glass could be treated in 45 liters of film forming solution with no change in measured solar transmittance values. For the pre-etched bath, over 40 m^2 of glass area could be treated in 45 liters of solution. After these treatments, all solutions were replaced.

Effect of Film Forming Parameters

The effect of the film pre-etch and film forming etch conditions on the AR coating was studied using factorial design techniques. Results indicated[11] that the film forming bath treatments had very little effect on the solar transmittance if they were maintained within the following ranges:

pre-etch immersion time: 15 $\pm$ 3 minutes;

film-forming etch bath temperature: 40 $\pm$ 5°C;

film-forming etch immersion time: 7.5 $\pm$ 2.5 minutes.

Thus for the remainder of the study, the film forming bath parameters were maintained within these ranges.

Effect of Heat Treatment Time

Solar transmittance values after heat treatment at 570°C for times up to 48 hours are shown in Figure 1. The solar transmittance rapidly increases as the heat treatment time increases and then reaches a constant value of approximately 0.98 for times greater than 15 hours. Similar results were obtained at 600°C and 615°C except that the time required to reach values >0.97 decreased at these higher temperatures to 6 and 3 hours, respectively. At 630°C, the solar transmittance increases rapidly for heat treatment times less than 3 hours, then decreases to values of only 0.93 with 7 hours of heat treatment. These results indicate that there is an "optimum" range of heat treatment times at each temperature where solar transmittance values greater than 0.97 can be obtained.

Optimum Heat Treatment Region

The time/temperature boundary for the optimum heat treatment region is shown in Figure 2 where data with solar transmittance values greater than 0.97 and equal to 0.95 are plotted. The shaded region indicates the optimum processing region that produce solar transmittance values >0.97. To the left of this region the transmittance values decrease as indicated by the contour connecting data points for transmittance values of 0.95. The right boundary of this region is currently limited to approximately 24 hours heat treatment time and a temperature range from 560°C to 615°C, the maximum studied here. Based on the results obtained at 630°C, it would be expected that the solar transmittance values would have eventually decreased for longer heat treatment times at these lower temperatures. The dashed line at the top of the figure approximately locates the upper boundary based on the limited data available.

It is seen from Figure 2 that the heat treatment time necessary to form optimum coatings increases as the temperature decreases. This dependence on temperature is expected since the separation of the glass into two different compositions is very slow due to the high viscosity of the glass in this temperature range.[7]

OPTICAL PROPERTIES

Typical spectral transmittance properties of both untreated and treated samples are shown in Figure 3. Note that the transmittance of the treated sample is increased over a very broad wavelength range in agreement with previous reports. In fact, the increase is >0.06 transmittance units from 360 nm to 2000 nm. Solar-averaged transmittance values were calculated to be 0.986 for this treated sample as compared to 0.915 for an untreated sample, an increase of 0.071 transmittance units. The measured solar-averaged reflectance values were 0.072 for the untreated sample and 0.006 for the treated sample or a decrease of 0.066 reflectance units. Thus, within experimental errors, the increase in transmittance for the treated sample is entirely accounted for by decreasing the reflectance losses.

FULL SCALE PROCESSING

Heat treating 3-m-long Pyrex envelopes resulted in sagging of the glass for temperatures in excess of 600°C, even though the glass was supported every 0.5 m. Because this was unacceptable for our application and procedures for continuous support of the glass envelopes were unsuccessful, the heat treatment temperature was lowered to 575 ± 5°C. The time-temperature corresponding to the final heat treatment process is shown in Figure 2 as the boxed area.

Figure 4 shows the assembly for heat treating the 3-m-long glass tubes. The alumina inserts holding 5 tubes were attached every 0.5 m to a central stainless steel rod which was free to expand relative to the alumina spacers. The glass holder assembly was placed inside a 22-cm-diameter steel container. The container provided ± 5°C temperature uniformity for the glass tubes at 575°C. A 10-burner, gas-fired furnace with circulating fans was used for production heat treatments. The heat-up, cool-down rates of the glass tubes were 2°C/min and 3°C/min, respectively.

Figure 5 shows the acid tank assembly containing five individual 15 cm I. D. by 3.6m PVC tanks. The ratio of the surface area of glass exposed to acid volume was 1 m^2 per 5 liters of solution. Immersion heaters were used to provide acid temperatures of up to 40°C with pumps to give a continuous acid flow down the length of the glass tubes. The glass tubes were cleaned after the heat treatment with detergent, rinsed in water and then subjected to the pre-etch bath for 15 minutes. They were then water rinsed and placed into the film forming etch at 40°C for 7.5 minutes, rinsed in water, given a final rinse in 50°C deionized water, and then air dried. The pre-etch bath solution was changed after processing 45 tubes while the film forming bath was changed after processing 15 tubes.

A total of over 50 tubes were processed as described above. Measurements of the solar transmittance using the portable solar reflectometer indicated that solar transmittance values of all tubes averaged 0.97 to 0.98. The tubes were very uniform ($< \pm 0.005$) around the circumference and varied by only $\pm$ 0.01 transmittance units from end to end.

Several of the glass tubes were installed in an optically advanced parabolic trough collector developed by Sandia's Solar Collector Technology Division. This system achieved a measured thermal efficiency of 70% at an outlet temperature of 315°C. This is the highest efficiency ever achieved in a parabolic trough collector system at this operating temperature.[12] Measurement of the solar transmittance after eight months of outdoor exposure indicated no significant change in the solar transmittance values.

CONCLUSIONS

The phase separation/etching process for forming an AR layer on Pyrex glass was optimized for solar applications. Solar transmittance values above 0.97 were obtained for a variety of time/temperature heat treatments. Because the full-scale (3-m long) Pyrex envelopes tended to deform at the higher phase separation temperatures (>600°C), the final heat treatment process was performed at 575°C for 22 hours. Adequate processing conditions for the pre-etch solution were determined to be a treatment time of 15 ± 3 minutes. For the film forming bath, satisfactory conditions were a temperature 40 ± 5°C for a treatment time of 7.5 ± 2.5 minutes. Over 50 3-m long Pyrex envelopes were processed having solar transmittance values of greater than 0.97.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge A. R. Mahoney for assistance with the optical measurements and E. J. Vavro for help processing the full-scale envelopes.

REFERENCES

1. G. W. Treadwell, "Design Considerations for Parabolic-Cylindrical Solar Collectors," Sandia National Laboratories Report SAND 76-0082 (July, 1976).*
2. For a recent summary of parabolic trough technology see "Proceedings of the Line Focus Solar Thermal Energy Technology Department," Sandia National Laboratories Report 80-1666 (Sept., 1980).*
3. V. E. Dudley and R. M. Workhoven, "Summary Report: Concentrating Solar Collector Test Results Collector Module Test Facility," Sandia National Laboratories Report SAND 78-0815 (May, 1978).*
4. D. Milan, "Damage-Resistance Antireflection Surfaces for High-Power Lasers," Energy and Technology Review, Lawrence Livermore Lab, p. 9 (March, 1982).
5. M. J. Minot and U. Orabasi, U. S. Patent 4, 086, 074 (April, 1978).
6. H. McCollister and N. L. Boling, U. S. Patent 4, 273, 826 (June, 1981).
7. B. F. Howell, J. H. Simmons, and W. Haller, Amer. Ceram. Soc. Bulletin 54, 707 (1975).
8. Identification of commercial equipment is included in order to adequately specify the experimental procedure. This does not imply endorsement by Sandia National Laboratories nor that the equipment identified is necessarily the best available for the purpose.

9. V. R. Weidner and J. J. Hsia, J. Opt. Soc. Am. 71, 856 (1981).

10. See M. A. Lind, R. B. Pettit and K. D. Masterson, J. of Solar Energy Engineering 102, 34 (1980).

11. H. L. McCollister and R. B. Pettit, "Antireflection Pyrex Envelopes for Parabolic Solar Collectors" (submitted to Solar Energy Engineering).

12. W. Vogel, Structure and Crystallization of Glasses (Pergamon, New York, 1971) pp. 60-80.

*Available from: National Technical Information Services
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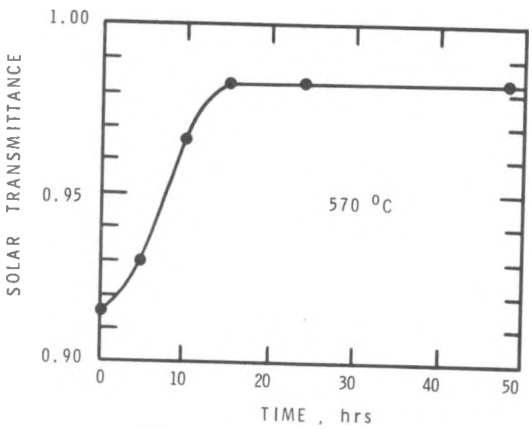

Figure 1
The solar transmittance as a function of heat treatment time at 570°C.

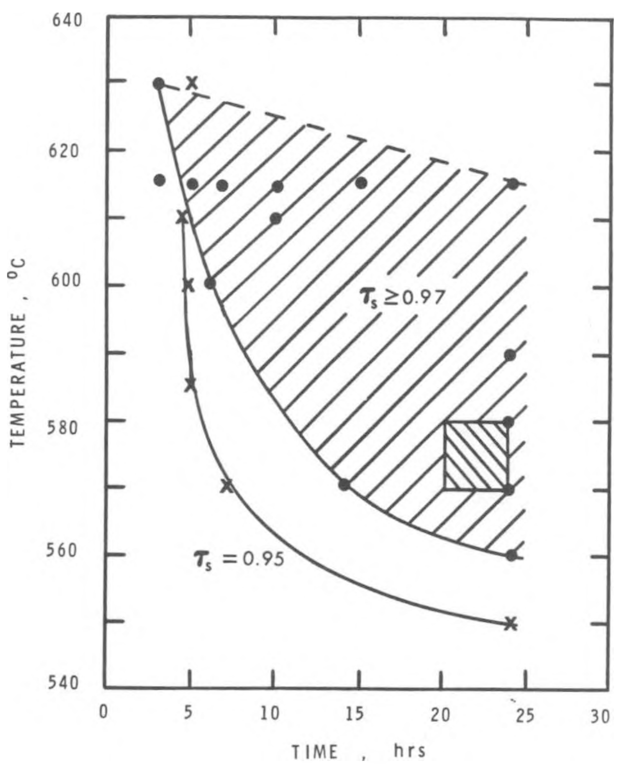

Figure 2.
Solar transmittance contours as a function of heat treatment time and temperature. Data indicated with (●) have solar transmittance values ≥0.97: data indicated with (X) produced solar transmittance values equal to 0.95. The square region centered at 575°C and 22 hours locates the final region used to process the full scale envelopes.

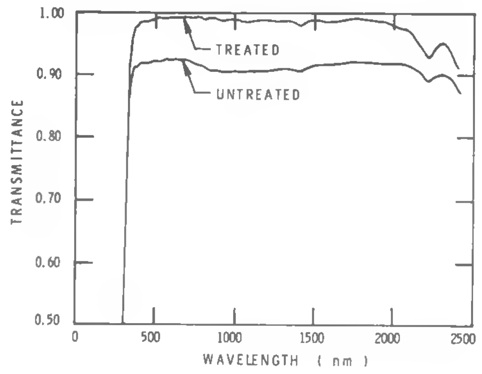

Figure 3.
Spectral transmittance properties of untreated and treated Pyrex samples.

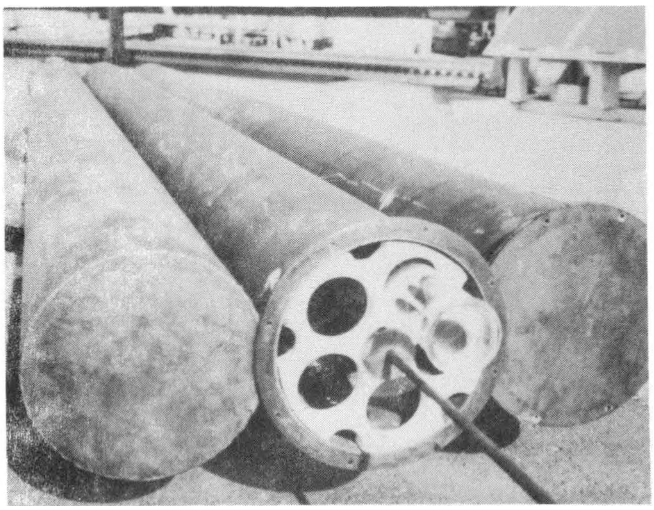

Figure 4.
Photograph of the heat treatment assembly showing the steel container, alumina insert, and central stainless rod.

Figure 5.
Acid tank assembly showing PVC cylindrical etching tanks and constant temperature bath configuration.

Sol-Gel Derived Antireflective Coatings

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Abstract

Porous sol-gel derived films prepared from aged polymeric solutions were deposited on PYREX™ and etched to produce antireflective (AR) coatings with solar averaged transmittance values greater than 0.97. Acceptable coatings were obtained for a wide range of processing parameters. This process appeared to produce single layer interference films rather than graded index films.

Introduction

Current parabolic trough designs employ cylindrical glass envelopes concentric with the receiving tube to reduce thermal losses.[(1)] Due to reflections at the inner and outer glass surfaces the solar averaged transmittance of candidate glass envelope materials, e.g., PYREX™, is typically 0.89-0.91. Antireflecting the glass surfaces can increase the solar averaged transmittance of PYREX to over 0.97.[(2)] Therefore to maximize collection efficiency, parabolic troughs must be designed with antireflective (AR) films on the inner and outer surfaces of the cylindrical envelopes.

There are three standard types of antireflective films: 1) single layer interference films, 2) multilayer interference films, and 3) graded index films. For single layer interference films the reflectance will be zero when the optical thickness, $\eta_f \cdot t$ (the product of the refractive index and the thickness of the film) is an odd multiple of one quarter of the wavelength of the incident light and the refractive indices satisfy the relation

$$\eta_f = \sqrt{\eta_g \eta_a} \quad . \qquad (1)$$

In eq. (1) η_g = refractive index of the glass substrate and
η_a = refractive index of the ambient atmosphere (usually equal to 1.00)

Single layer interference films exhibit discreet minima in reflectance as a function of wavelength.

Multilayer interference films use two or more discreet layers of transparent dielectrics which have different refractive indices. The reflectance depends on the number and thickness of the layers. Two or four layer AR films can reduce reflectance values to less than 0.1%[3] for a particular wavelength and generally reduce reflectance over a broad spectral region. The practical limitation of the technique is that both thickness and refractive index of each layer must be very carefully controlled.

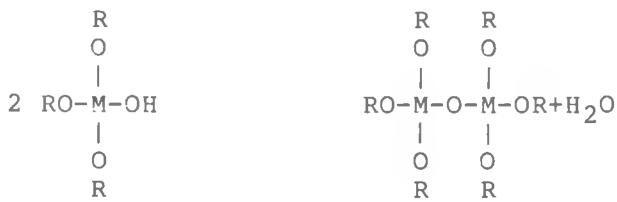
Graded index films are normally prepared by selective leaching of phase separated glasses. The glass may be phase separated in bulk[4] or a phase separable film may be applied to the bulk glass, e.g., by the sol-gel process.[5] For graded index films, the reflectance is small for all film thicknesses greater than one-half wavelength and is insensitive to the exact film thickness. This causes the reflectance to be low over a wide spectral region as compared to single layer interference films which exhibit specific minima. Graded index films do have practical limitations, however. Because liquid-liquid phase separation is kinetically limited, many phase separable compositions require temperatures near the glass softening point (or very long times at lower temperatures) to produce a microstructure suitable for selective leaching.[2] Additionally, many glass compositions which may be of practical interest for solar designs, i.e., inexpensive, may not be phase separable at all.

As discussed above, each of the usual methods of AR film formation have limitations of either a practical or fundamental nature. Therefore, the purpose of the present investigation was to prepare AR coatings on PYREX at low temperatures (below the deformation temperature of PYREX) by a process which did not rely on liquid-liquid phase separation (and thus was not compositionally or kinetically limited) and which was relatively insensitive to film thickness criteria.

Sol-Gel Concept

The sol-gel process uses metal alkoxides $M(OR)_y$ where $R = (C_xH_{2x+1})$ of network forming cations, i.e., Si, B, Al as oxide glass precursors. In alcoholic solutions catalyzed by additions of acid or base, the metal alkoxides are partially hydrolyzed and polymerized to form a glass-like polymeric network linked by bridging oxygen atoms:

(2)



(3)

Gelation occurs when the polymer species grow and link together to form an infinite network within the solution (Figure 1). Water content and pH determine polymer shape (e.g., chains versus colloidal particles)[6], while solution concentration, pH, and temperature primarily control polymer growth prior to gelation. For many pH-water regimes polymer growth can be depicted as three dimensional growth of discreet clusters.[7] Generally higher pH, increased water content, higher temperature and lower concentration promote cluster growth prior to gelation.[8] Although the average concentration of polymer and solvent (alcohol) do not change during gelation (i.e., there is no precipitation), on a local scale there is necessarily a separation into a polymer rich and solvent rich region. Thus for the case of discreet cluster growth a liquid-solid phase separation occurs.

Sol-Gel Film Formation

Thin films are formed by depositing the solution on the substrate prior to gelation. Evaporation of the solvent during drying concentrates the solution in polymers and results in surface tension forces which aggregate the polymer clusters and promote gelation. Final removal of solvent results in interconnected microporosity, the size of which depends on the polymer size prior to film formation (Figure 2).

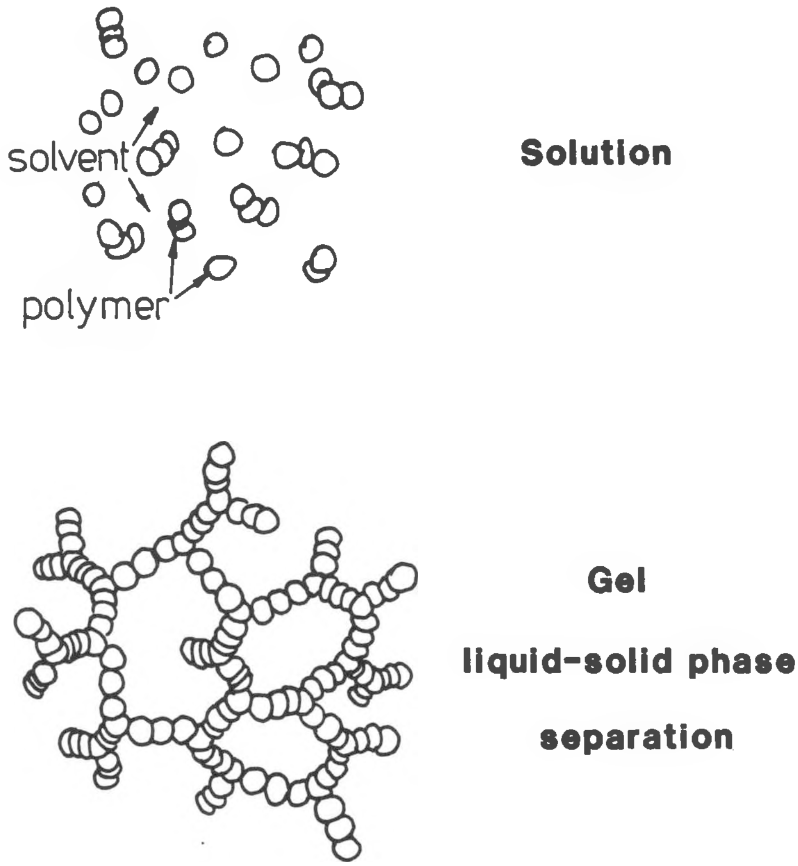


Figure 1. Schematic representation of solution and resulting gel. Polymer growth and gelation result in liquid-solid phase separation.

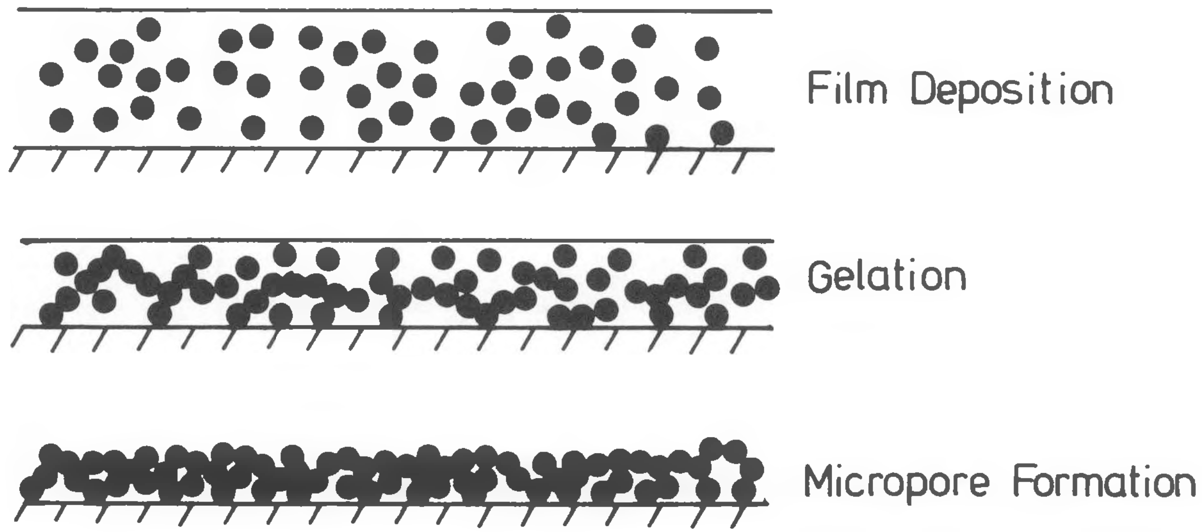


Figure 2. Schematic showing film deposition followed by gelation after partial solvent removal. Each dot represents a polymer cluster that formed in solution before deposition. Upon complete solvent removal, a microporous film is formed.

For a particular sol-gel composition, a range of film microstructures can therefore be obtained by growing polymer clusters to various sizes before film deposition. Increased solution "aging" prior to film deposition is then expected to result in increased pore size in the deposited film.

Acid leaching of a microporous film is expected to increase the average pore diameter and to decrease the film thickness. Thus both the refractive index and the thickness of the film should decrease with etching time. A graded refractive index could occur by additional selective leaching of the gel phase, e.g., by removal of borate from a borosilicate phase or by a mechanism in which the pore diameter near the surface increases more rapidly than the pore diameter near the substrate. The etching of a porous multicomponent film is a very complicated issue, the discussion of which is beyond the scope of this paper. However, it can be generally stated that a critical pore diameter must be exceeded before etching could result in enlargement of the pore diameters. This is due to the considerable difference in dissolution rates of surfaces with positive and negative radii of curvature.[8]

Experimental

Sol-gel solutions of the following oxide composition (wt %) were

$$71\ SiO_2;\ 18\ B_2O_3;\ 7\ Al_2O_3;\ 4\ BaO$$

prepared by a process described previously.[9] Films formed from solutions with varied amounts of aging were deposited on PYREX slides at room temperature. The deposition process consisted of suspending the substrate in the solution, withdrawing the solution at a constant rate (~14 cm/min), and drying the film at approximately 80°C and 25% R.H. This process was repeated up to four times to produce thicker, multilayer films. The coated substrates were heated at 500°C for times ranging from 60 to 1000 minutes. This treatment only partially solidified the film to form a durable porous layer. After heating, the films were etched at 24°C in a stirred solution of 25 mℓ H_2SiF_6 and 0.75 g NH_4HF_2 dissolved in 5475 mℓ H_2O. The spectral transmittance and reflectance properties were measured as a function of etching time using a Beckmann Model 5270 spectrophotometer over the wavelength range

300 nm - 2400 nm. Integrated solar transmittance values were also measured using a Devices and Services, Model SSR, solar transmittance instrument. Film thickness and refractive index were measured on a Gaertner Model L119X ellipsometer.

Results

The solar transmittance properties are shown in Table 1 as a function of etching time for a sample coated two times with an aged solution (2 mo.) and heated for 60 min at 500°C. Also listed for comparison is the transmittance value measured for an uncoated substrate. Ellipsometry measurements performed on films deposited from aged solutions onto silicon substrates indicate that etching initially reduces the film index, η_f, while slightly decreasing the film thickness. Further etching significantly reduces both thickness and index (Table 2). For aged solutions, there were a wide range of coating and heat treatment parameters which resulted in transmittance values ≥ 0.970 after optimum etching times as shown in Figure 3. Conversely no combination of coating thickness and heat treatment time resulted in transmittance values greater than 0.93 for unaged solutions.

Discussion

The single most important processing parameter in the formation of AR films by the process described above is solution age. This indicates that polymer growth in solution prior to coating is necessary for AR film formation. The question as to whether a graded index or a single index film results during etching may be qualitatively answered by consideration of the wavelength dependence of transmittance. As shown in Figure 4, a discreet maximum in transmittance (which corresponds to a discreet minimum in reflectance) is observed near 600 nm, which is characteristic of single-layer interference films. This suggests the following possible explanation for AR film formation. After a requisite amount of solution aging the pore diameter of the deposited film is sufficiently large (due to sufficiently large polymers) so that etching will increase the pore diameter rather than simply decrease the film thickness. This constraint in pore size occurs because surfaces with small negative radii of curvature, i.e., surfaces of pores, are much less soluble than surfaces with larger and/or positive radii of curvature, i.e., the exterior film surface.

Table 1

Integrated Solar Transmittance as a Function of Etching Time

Etching Time (min)	Solar Averaged Transmittance
0	0.937
0.25	0.953
1.0	0.955
2.0	0.959
5.0	0.964
8.0	0.967
10.0	0.970
11.0	0.969
12.0	0.968
14.0	0.965
Uncoated slide	0.915

Table 2

Refractive Index and Film Thickness as a Function of Etching Time

Etching Time (min)	η_f	t (nm)
0	1.420	561
5	1.354	559
10	1.265	534
20	1.113	20

Number of Coats	60	300	1000
4	97.1	97.4	97.4
3	97.6	97.3	96.9
2	97.0	96.9	96.7

Heat Treatment Time (min)

Figure 3. Solar-averaged transmittance values for combination of number of coats and heat treatment times. Films were etched until the transmittance was a maximum.

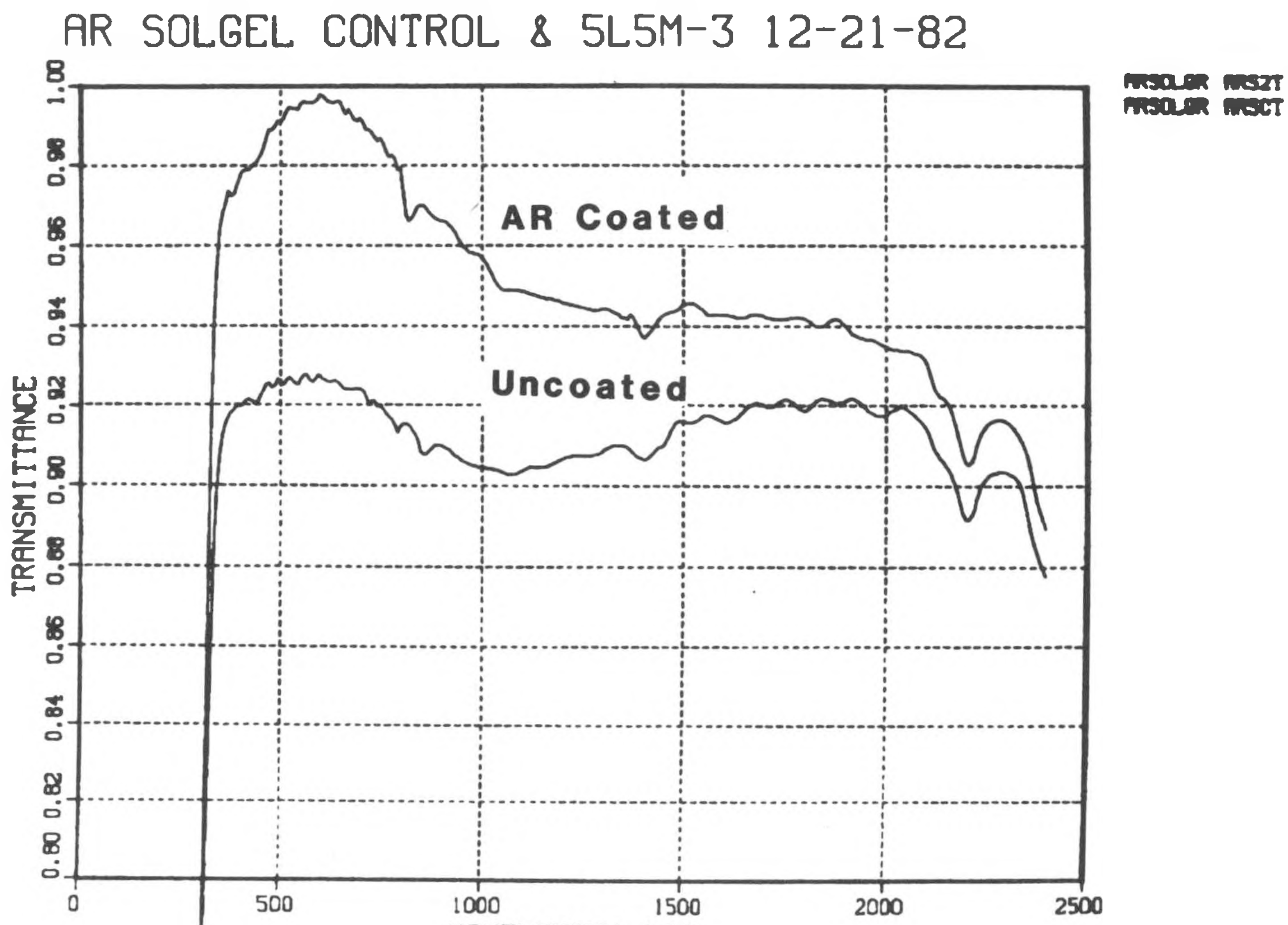


Figure 4. Spectral Transmittance of AR coated and uncoated PYREX.

Larger initial pore size increases the rate of pore enlargement with respect to the rate of decrease in film thickness. Because of the extremely large numbers of pores per unit volume, only a slight enlargement of the pores, 1-2 nm, is expected to greatly decrease the refractive index.

AR films may form during etching by one of two mechanisms. The pores may increase uniformly in diameter through the thickness of the film, while at the same time film thickness decreases. At the optimum etching time both the refractive index and film thickness criteria are satisfied (Mechanism 1). Alternatively, etching may cause a region of larger diameter pores to grow into the film from the exterior surface. The maximum in transmittance occurs when the thickness of this region is an odd multiple of quarter wavelengths of the incident light (Mechanism 2). This mechanism would in fact produce a double layer film. However, because the index of the unetched film, 1.42, is close to that of PYREX, 1.47, this double layer film may behave optically like a single layer film. These mechanisms are depicted in Figure 5.

The practical consequences of these mechanisms of film formation are that they appear to be insensitive to film composition (i.e., they do not occur by selective leaching) and as shown in Figure 3 they do not depend strongly on initial film thickness (numbers of coats) although a minimum thickness is required. It has not yet been established whether there exists simply a minimum solution aging time which must be exceeded or there exists an optimum solution aging time. It is expected however that, depending on aging temperature, polymer growth in solution stops after a certain amount of aging(8) and therefore there exists simply a minimum in aging time.

Conclusions

Sol-gel derived films prepared from aged polymeric solutions were deposited on PYREX, heated to a temperature below the film solidification temperature and etched to produce AR films. This process, which appears to produce a single layer interference film, was shown to be relatively insensitive to such processing parameters as coating thickness and heat treatment time and is believed to be independent of film composition. This method is currently being scaled up for use as an AR coating in parabolic trough receiver designs.

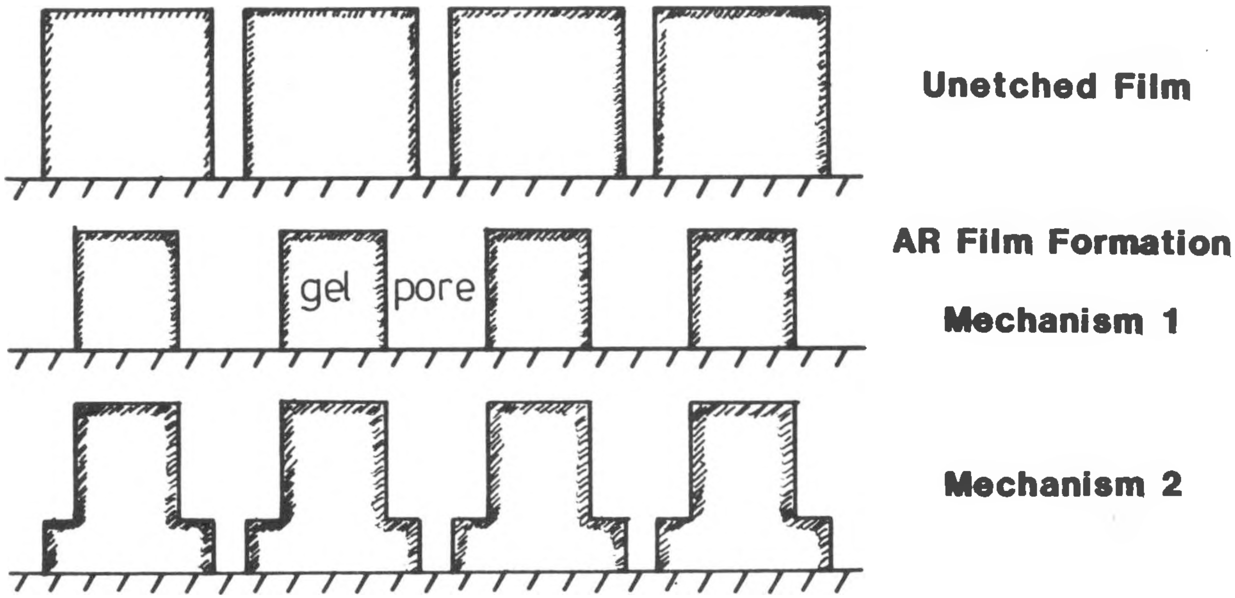


Figure 5. Unetched film and two possible mechanisms of single layer AR film formation.

References

1. See "Proceedings of the Line Focus Solar Thermal Energy Technology Development," SAND80-1666 (September 1980).

2. H. McCollister and R. B. Pettit, "Antireflection Pyrex Envelopes for Parabolic Solar Collectors," Proceedings ASME Solar Energy Division, Apr. 19-21, 1983, Orlando, FL (to be published).

3. D. Milam, "Damage-resistant Antireflection Surfaces for High-Power Lasers," Energy & Technology Review, Lawrence Livermore Lab, p. 9 (March 1982).

4. T. H. Elmer and F. W. Martin, "Antireflection Films on Alkali-borosilicate Glasses Produced by Chemical Treatments," Ceramic Bulletin 58[11] 1092 (1979).

5. H. McCollister and N. L. Boling, U. S. Patent 4,273,826 (June 1981).

6. D. W. Schaefer, K. D. Keefer, C. J. Brinker, "Characterization of Polymers and Gels by Intermediate-angle X-ray Scattering," presented at International Union of Pure and Applied Chemists MACRO 82 Amherst, MA, July 12-16, 1982.

7. C. J. Brinker, K. D. Keefer, D. W. Schaefer, C. S. Ashley, "Sol-gel Transition in Simple Silicates," J. Non-Crypt. Solids 48 [1] 47-64 (1982).

8. R. K. Iler, The Chemistry of Silica, John Wiley & Sons, NY, 1979.

9. C. J. Brinker and S. P. Mukherjee, "Conversion of Monolithic Gels to Glasses in a Multi-Component Silicate Glass System," J. Mat. Sci. 16 [7] 1980-88 (1981).

STATUS OF BLACK CHROME COATING RESEARCH

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ABSTRACT

This report summarizes recent results regarding the optimization of electrodeposited black chrome solar selective coatings for operation in solar collectors at temperatures up to 300°C. Careful control of the electroplating bath composition and special regard for bath contamination are required in order to obtain coatings that will survive daily collector operation for tens of years. An accelerated temperature aging test is described which can be used both to estimate the coating lifetime and to monitor the coating during production. Finally, the use of sol-gel protective films to extend the lifetime of the black chrome coating is also discussed.

I. INTRODUCTION

Electrodeposited black chrome solar selective coatings have experienced a degradation in optical properties when used at temperatures of 300°C in parabolic trough collectors.[1] Typically, the solar absorptance of the coating decreases from initial values of > 0.96 to values below 0.90 in only tens of hours of operation. This report summarizes the results of research aimed at improving the thermal stability of these coatings. Included is a discussion of the plating process controls that are required in order to obtain black chrome coatings with improved thermal stability properties. Using accelerated temperature testing techniques, the projected lifetime of coatings can be obtained after limited aging at elevated temperatures. Finally, the use of protective sol-gel coatings to extend the useful lifetime of black chrome coatings is also presented.

II. PLATING PROCESS CONTROL

A study of the plating process concluded that proper control of several process variables is critical for obtaining coatings with the best thermal stability characteristics. Details of this study are contained in a published report (see Ref. 2); only the significant results are summarized here. Plating variables studied included the four electroplating bath constituents (chromic acid, addition agent, trivalent chromium and iron), plating current density, bath temperature, type of substrate and the plating time.

The trivalent chromium and addition agent bath constituents had the biggest effect on the thermal stability of plated coatings as shown in Figure 1. In this figure, contours of constant solar absorptance values after thermal aging for 40 hours at 450°C in air are plotted as a function of the trivalent chromium and addition agent concentrations. Note that the most stable coatings are obtained for trivalent chromium concentrations slightly above 7 g/ℓ and addition agent concentrations above 24.5 vol %. For concentrations below these values, coatings were obtained that had solar absorptance values below 0.90 both as-deposited and after thermal aging. Various combinations of plating current density and plating time could not increase the solar absorptance above this value. These coatings have been called "gray" coatings because of their visual gray appearance. High values for these bath variables produced coatings with acceptable optical properties as-deposited, but when heated to 300°C in air, the solar absorptance rapidly decreased. This region corresponded to plating bath conditions that produced coatings with the same degradation in optical properties observed in collector tests.[1] Between these two ranges of bath compositions, thermally stable coatings with solar absorptance values > 0.96 were obtained. The results shown in Fig. 1 can be useful in defining an acceptable plating region based on bath composition control limitations (see Ref. 2).

The other plating variables studied did not adversely affect the coating thermal stability within reasonable limits. Thus, the bath temperature could be varied from 10°C to 20°C and the current density over the range

140-230 mA/cm^2 with no significant effect on the coating thermal stability. In addition, four substrates, consisting of nickel foil, 302 stainless steel, sulfamate nickel on mild steel and a metallic chromium flash one sulfamate nickel, gave similar results.

It was also observed that contamination of the black chrome plating solution with chloride ions in quantities above 10 mg/ℓ decreased the thermal stability of plated coatings. However, through the addition of silver oxide, the chloride ion concentration could be reduced to values below 2 mg/ℓ.[2] Sources of chloride contamination included both the tap water used for bath dilution and the chromic acid used for bath makeup.

III. METHODS OF BATH COMPOSITION ANALYSIS

Analytical methods for determining the composition of black chrome plating solutions are described in Harshaw Chemical Co. Bulletin 32-0884[3] and have recently been summarized by Erickson.[4] Additional analytical techniques were developed at Sandia by Erickson[4] and Whiteley[5] for the determination of the trivalent chromium concentration. These techniques either improve the accuracy or are faster and easier to implement for a small plating shop as compared to Harshaw's procedures. Finally, both gravimetric and turbidimetric analysis techniques were developed for chloride ion analysis. These techniques offer an accuracy of $\pm$ 0.3 mg/ℓ.[4]

IV. THERMAL STABILITY TESTING

Recently completed experiments[6] have investigated changes in the optical properties of black chrome coatings after aging for up to 5,000 hours over the temperature range 350-450°C. Changes in the solar absorptance and emittance properties were measured during the thermal testing; typical changes in the solar absorptance with time are shown in Figure 2. Note that the solar absorptance initially remains relatively constant and then decreases slowly with increasing time. As expected, the initial plateau region extends for longer times as the temperature is decreased from 450°C to lower values.

Solar absorptance versus aging time data obtained at different temperatures could be made to overlap by scaling the time axis by a constant amount (see Figure 3). For simplicity, all data for temperatures below 450°C have been scaled to agree with the 450°C data. Thus, the scaled times at each temperature, $t^*(T)$, are related to the actual aging time, t, by a scale factor, $a(T)$, such that

$$t^*(T) = t \cdot a(T) \qquad (1)$$

Note that $a(T)$ is only a function of the aging temperature and that $a(450°C) = 1.00$. Scale factors determined from the data shown in Figure 2 are listed in Figure 3. At 350°C, for example, changes in the solar absorptance are a factor of 0.0063 times <u>slower</u> than at 450°C.

In order to extend these results to the typical collector operating temperature of 300°C, the temperature dependence of $a(T)$ must be known. It was found that the scale factor obeyed an Arrhenius relationship where

$$a(T) = a_o \exp\left(\frac{-Q}{RT}\right) . \qquad (2)$$

In this equation, a_o is a constant, R is the universal gas constant (= 1.986 cal/mole-K), T is the absolute temperature (in K), and Q is the activation energy. Experimentally Q was determined to be (46.2 ± 0.9) kcal/mole. Using this equation and the aging behavior determined at an elevated temperature, the expected aging behavior at 300°C can be calculated. Thus, if 20 hours are required at 450°C (723 K) for the solar absorptance to decrease from 0.97 to 0.92, then the time required for the same change to occur at 300°C (573 K) is calculated as:

$$\begin{aligned} t(300°C) &= t(450°C) \exp \frac{Q}{R}\left[\left(\frac{-1}{723} + \frac{1}{573}\right)\right] \\ &= 20 \text{ hrs} \cdot \exp\left[\left(\frac{46,200}{1.986}\right) \cdot \left(\frac{150}{723 \cdot 573}\right)\right] \qquad (3) \\ &= 20 \text{ hrs} \cdot 4,550 = 91,000 \text{ hrs} \end{aligned}$$

For a collector operating on an average of 10 hrs/day, this corresponds to 9,100 days or over 20 years of daily operation.

The acceptance test developed for monitoring the plating process specifies a decrease in solar absorptance of less than 0.01 after 8 hours at 450°C.[7] Extrapolating this test time to 300°C results in over 36,000 hours of continuous aging or over 9 years of daily collector operation. Thus, thermal aging at 450°C for relatively short periods of time can be used to monitor the thermal stability of coatings during a production situation.

V. SOL-GEL PROTECTIVE COATINGS

The thermal degradation of black chrome coatings has been shown to be caused by a slow oxidation of metallic chromium particles within the film to form Cr_2O_3.[8,9] If the oxidation rate can be reduced through the use of a protective coating, the useful lifetime of the black chrome film might be extended.

One suitable protective coating is a sol-gel film that can be deposited on large surfaces at relatively low costs. In the sol-gel process, glass-like macromolecules of various inorganic oxides, such as SiO_2, B_2O_3, TiO_2 and Al_2O_3, are formed in a solution which can then be applied to a surface by dipping, spraying or spinning. When dry, the porous gel coating is fired to a moderate temperature (less than the softening point of the bulk glass composition) where it converts to a dense, transparent glass layer. Various sol-gel coatings were applied to black chrome films as a protective layer and the resulting optical properties and thermal aging behavior were determined.[10] The results indicated that the best combination of sol-gel composition and processing variables increased the lifetime of the black chrome coating by a factor of 2.7 as compared to an uncoated sample when aged at 400°C in air.

Present research in this area is aimed at determining the effect of other processing variables on the protective nature of the sol-gel films.

These variables include changes in the sol-gel coating as a result of natural solution aging with time as affected by the solution pH and concentration. The thermal aging behavior over a range of temperatures is also being studied and compared to the results obtained for uncoated samples. Finally, the process control necessary to coat 3m-long receiver tubes is being investigated.

VI. CONCLUSIONS

Through proper control of both the trivalent chromium and addition agent concentrations in the electroplating bath, black chrome coatings can be obtained which will survive tens of thousands of hours at temperatures as high as 300°C. Contamination of the plating bath, particularly with chloride ions, must be avoided. Analytical techniques have been developed which permit effective monitoring of the four bath composition parameters as well as levels of chloride ion contamination.

By thermally aging plated samples at temperatures as high as 450°C for short periods of time, the long-term aging behavior at 300°C can be predicted. The high-temperature testing can also be used to effectively monitor the lifetime of coatings made by the electroplating process in a production situation.

Finally, the application of a sol-gel protective films over the black chrome coating can increase the useful lifetime by preventing oxidation of metallic chromium within the coating during high-temperature aging. In particular, SiO_2/B_2O_3 sol-gel films were effective in increasing the lifetime of coated samples by a factor of 2.7. However, additional research is required to further define the effect of additional process variables on the protective capabilities of sol-gel films.

REFERENCES

1. See "Proceedings of Line-Focus Solar Thermal Energy Technology Development Conference," September 9-11, 1980, Albuquerque, NM (Sandia National Laboratories Report SAND 80-1666).*

2. R. B. Pettit, R. R. Sowell and I. J. Hall, "Black Chrome Solar Selective Coatings Optimized for High-Temperature Applications," Solar Energy Materials 1 (1982), pp. 153-170.

3. Analytical Method 32-0884, "Determination of M and R in ChromOnyx® Plating Solution," Harshaw Chemical Co., Cleveland, OH.

4. S. L. Erickson, "Analytical Methods for the Control of ChromOnyx® Black Chrome Plating Baths," Sandia National Laboratories Report SAND 82-0467 (March 1982).*

5. R. V. Whiteley, "Determination of Chromium (III) in the Presence of Large Amounts of Chromium (VI)," Analytical Chemistry 51 (1979), p. 1575.

6. R. B. Pettit, "Accelerated Temperature Aging of Black Chrome Solar Selective Coatings," Solar Energy Materials Vol. 7 (1983) (to be published).

7. See Sandia National Labs. Process Specification SS-S34732, "Electroplating Mild Steel Receivers for Concentrating Solar Collectors" (Dec. 1981).

8. R. B. Pettit, J. N. Sweet and R. R. Sowell, "Variation in the Microstructure of Electrodeposited Black Chrome Solar Coatings," Proceedings MICON 82: Optimization of Processing, Properties and Service Performance Through Microstructure Control, ASTM STP 792 (1982), pp. 263-281.

9. P. H. Holloway, K. Shanker, R. B. Pettit, and R. R. Sowell, "Oxidation of Electrodeposited Black Chrome Selective Solar Absorber Films," Thin Solid Films 72 (1980), pp. 121-128.

10. R. B. Pettit and C. J. Brinker, "Sol-gel Protective Coatings for Black Chrome Solar Selective Films, Proceedings SPIE Optical Coatings for Energy Efficiency and Solar Applications, Vol. 324 (1982), pp. 176-182.

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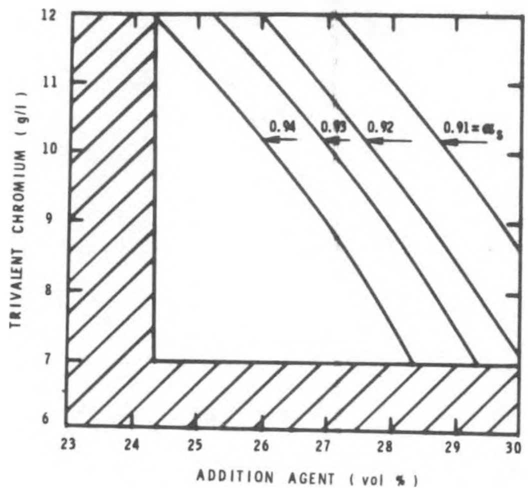

Figure 1
Contours of constant solar absorptance values, determined after thermal aging at 450°C for 40 hours, as a function of the trivalent chromium (Cr^{+3}) and addition agent concentrations. (Chromic acid and iron concentrations were fixed at 330 g/ℓ and 10.3 g/ℓ, respectively). The shaded region locates areas where gray coatings (solar abosportance 0.90) were obtained.

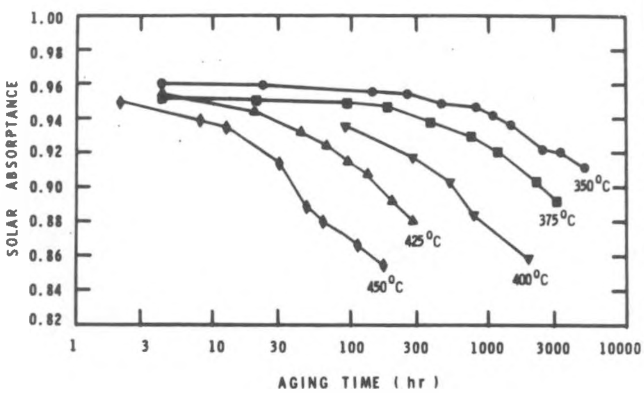

Figure 2.
Solar absorptance values as a function of thermal aging time for five temperatures between 350-450°C. Black chrome coatings were obtained from a bath containing 319 g/ℓ chromic acid, 28.0 vol % addition agent, 8.9 g/ℓ trivalent chromium and 10.1 g/ℓ iron.

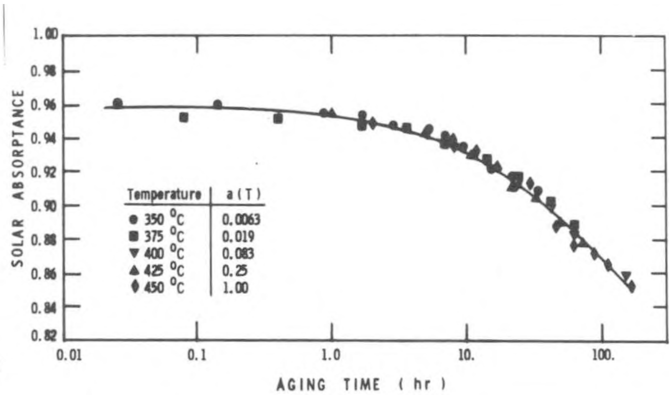

Figure 3.
Solar absorptance values obtained at five aging temperatures after scaling the time axis of each curve by a (T) as indicated in the table. (See discussion in text.)

Integrated Solar Tracker Development and Test

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Introduction

Solar collectors that track the sun on only a single axis commonly use one of three different tracking concepts. These are shadow band, computed sun position tracking (both indirect view optical tracking) and receiver flux sensor tracking (direct view optical tracking).

Shadow band systems track the sun satisfactorily under ideal conditions, but user experience has shown operational problems. Disadvantages of shadow band trackers include differential aging of the light sensors, dirt or dust on the sensors and unequal light intensity from cloud edges, all of which cause tracking errors.

When computer tracking is used, the sun's position is calculated as a function of time, and the collector is aimed at the calculated position in the sky. A highly accurate angle-measuring device, such as a digital shaft encoder, must be installed on the rotating axis in order to position the collector to the calculated angle. Computer tracking has advantages over the shadow band technique in that light reflections, clouds, varying levels of sunlight, etc., cannot affect tracking accuracy, but equipment costs are much higher.

This report describes the development of an integrating direct view optical resistance wire solar flux sensor. The system combines a microprocessor to calculate the sun's position and then rotates the collectors to the calculated angle. The programmed microprocessor then generates corrections to the calculated angle by seeking the tracking wires null signal. This hybrid tracking control system has the advantages over both indirect computer sun angle and shadow band tracking in that the high-cost optical shaft encoder required for computer sun tracking can be replaced with a low-cost inclinometer angle sensing device. Direct tracking sensors generates its tracking signal from incoming concentrated solar flux at the receiver tube. This method has the potential to minimize the effect of integrate optical imperfections and trough misalignments.

Tracker Description

The solar flux wire tracker was designed for use on parabolic-cylindrical solar collectors. A schematic of the tracking system is shown in Figure 1. The sensing wires are mounted on the absorber tube, one on each side, parallel to the axis of the trough. Incoming solar flux from the reflector heats the wires and changes their resistance. A sensing circuit detects the change in wire resistance and generates a voltage proportional to the resistance change which is then used for tracking. Figures 2 and 3 show the wires installed on the Performance Prototype Trough. Major components of the device are two-nickel wires, spring clips with insulators, expansion springs, feed-through insulators and jumper wires.

The spring clip provides both alignment and spacing for the sensing wire. Mullite oval, double-bore ceramic tubing was used to provide electrical insulation for the nickel wires. Ceramaseal [1] subminiature feed-through insulators were laser welded into the stainless-steel receiver tube "O"-ring collar. The wires and other components are capable of continuous operation in air at 900 degrees F.

Type 201, 0.005-inch diameter uninsulated nickel wires were installed as the sensing device for the tracker. Nickel has good mechanical strength, reasonable thermal conductivity, high resistance to corrosive atmospheres and ease of joining itself to other metals. Elgiloy (an alloy of nickel, iron, chromium, and cobalt) was selected to fabricate the spring clip and expansion spring. Elgiloy is suitable for temperatures from sub-zero to 900 degrees F. The alloy has less than 1.5% relaxation at stress levels of 75 Ksi and at temperatures below 850 degrees F.

The feed-through insulators are high-alumina ceramic and the metal sleeves are nickel. The flux sensing wires are terminated at the expansion/torsion spring with BAG-7 silver solder. The spring maintains tension on the sensing wires and prevents overstress during thermal cycling. The jumper wire between receiver tubes uses #22 AWG nickel, high-temperature, fire-resistant wire, and can operate continuously at 800 degrees F. BAG-7 silver solder is again used to join the jumper wires at the feed-through insulators. Ceramic tubing is placed over the jumper wire and feed-through junction to prevent shorting. A loop at each end of the jumper wire relieves stress on the feed-through junction.

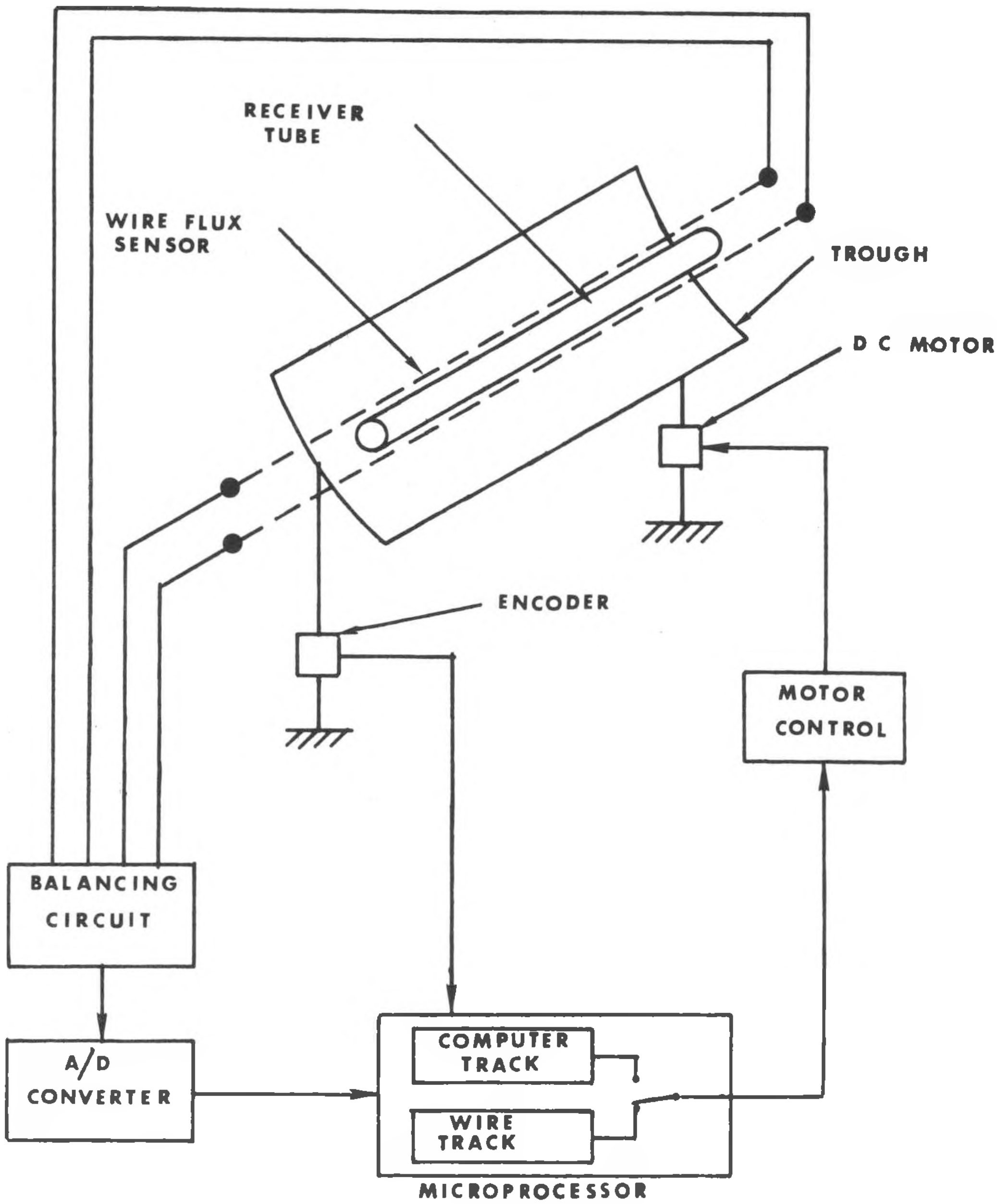


Figure 1. Engineering Prototype Trough Tracking System.

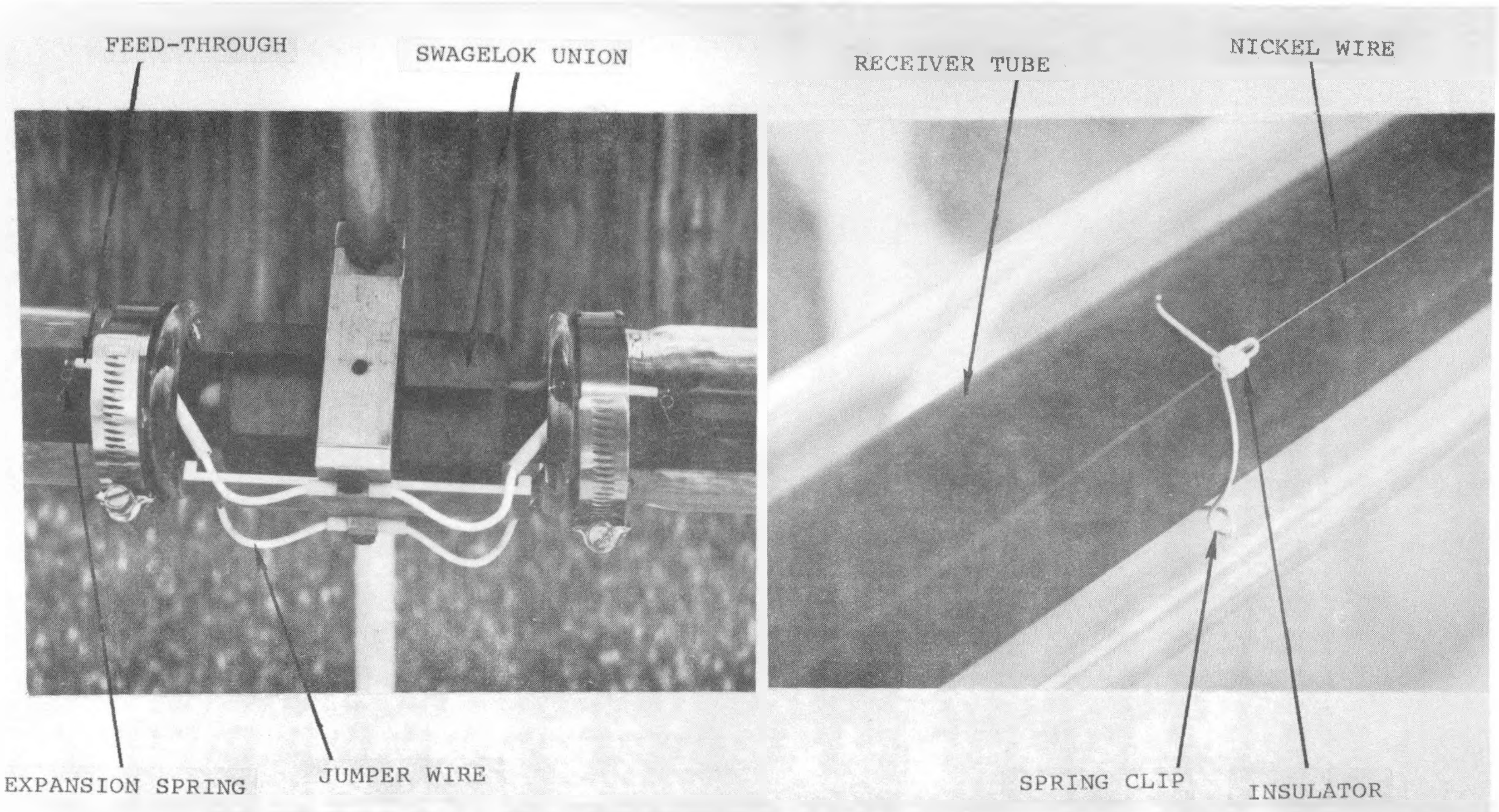


Figure 2. Flux wire sensor as installed on Performance Prototype Trough.

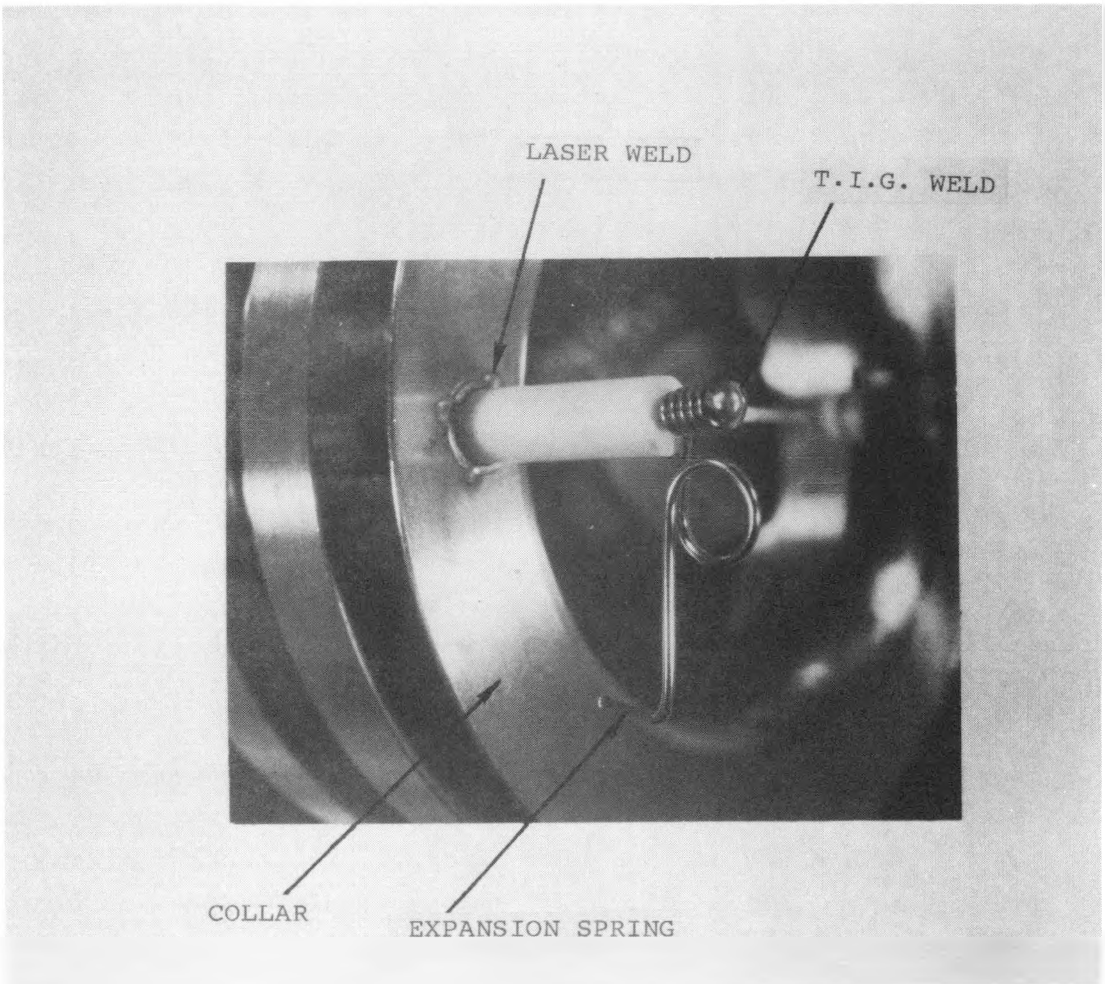


Figure 3. "O"-ring collar assembly.

Preliminary Test

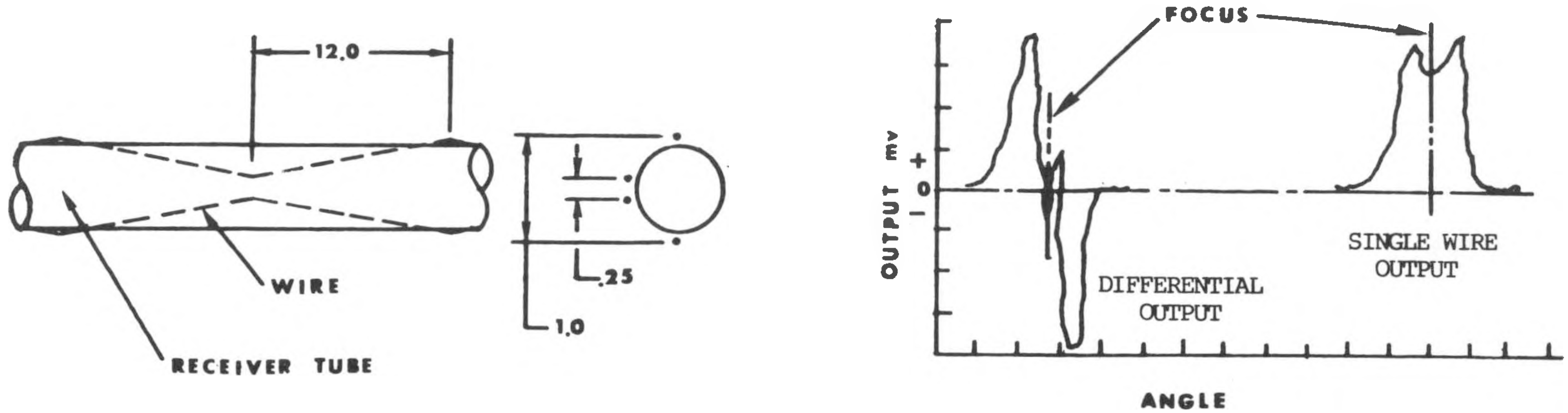
The preliminary tests of the resistance wire tracking system were run at the Collector Module Test Facility (CMTF). The tracking system was installed on the Sandia Mod. 2 Engineering Prototype Trough (EPT-2) [2]. The EPT-2 collector used two 2 m x 6 m troughs and four 25 mm x 3 m long receiver tubes.

To obtain a better understanding of the output signal response of the heat flux sensor, four different configurations of the resistance wire were investigated. Each configuration was installed on a 3 m length of receiver tube for testing. Voltage output from the resistance wire flux sensor was recorded as the receiver was driven slowly through the focused sunlight from the collector. Figures 4 and 5 show the results obtained from each configuration study.

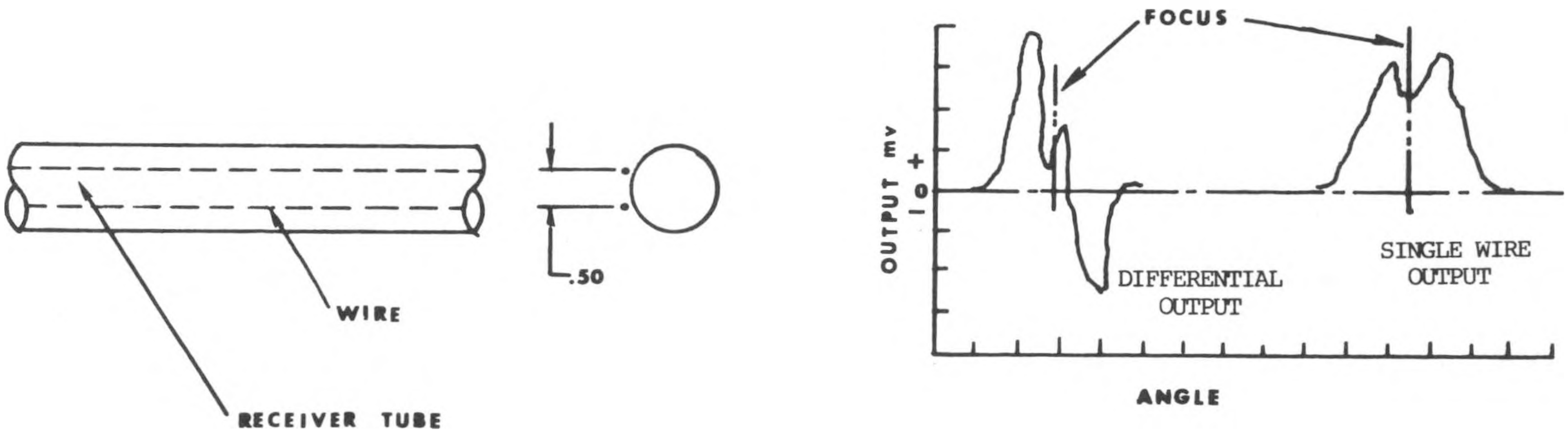
Configurations A, B, and C show that the best focus for optimum tracking occurred when the voltage output was less than maximum. However, configuration C and D shows that increased wire spacing caused optimum focus to occur at the wire's maximum voltage output with a resulting difference signal that is adequate for tracking. A tracking envelope similar to that shown for A, B, and C was reported in previous tests by Kohler and Wilcoxen [3]. The results of this test show that the single-peak envelope signal from configuration D (Figure 6) would provide sufficient output and sensitivity for accurate tracking.

During initial testing, the signal from the resistance wire flux sensor showed an angle offset from the tracking null which varied with both operating temperature and time-of-day. The tracking signal offset resulted in a tracking error of 0.6 degrees at 300 degrees C fluid temperature at various times during the day. A tracking error of no more than 0.2 degrees is required to insure that all the reflected light will fall on the receiver at all hours of the day. Further testing was conducted to investigate the causes of the tracking signal offset and the resulting collector tracking errors.

The fluid temperature in the receiver was stabilized at ambient air temperature with the collector out of focus and at 100, 200 and 300 degrees Celsius. At each temperature, the collector was positioned



(A)



(B)

Figure 4. Results of A and B configuration test.

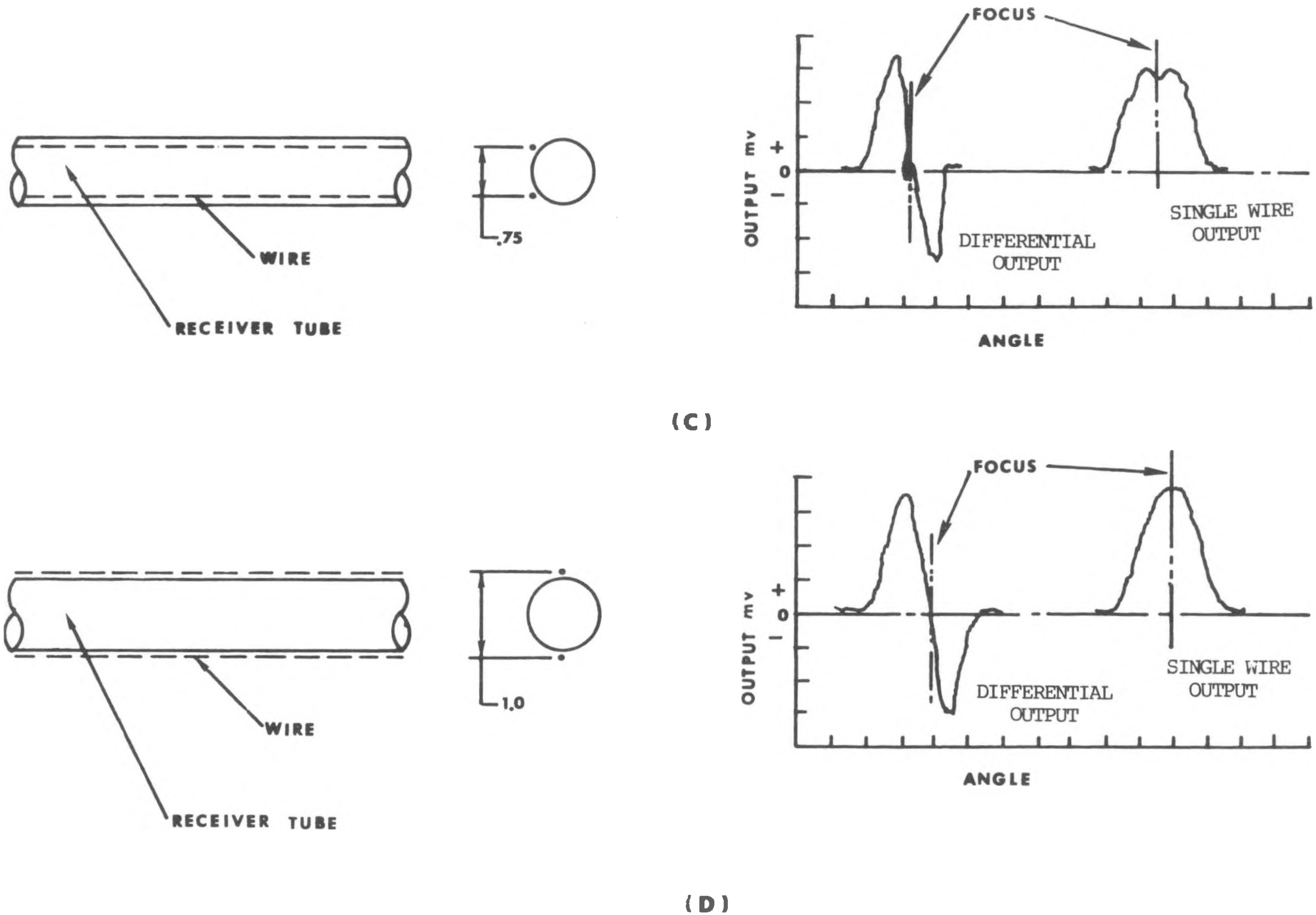


Figure 5. Results of C and D configuration test.

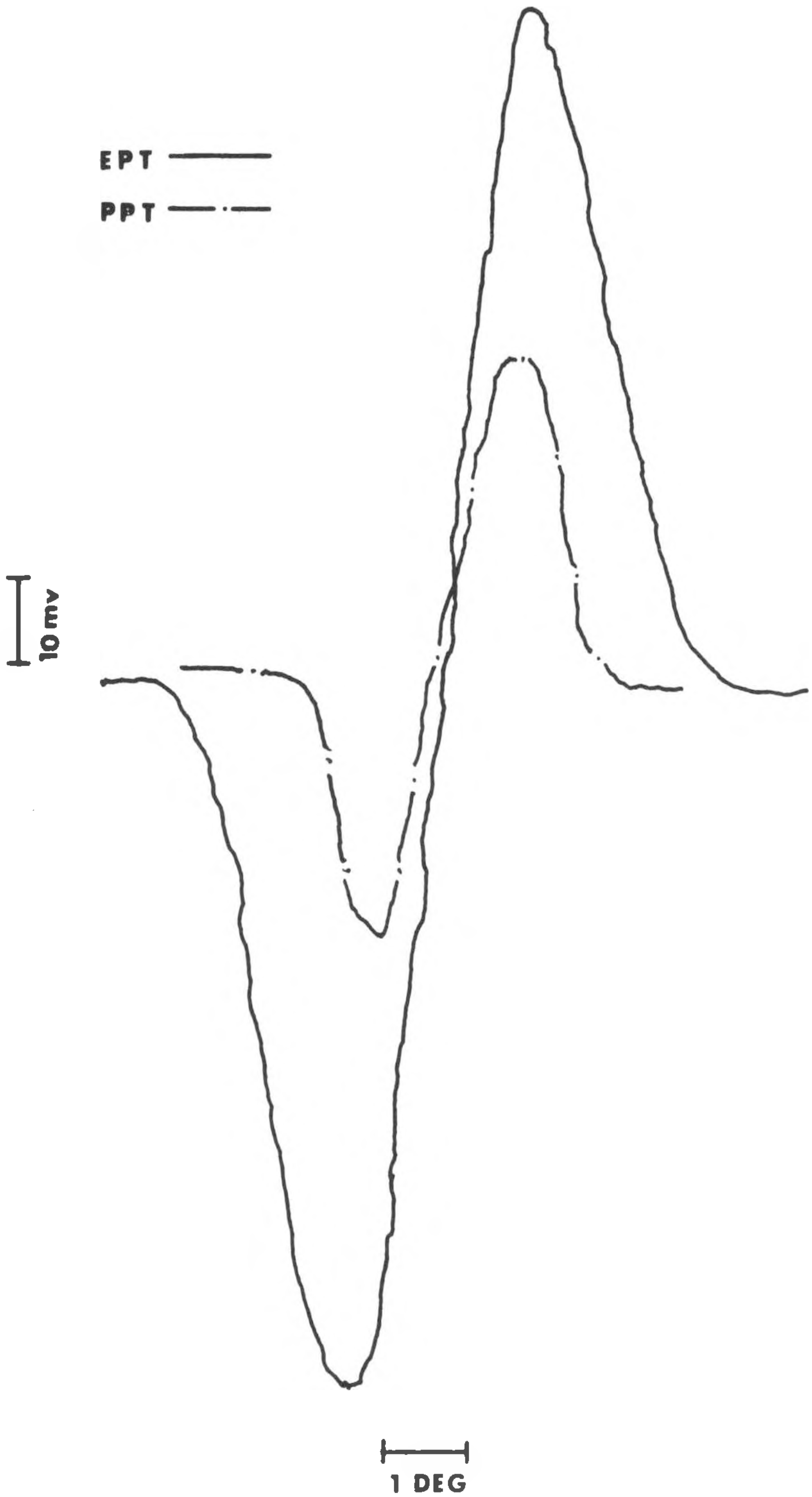


Figure 6. Configuration D Output vs Trough Angle

at 90 degrees south, horizontal and 90 degrees north and the differential output of the wire flux tracker was recorded. The results are shown in Figure 7. The data shows that the flux sensor offset angle is dependent on trough angle and fluid temperature, both of which affect the temperature distribution within the receiver tube. The tracking offset angle is most likely caused by convection air currents within the receiver annulus unequally heating the two resistance wires. The effects of natural air convection in annular receiver tubes have been reported by Hickox and Gartling [4].

From the data in Figures 6 and 7, an offset angle algorithm was written:

$$\Delta\theta = K_4 \left\{ \epsilon + \left[K_3 + K_2 (T - K_1) \cos\theta \right] \right\}$$

From curve:

K_1 = 5°C (offset)
K_2 = .466 mv/°C (slope)
K_3 = 10 mv (offset)
K_4 = .007 DEG's/mv (slope) from tracking wire output single

T = fluid temperature (°C)
ϵ = error signal from wire (mv)
θ = collector angle from horz. (deg.)
$\Delta\theta$ = error in trough position (deg.)

The offset angle algorithm was inserted into the wire sensor tracking software. Peak efficiency data was obtained at approximately 100, 200 and 300 degrees Celsius.

Peak efficiency vs output temperature for both flux wire and computer tracking is shown in Figure 8. The plot shows that efficiency of the collector decreases as the temperature is increased; the decrease in efficiency is caused by increasing thermal losses from the receiver. Both tracking methods produced approximately the same collector efficiencies.

Performance Tests

After establishing the basic design and operating characteristics of the wire sensor from the preliminary tests, configuration D was installed on the PPT collector field.

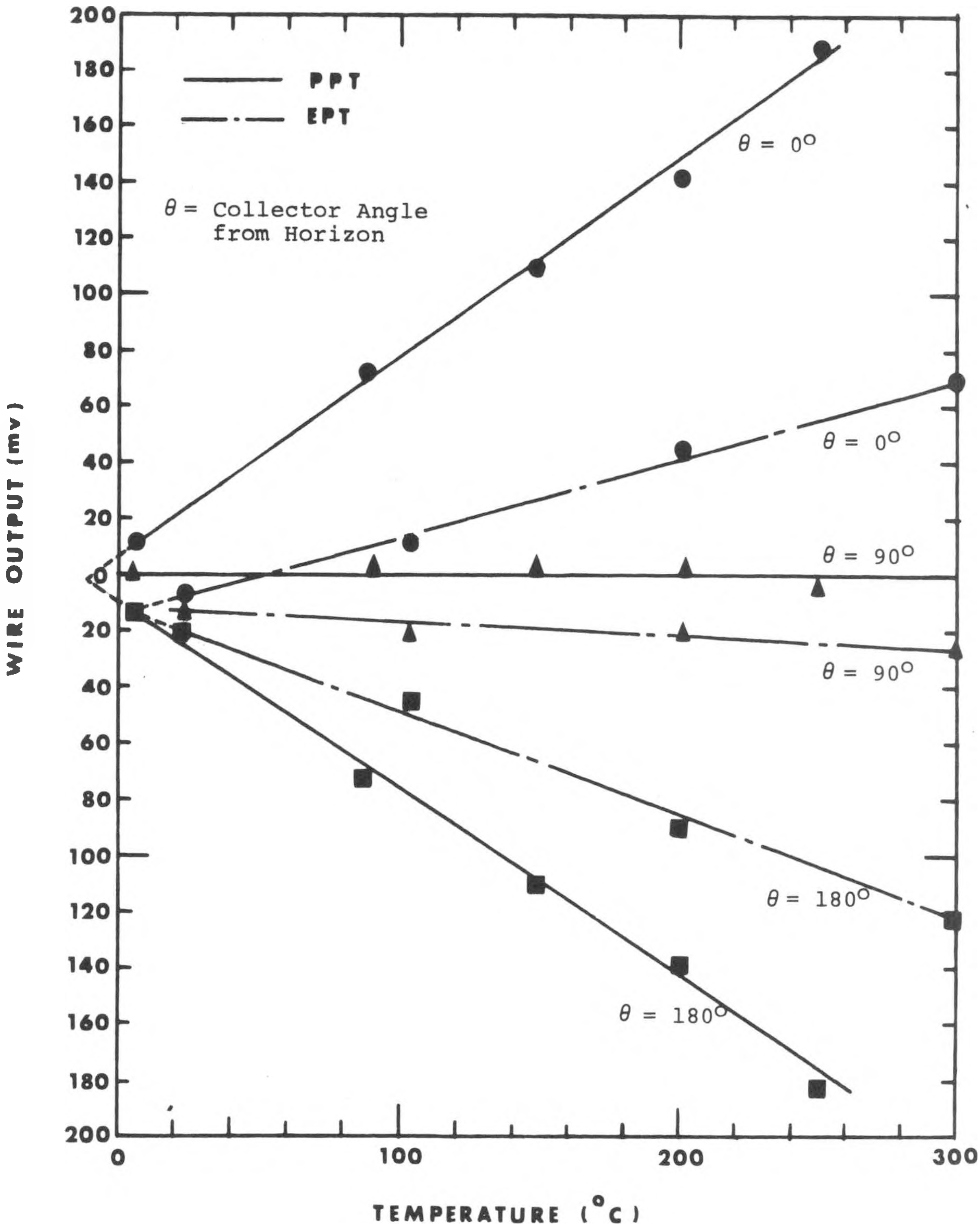


Figure 7. Flux wire differential output vs. fluid temperature.

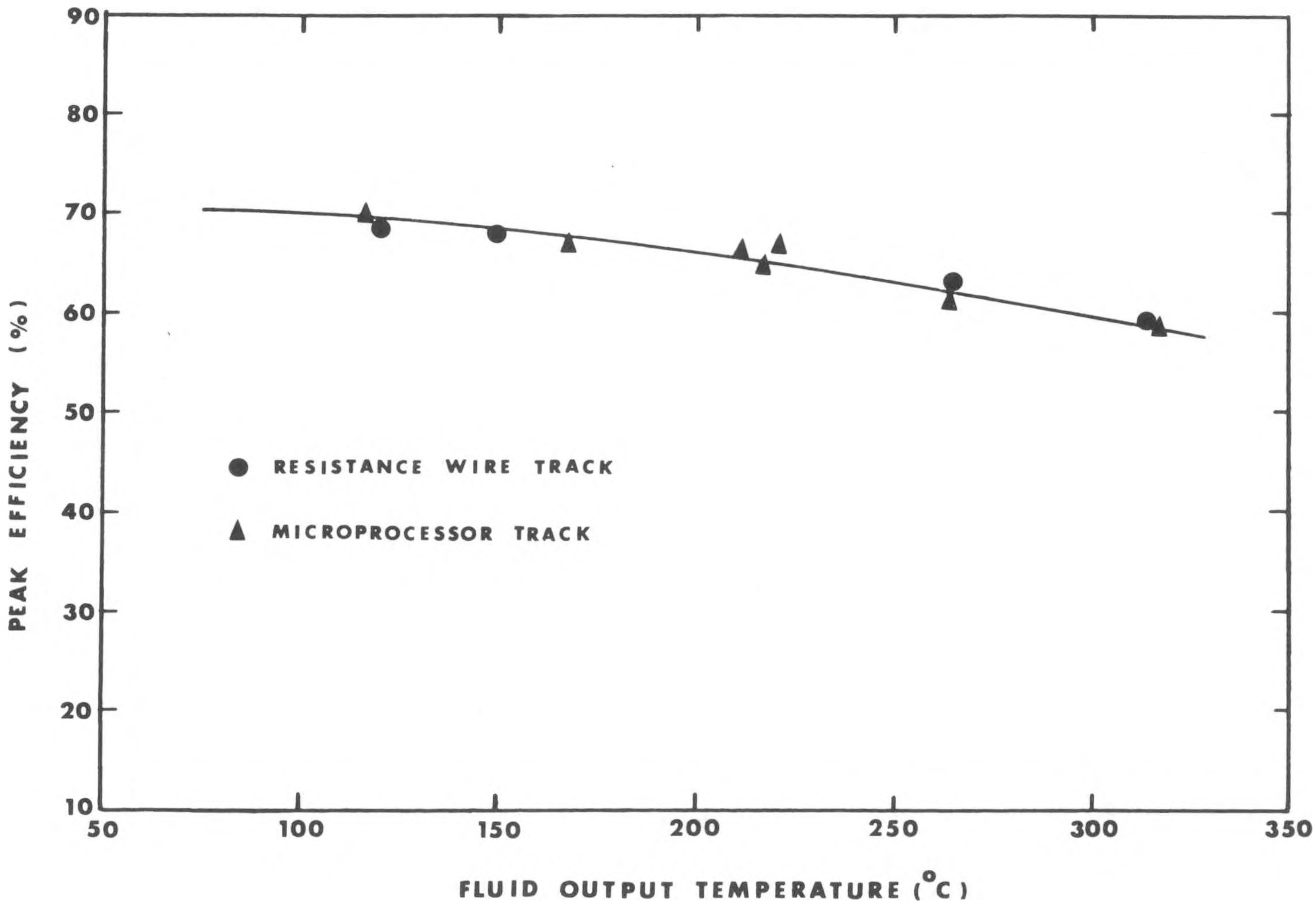


Figure 8. Flux wire and computer tracking peak efficiency vs. output temperature.

The resistance wire signals were electrically balanced at ambient temperature with the three collector drive strings in the horizontal position (reflectors aimed at the zenith). The offset angle algorithm used with PPT was derived from string #4 and the results are shown in Figure 7. From the curves in Figures 6 and 7, the offset angle for the PPT collector field was written:

$$\Delta\theta = K_4 \left\{ \epsilon + \left[K_3 + K_2 \left(T - K_1 \right) \cos\theta \right] \right\}$$

From curve:

K_1 = -15°C (offset)
K_2 = .722 mv/°C (slope)
K_3 = 0.0 mv (offset)
K_4 = .025 DEG's/mv (slope) from tracking wire output single

T = fluid temperature (°C)
ϵ = error signal from wire (mv)
θ = collector angle from horz. (deg.)
$\Delta\theta$ = error in trough position (deg.)

The offset angle data from the PPT collector field shows a symmetrical curve pattern about the axis of the plot, while the data from the EPT-2 (Figure 7) shows an offset of the curves. The improved symmetry obtained on the PPT installation was due to the more precise location of the tracking wires that resulted from using an improved assembly fixture.

After inserting the offset angle algorithm into the Honeywell collector control system, an all-day efficiency test was conducted on the flux wire tracker. The results of this test from string #4 are shown in Figure 9. The drive string established thermal equilibrium at 0830 solar time and an output temperature of 585 degrees F. The solar flux tracker system maintained stable tracking to 1630 hours, at which time the angle of incidence was 67 degrees and solar radiation normal to the trough was 325 (W/m^2).

A test was designed to demonstrate the performance of the flux wire sensor tracking system with that of computer and shadow band tracking.

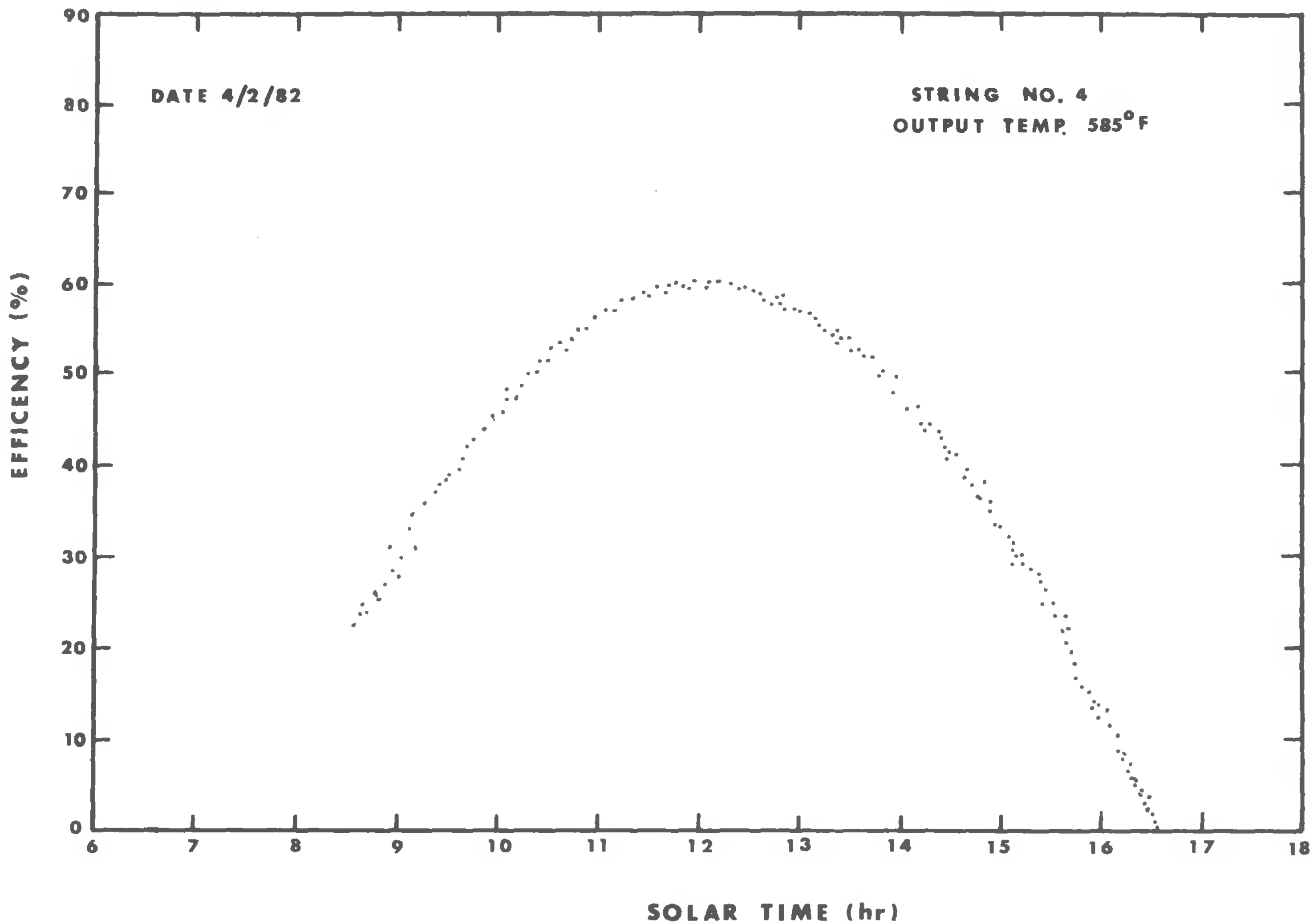


Figure 9. String #4 efficiency vs. solar time.

In the computer-control tracking technique, the calculated tracking angle could change from the ideal tracking angle because of misalignment and imperfections in the collector's string. The PPT computer angle error offset was determined by measuring the system fluid temperature rise as a function of angle. The measured angle error offset was then inserted into the computer software to provide peak efficiency computer tracking for the PPT configuration. A shadow band tracking device was mounted to string #4 of the PPT configuration and, for the same reason given above, the optimum tracking angle may differ from the calculated angle. Therefore, the device was adjusted for null at 0900, 1200 and 1500 hours solar time for three consecutive days to insure the best possible alignment. No alignment or adjustment was made on the flux wire sensor.

Tracking of string #4 was switched between the three tracking modes at intervals of approximately 15 minutes during the test day. The results of the test are shown in Figure 10. The shadow band tracking curve indicates a continual efficiency loss throughout the day. Imperfections such as optical quality of the reflector, sagging of the receiver tube, misalignments between the shadow band and reflector and reflector and foundation are the results of efficiency loss for the shadow band tracking. The efficiency curves for both flux wire and fine-tuned computer tracking modes show no difference in the tracking performance of the collector string, but with aging of the collector string such as warping of collector components and foundation movement would require the computer angle offset to be tested and adjusted to maintain peak efficiency. The as-installed flux wire sensor showed the ability to integrate imperfections from the collector components by direct view tracking from the incoming heat flux of the collector.

Cost

It has been generally accepted that computer sun position tracking be utilized as the tracking device for most single-axis parabolic collectors. For this reason, a cost estimate of the two systems has been compared. The estimated cost is based on one drive string from a large collector array of 24 strings. The results are shown in Table I.

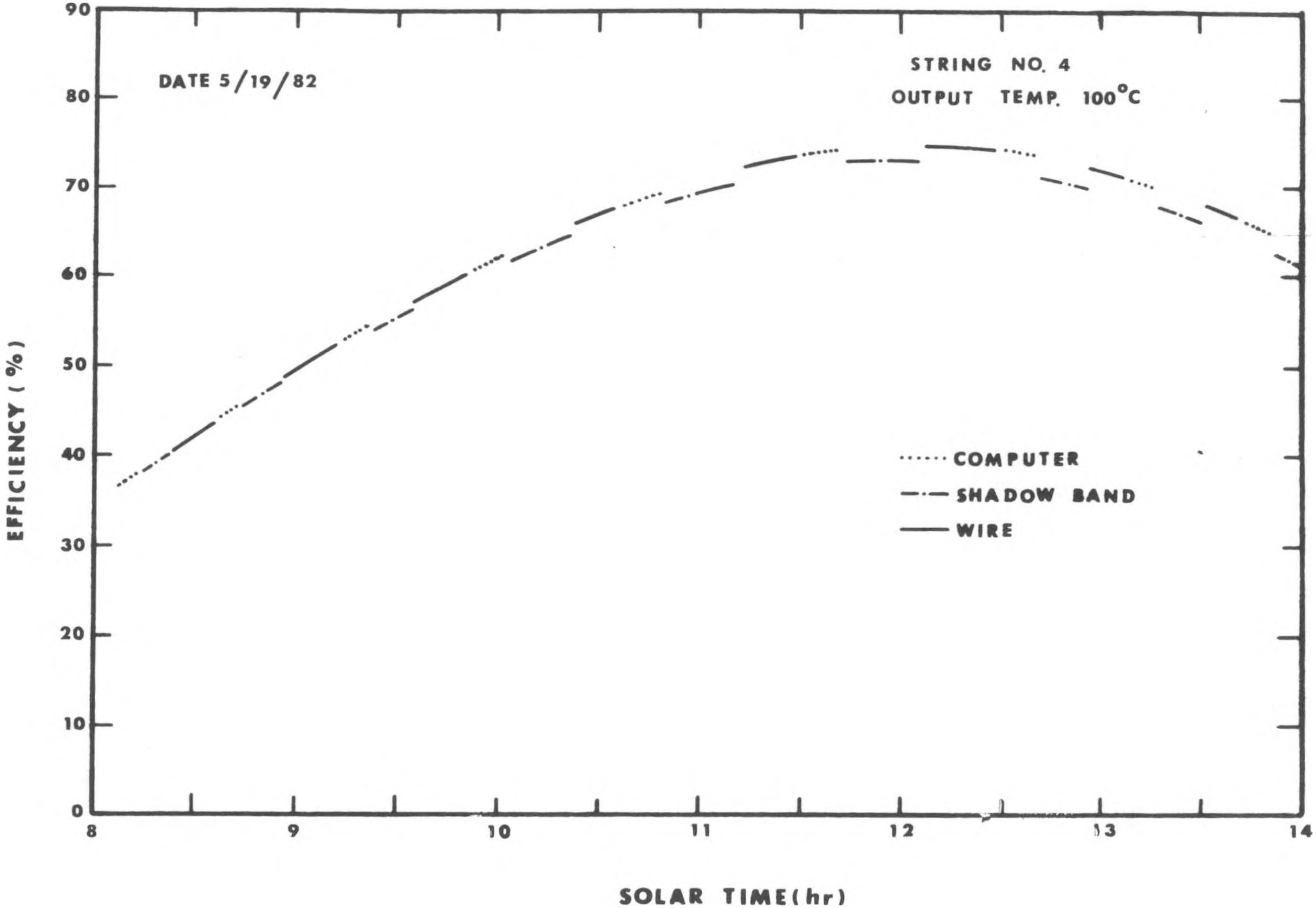


Figure 10. Performance test of shadow band, computer, and flux wire tracking.

Table I

Item	Computer	Flux Wire
Sensor fabrication	--	40.00
Sensor installation	--	320.00
Optical encoder	1200.00	--
Inclinometer	--	300.00
Field controller	100.00	75.00
Collector controller	500.00	400.00
Wiring	300.00	200.00
Efficiency (adjustment)	100.00	--
String (alignment)	150.00	75.00
Tooling	200.00	--
TOTAL	$2550.00	$1410.00

It is expected that with manufacturing development, the cost in Table I would be reduced substantially.

Conclusions

A solar flux wire tracker has been developed and tested that allows accurate tracking of parabolic-cylindrical solar collectors. A microprocessor control system is used in combination with the flux wire output signal to drive the collectors to optimum tracking angle.

The preliminary and design test data established wire sensor configuration, offset angle algorithm and tracking performance for the flux wire tracking system. The direct view tracking device provided the optimum tracking angle by integrating misalignments from the collector's components.

The estimated total cost of the system when compared with computed sun angle tracking was reduced by 45%, mainly due to component and maintenance cost of the system.

References

1. Ceramaseal, Inc. (subsidiary of Interpace) New Lebanon, New York 12126.

2. K. D. Bergeron, R. L. Champion, and R. W. Hunke, editors, "Line-Focus Solar Thermal Energy Technology Development FY 79 Annual Report for Department 4720," SAND80-0865, pp. 18-23.

3. S. M. Kohler and J. L. Wilcoxen, "Development of a Microprocessor-Based Sun-Tracking System for Solar Collectors," SAND79-2163, 1979.

4. C. E. Hickox and D. K. Gartling, "The Effects of Nonuniformities on Natural Convection in Annular Receiver Geometries," SAND77-1641, 1977.

5. K. D. Boultinghouse, "Development of a Solar Flux Tracker for Parabolic Trough Collectors," SAND82-1600, 1982.

HEAT LOSS STUDIES

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INTRODUCTION

During the course of engineering evaluation of various solar thermal systems at MSSTF a substantial descrepancy was observed to exist between the predicted and the measured heat loss from the thermal energy transport and storage systems. The heat loss predictions were based on conduction rates computed from manufacturers data for the insulation used on these systems. A series of experiments were initiated to verify the insulation model and to measure the relative contribution of system components such as pumps, anchors, hand and control valves. Further investigations were made into natural convection in both piping and storage systems.

DESCRIPTION OF PIPE HEAT LOSS TEST LOOP

A 48.7 meter (150 ft) pipe loop was constructed of 2 in. schedule 40 black iron pipe welded at the joints. The system was insulated with two inner layers of 2.54 cm. (1 in) thick fiberglass and an outer layer of 2.54 cm thick polyurethane foam. An aluminum jacket provided weather protection.

The test section was supported on horizontal ladder-type trays normally used to support electrical cable. This method eliminated pipe supports in direct contact with the metal pipe and prevented sagging of the insulation between supports. Air circulated freely between the support rungs and over the test section surfaces. No expansion loops or bellows were incorporated in the test section. Anchors and valves for control are installed outside the test section in the support piping. This piping was located 30.5 cm (12 in) lower than the test section to prevent convective exchange between the test and support piping. Flanges were provided for insertion of piping components for testing.

The instrumentation system included immersion, pipe surface, and insulation profile thermocouples, fluid flow rate, and meteorological data, see Figure 10.

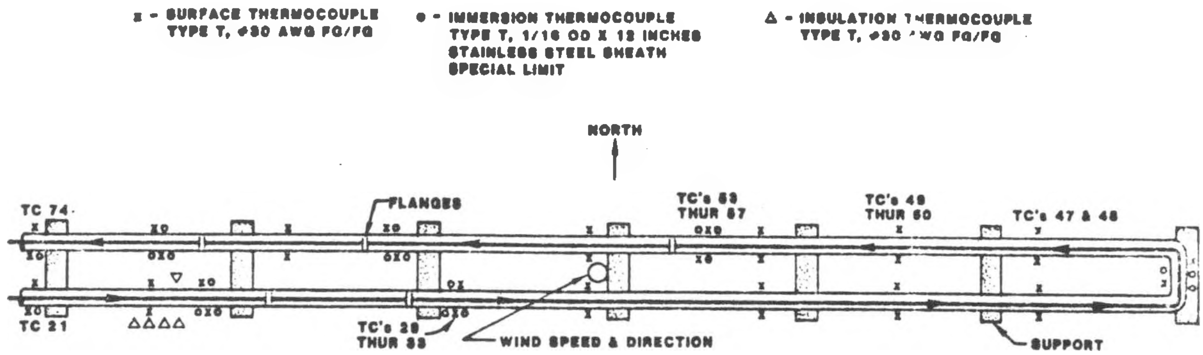

Figure 10. Permanent Thermocouple Locations

BASELINE HEAT LOSS TESTS

A series of tests were run on the pipe heat loss system to measure the overall heat transfer coefficient (U) and to establish a standard baseline from which the contribution to the system heat loss by components could be determined. The heat loss values determined from the experimental data during forced flow and cooldown had very close agreement with the predicted values using manufacturers data. The calculated U from the experimental data was .067 BTU/ft^2-h-°F vs .064 BTU/ft^2-h-°F using manufacturer's data. The cooldown comparison presented in Figure 8 demonstrates that the heat loss from a system without attachments can be predicted with good accuracy.

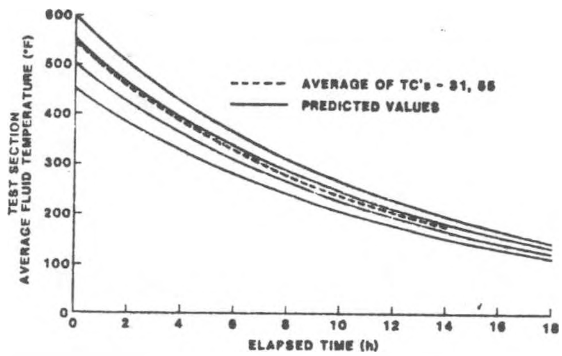

Figure 8. Plot of Measured vs Predicted Test Section Cooldown

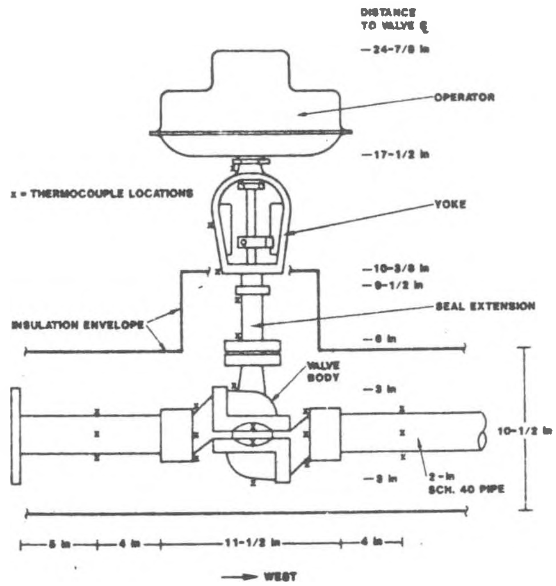

Figure 18. Sketch of the Control Valve, Showing Thermocouple Locations

CONTROL VALVE HEAT LOSS

The control valve heat loss test was conducted to determine the relative heat loss from a MSSTF type control valve, the effect of both insulation and of orientation of the control valve stem with respect to the pipe. The valve selected was a 2 in (5 cm) ANSI class 600 rated for service at 400°C. It consisted of a cast iron body, a seal extention housing and yoke assembly of steel and a pneumatic operator. Figure 18 is a sketch of the valve and insulation envelopes.

The net loss by the control valve is plotted in Figure 26 for both the insulated and uninsulated configurations. There was no observable difference in the heat loss due to valve orientation. The effect on the rate of cooldown of the piping system is displayed in Figure 31 which plots time vs temperature for a pipe surface TC located 24 ft. from the valve. Evidence of a convective cell is presented in Figure 33, which plots pipe surface temperatures 4 ft. from the valve. Insulating the valve reduced the heat loss from 4000 BTU/h to about 1000 BTU/h at 590°F.

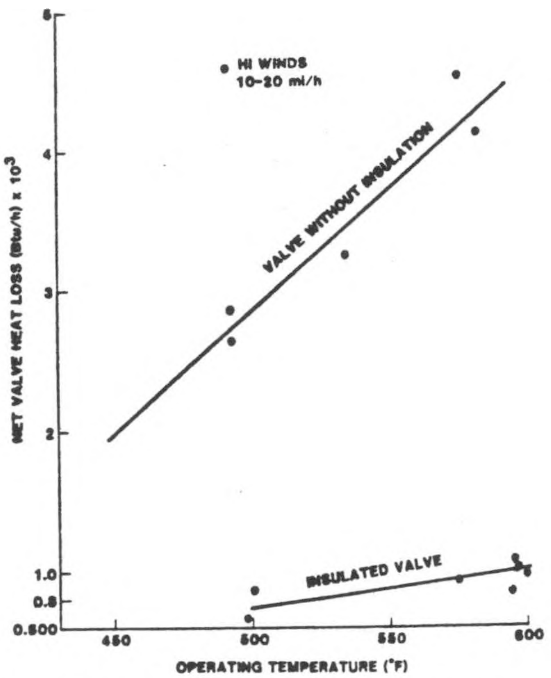

Figure 26. Control Valve Net Heat Loss vs. Temperature

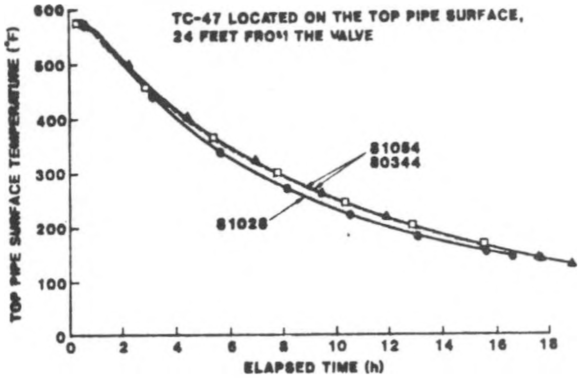

Figure 31. Pipe Surface Temperature 24 feet (8 meters) Upstream from the Control Valve

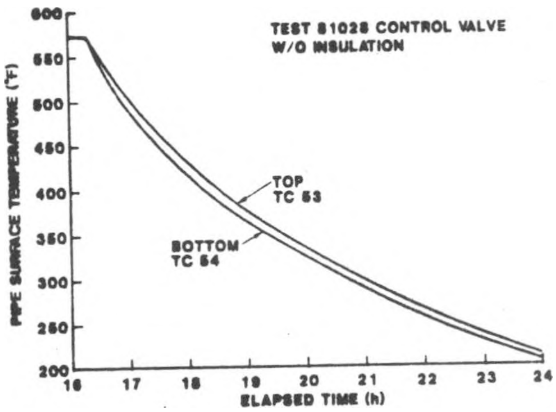

Figure 33. Pipe Top and Bottom Temperatures 4 feet (1.3 meters) from the Control Valve

HAND VALVE HEAT LOSS

Three 2 in. globe valves were installed in series and tested for heat loss with and without insulation. These valves were socket weld types rated for 800 psi service. A total of 8 tests were run, 5 with insulation and 3 with the insulation removed back to the weld sockets.

Figure 55 plots heat loss of the 3 valves vs temperature for both cases. The heat loss for the uninsulated valve is about 7 times higher than the insulated case. This effect is also apparent in the increased rate of the cooldown. Figure 56 plots TC#55 located about 12 ft. (4 m) from the hand valves for the hand valve configurations vs the baseline

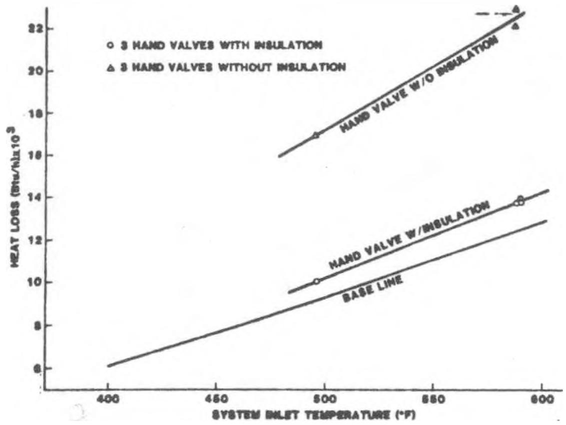

Figure 55. Hand Valve Test Heat Loss vs Temperature

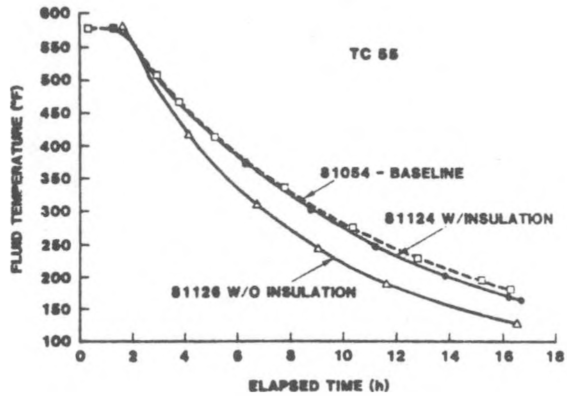

Figure 56. Hand Valve Test Cooldown Comparison

The rate of heat loss per hand valve for each case is listed below.

	Net Loss per Valve BTU/hr.	Equivalent kW	Equivalent H.P.
Insulated	433	0.27	0.17
Uninsulated	3100	0.908	1.22

PIPE HEAT LOSS THERMAL SIPHON TEST

Thermosiphon phenomena are characterized by the transport of hot fluid to a heat sink via a convection loop. Transport can occur over large distances and has been observed both in the laboratory and in the solar installation at Coolidge, AZ. The objective of these thermosiphon tests, conducted as part of the pipe heat loss experiment, was to observe under what conditions thermosiphon phenomena associated to accelerated heat loss from the insulated piping manifold. No concentrated attempt was made to quantify the contribution of the thermosiphon mechanisms, rather to demonstrate the piping geometries that would allow or eliminate the convective exchange between the receiver and the manifold.

The thermosiphon section was fabricated to simulate the geometry of an actual installed collector receiver tube. The receiver tube was mounted about 58 in. (147 cm) above the insulated piping manifold. Insulated flex hoses connected the receiver tube to a section of insulated 1 in (2.5 cm) diameter steel tubing that in turn was connected to the pipe heat loss manifold. A hand valve was installed in the downstream end and a check valve installed in the upstream end. The check valve had a 1/8 in (.3 cm) hole drilled in it to allow make-up to the receiver as it cooled down.

In Figure 67 the various configurations are compared to the baseline cooldown, (curve 1) for TC#55, an immersion thermocouple located about 15 ft upstream from the center of the receiver tube. Curves 2 and 3 represent the cooldown profile when either the check valve or the cold trap were present. These curves are nearly identical and show only a slight increase in the cooldown rate. On the other hand, curves 4 and 5 (cold trap and check valve removed), demonstrate a marked increase in the cooldown rate at TC#55. These two curves are the cooldown rates for the inverted stow position, (curve 4) and the elevated stow position, (curve 5) which have similar heat loss rates.

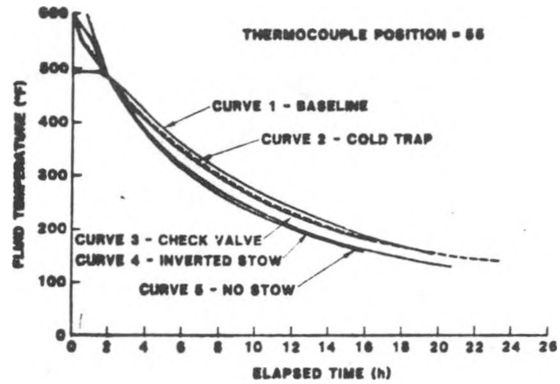

Figure 67. Summary of Thermosiphon Test Results

It can be concluded from this series of experiments that a receiver tube can incresae the rate of cooldown on an adjacent insulated piping manifold. A cold trap or check valve does, however, reduce the accelerated heat loss.

THERMOSIPHON TESTS AT COOLIDGE

A series of tests were conducted at Coolidge where pipe surface temperature instrumentation was used to investigate the thermosiphoning phenomena. The geometry of the Coolidge system, as originally configured, is sketched in Figure 61a. The locations and identification numbers of thermocouples are marked on the sketch. On November 20, 1980, a cooldown test was conducted in which the buffer tank isolation valves were closed. Temperature readings from the thermocouples are listed in Table 8. Thermocouples 76 and 77 showed a temperature difference for about 4 hours after start of the cooldown. It is believed that the energy to maintain this small difference is supplied from the collector return manifold rather than from the buffer tank. It is possible that the energy flow from the buffer tank is dissipated through the control valve and pipe anchor, which are located between the isolation valve and the GFH line. The stable 2°F (1°C) temperature difference that remains after 5 hours of cooldown appears to be the natural stratification due to cooling through the insulation.

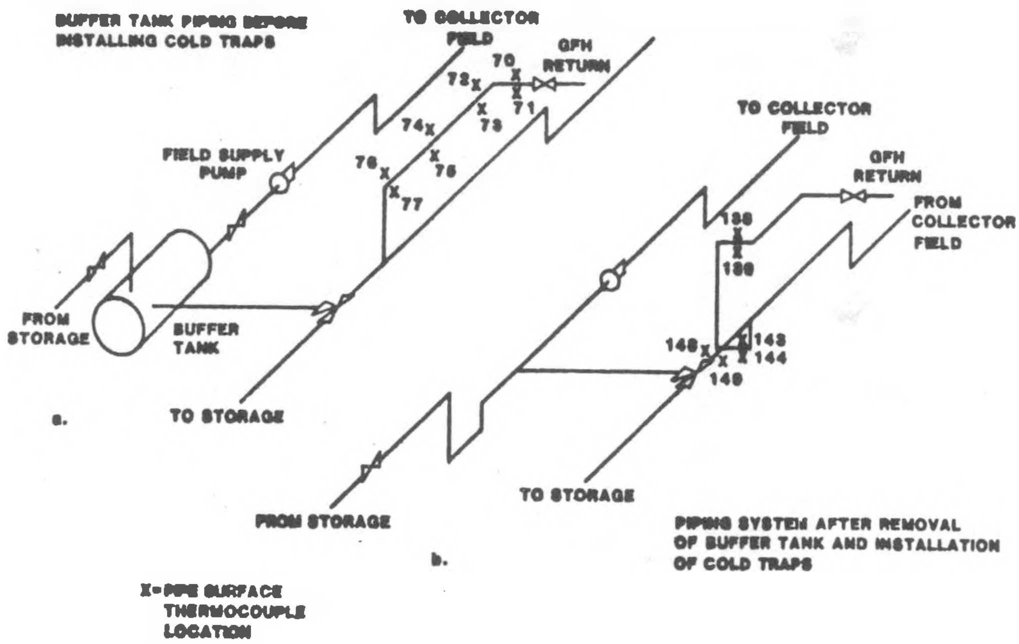

Figure 61. Piping Geometry and Thermocouple Locations at the Coolidge Irrigation Facility

TABLE 8. SYSTEM COOLDOWN,* NOVEMBER 20, 1980

	Time			
TC No.	1422	1823	2223	0123
70	397°F	332°F	234°F	175°F
71	372	319	227	Missing
72	402	335	246	183
73	379	323	238	178
76	417	342	256	196
77	401	339	254	194

*Buffer tank isolation valves closed. Calculated heat loss from buffer tank = 2.26 kW for 12 hours.

On November 21, 1980, the cooldown test was repeated with the buffer tank isolation valves left open. Top-to-bottom surface temperature differences along the GFH line occurred for the duration of the test. Energy is coupled from the buffer tank to the GFH line, as can be seen from the temperature data in Table 9. The heat loss values shown with Table 9 are totals for the 12-hour test period and include losses from the buffer tank by all three lines when the isolation valves are left open.

A forced flow test was conducted on November 23, 1980. At start-up, the system temperature was about 100°F (38°C). Fluid was circulated from the buffer tank through the collector field and back to the buffer tank at a minimum flow rate until the collector outlet temperature reached 480°F (249°C). The fluid was then directed to storage, and the flow rate was increased to maintain an outlet temperature of 480°F (249°C). The maximum flow rate was 30 gal/min (1.9 ℓ/s). The temperature of the system began to rise at 0930, reached 480°F (249°C) at 1230, and remained stable at that temperature for 3 hours. The GFH line temperatures for this test, listed in Table 10, reflect these events. After the 480°F (249°C) temperature was attained, an operating convection cell was established with a temperature difference of 15°F (8°C), as measured by the thermocouples on the outside pipe surfaces.

TABLE 9. SYSTEM COOLDOWN,* NOVEMBER 21, 1980

	Time			
TC No.	1608	2008	0008	0408
70	350°F	285°F	261°F	238°F
71	336	277	252	229
72	353	287	263	240
73	335	278	260	232
76	372	299	277	255
77	355	270	270	249

*Buffer tank isolation valves open. Calculated heat loss from buffer tank = 3.29 kW.

The System was then modified by removing the buffer tank and installing cold traps in the GFH line and the storage supply line. The modified system was operated on January 18, 1982. The GFH line was not affected by the temperature in the manifold even though the isolation valve to the heater was left open (see Table 11). There was no evidence that the GFH line would develop thermosiphoning action at any time with the cold traps installed.

TABLE 10. SYSTEM HEAT-UP,* NOVEMBER 23, 1980

	Field Return Line Temperature 480°F Time		
TC No.	1308	1408	1508
70	371 °F	367 °F	379 °F
71	347	346	355
72	375	371	383
73	354	352	361
76	389	385	398
77	376	373	383

*Heat-up to 480°F with collectors. Flow rate 30 gal/min.

The temperature difference between TCs 76 and 77 is plotted versus elapsed time in Figure 62.

TABLE 11. AFTER INSTALLATION OF COLD TRAPS IN GFH LINE,* JANUARY 18, 1982

TC No.	Temperature (°F)
138	72
139	71
143	75
144	73
148	481
149	480

*Operating temperature = 480°F. Flow rate = 35 gal/min. Ambient temperature = 72.4°F.

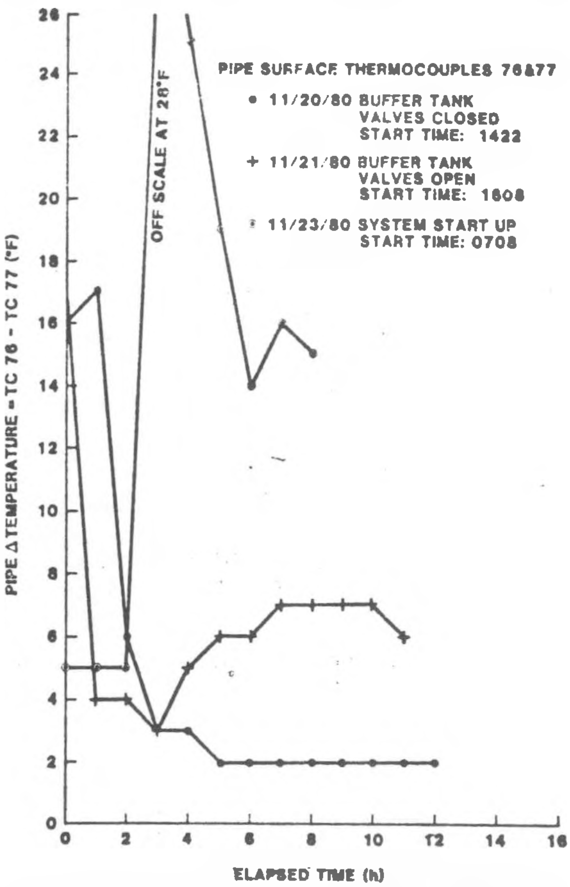

Figure 62. Top Surface to Bottom Surface Temperature Difference vs Elapsed Time for the Coolidge Thermosiphon Tests

The insulation on the Coolidge system is a nominal 3 inches of fiberglass with a metal cover. The k value of the insulation is approximately 0.31 BTU-in/ft^2-°F-h (0.04 W/m^2-°C). Using the data from Tables 8 and 9, the loss prior to modification was about 800 BTU/day (234 Wh/day) for each foot of length, not including losses from anchors and valves in the line. Thus, the installation of the cold traps saved 12,000 to 14,000 BTU/day (3.5 to 4.1 kWh/day), equivalent to adding about 15 ft^2 (1.4 m^2) of collector surface.

HEAT TEMPERATURE STORAGE TANK HEAT LOSS TESTS

During tests involving calibration of the tank fluid level measuring system it was observed that after an overnight cooldown, the temperature of the fluid at the bottom of the tank was much lower than anticipated. A series of tests were conducted to determine the cause. It was apparent from these tests that a large discrepancy existed between the predicted heat loss values of 2000 to 3000 BTU/hr. and the measured value nearly 9000 BTU/hr. As a result the west storage tank was instrumented with surface thermocouples on a support leg and the adjacent tank wall. In addition, the hot discharge line had three pair of top and bottom surface thermocouples installed.

The HTST system at MSSTF consists of three identical 3377 gal (12.78 m^3) tanks. Wall thickness is .25 in (6.35 mm), the dished ends are .375 in (9.52 mm) thick of mild steel. The cylindrical section of the tank is approximately 100 in (2.54 m) in height and 96 in (244 m) in diameter. Support is provided by three legs that rest on a 2 in (5.08 cm) thick pad of marinite insulation. The bulk insulation consists of 20 in (50.8 cm) of fiberglass, which covers the top and sides. The space beneath each tank is filled with bulk insulation.

At the bottom of each tank an 18 in (45 cm) diameter well is provided to which all three fluid handling lines are connected. These lines are constructed of 2.5 in by .065 in wall steel tubing. Each line has a remotely operated control valve that can control access to the external piping system. Adjacent to each valve is an immersion thermocouple. Piping and valves are insulated with 2 in (5.08 cm) fiberglass and 1 in (254 cm) of urethane foam. The piping layout is shown in Figure 77. Each tank is instrumented with a level transmitter, a 21 point temperature probe, and 10 surface thermocouples.

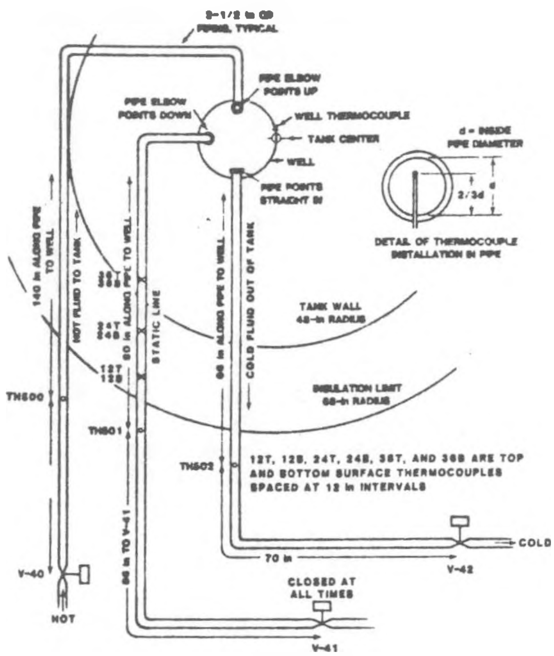

Figure 77. Piping Layout for the High-Temperature Storage Tank

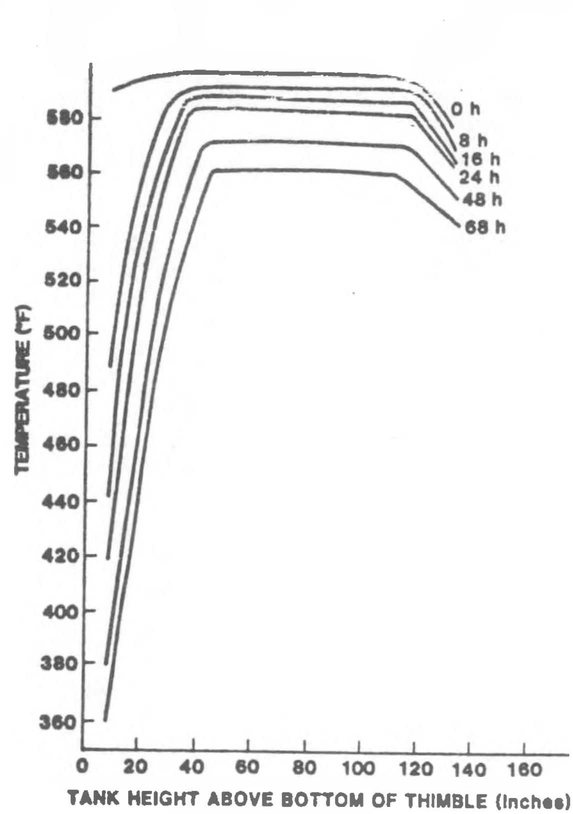

Figure 78. Temperature Profiles at Various Elapsed Times During Test, West Tank

To prepare for the tank heat loss test the west tank was heated each day for four consecutive days to 590°F (300°C). On the fifth day, Friday, the tank was again heated to 590°F, all valves closed and the heat loss test began and allowed to run for the entire weekend. It is important to remember that the lines with V 140 and V 42 were closed except for the heat up cycle, V41 was not opened at any time. Figure 78 shows the tank temperature profile at the end of the heat up and at various times during the cooldown.

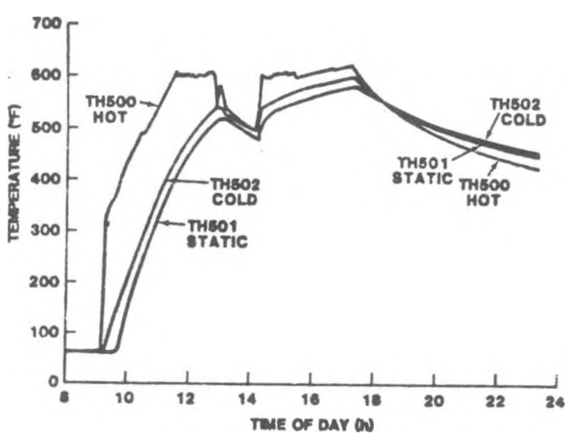

Figure 80. Temperatures at TH 500, TH 501, and TH 502 During Warm-Up and Cooldown

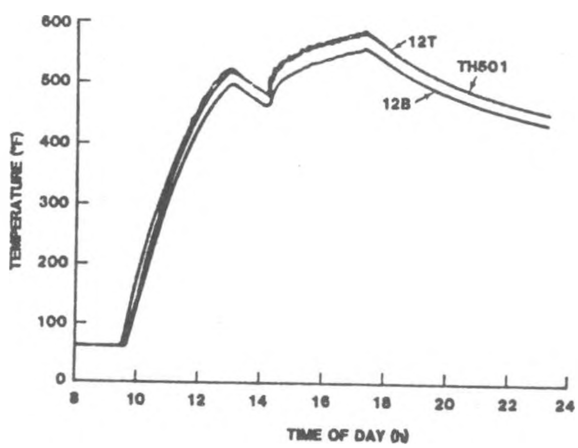

Figure 81. Temperatures at TH 501, 12T, and 12B on the Static Line During Warm-Up and Cooldown

In Figure 80, the temperature data from thermocouples TH500, TH501, and TH502 are plotted for the heat up cycle and the first 6 hours of the cooldown. In Figure 81 the data from TH501 and pipe surface thermocouples 12T and 12B are plotted vs time for the same period as Figure 80. The temperature at the top surface of the pipe (12T) is nearly identical to that of the immersion thermocouple (TH501), while the bottom thermocouple (12B) follows the same pattern but is always lower by about 18°F. This indicates that hot fluid from the well flows at the top of the pipe toward the valve (V41), the valve acts as a heat sink, cooling the oil. The cooler oil flows along the bottom of the pipe back toward the well. Figure 81 plots these temperatures for the entire 60 hr. test. The difference temperature from top to bottom across the pipe is an almost constant 18°F (10°C) for the complete period.

Data from the tank probe and external wall thermocouples indicate that radial temperatures vary less than 5°F. The cooldown rate at 88 in is 0.4°F/hr vs 4.2°F/hr at the well surface. Calculated losses through the insulation on the top and sides were 1945 BTU/h (.57 kW) and 614 BTU/h (0.18 kW) losses by the legs and connecting lines due to conduction. Possible losses of 1024 BTU/h (0.3 kW) existed for each of the three horizontal pipes due to convection. The measured losses from the tank averaged 8837 BTU/h (2.59 kW) and are essentially constant for the duration of an 85-hour cooldown period. The identifiable conduction plus convection losses then total 5630 BTU/h (1.65 kW) resulting in a discrepancy of 3207 BTU/h (0.94 kW).

CONCLUSIONS

Large quantities of heat can be lost from a well-insulated storage system by subtle, but substantial convective cell exchange or thermal siphoning. In the case of the HTST, the three 2.5-in (6.35 cm) fluid-filled lines, isolated by a closed control valve, dissipate more than 1.5 times as much energy to the envionment as does the bulk insulation. This siphoning process is spontaneous and cannot be terminated by valving alone.

There are no large bulk convection cells existing in the tank which would tend to cool the whole tank at a uniform rate. The tank probably establishes two discrete regions due to the high heat loss at the bottom (see Figure 78). The rapid cooling from the bottom establishes a thermocline which essentially isolates the two portions which then operate two separate convective cell circuits. The decrease in temperature by the top portion represents the bulk losses from the tank boundaries; the decrease in the bottom portion energy content is mainly due to convective exchange to the external piping.

The natural convection process operates as a result of the density difference created by a change in temperature. The easiest way to control the process is to block the convective exchange with the piping geometry that can be used to trap the higher density cold fluid at a desired location. The principle is to keep hot portions of a piping system above the cooler portions or to isolate them with "cold traps." A cold trap can be either a vertical pipe section or a U-shaped section where subcooled fluid can collect.

In the HTST 3 tank thermal storage system it is estimated that the above measures could save in the range of 2×10^5 BTU/day (60kW/day). A solar collector system delivering 1,000 BTU/day/ft^2

would require
an additional 200 ft^2 of collector at $\$40/ft^2$ to make up the preventable thermal siphon losses from this storage system.

The tank bulk insluation cost about $20,000 installed. The estimated cost of cold traps in each of the nine connecting lines is a few hundred dollars.

CONCLUSIONS

The experiments reported here include data that is applicable to nearly any thermal energy transport or storage system. The value of insulation on such equipment as valves, pumps, and storage system is readily apparent. Heat losses from an insulated piping system not encumbered with valves, anchors, etc., is fairly predictable. The calculated heat losses from such a system in this experiment had very close agreement with the measured values. The addition of valves, anchors, pumps, and unused branch lines can produce large uncertainties, particularly if not well-insulated. However, the effect that piping geometry can have on the heat loss values was unexpected.

Normally, when evaluating the overall system losses of a transport system, one would ignore all the branch piping and assess only those components actually used to transport the energy. This can result in large discrepancies because of the ability of the system to establish convective exchange to inactive branch systems. It has been shown that these losses can be substantial even in a well-insulated system.

Simple changes in piping geometry that provide cold trap isolation will reduce convection losses in branch systems to values below casual means of measurement. From a capital investment point of view, these savings are very cost-effective.

It would appear that the large discrepancy observed in the original MSSTF heat loss measurements resulted from two factors: (1) the loss rate of the components was underestimated and (2) the branch lines losses due to thermosiphoning were not considered.

Handbook for the Conceptual Design of Parabolic Trough Solar Energy Systems

Process Heat Applications

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The goal of this handbook(1) is to provide easily used techniques which will allow the rapid achievement of conceptual designs. Much has been learned about expected collector performance, variation of solar radiation within the United States, and how parabolic trough solar collectors can be integrated with thermal energy storage. This handbook integrates this and other state-of-the-art information into the conceptual design process.

A conceptual design evaluates the ability of alternative design options to meet the energy demands of a potential process heat application. The objective is to quickly sort through the various potential solar energy system designs and to choose one or two, if any, that have good potential for servicing a thermal energy demand cost-effectively. The conceptual design should estimate

1. the area of solar collectors required,
2. the land area needed by the solar collectors,
3. storage requirements and
4. the fraction of the fossil fuel which could reasonably be displaced by a solar thermal energy system.

In addition, a well-executed conceptual design allows approximation of the capital cost of the solar energy system needed to service the demand.

As a result, the conceptual design serves as a screening tool. If the conceptual design reveals severe constraints on the solar energy system (e.g., too little land available for collector deployment), the application of solar energy to the process should be questioned before continuing with the design process. If the conceptual design indicates good compatibility between the solar energy system concept and the application, the conceptual design serves as a foundation from which the preliminary and detailed design processes can begin.

The logic path from definition of the demand through achievement of the conceptual design is outlined in Figure 1. The design process starts with the definition of the demand characteristics. The temporal profile of the demand defines which Storage Sizing Graph (see below) to use. The temperature characteristics of the demand, when taken together with the desire to have a system which either includes storage or has no storage, define the collector field ΔT. Typically both storage and no-storage designs are examined.

The collector field ΔT in turn defines the collector operating temperature which, together with collector performance characteristics, provides the average annual collector performance. Nomographs are provided which allow the projection of annual collector performance for collectors which have only efficiency versus $(T_{col} - T_{amb})/I$ $(\Delta T/I)$ test data available. Published average annual performance data can be used if available.

Storage Sizing Graphs are used to determine the relationship between needed collector output, storage capacity, and demand. Only solar energy systems which provide near-100% utilization of the collected solar energy are typically selected. In the case of systems incorporating storage, the design point is termed the maximum displacement point. Multiplying the fractional displacement by the demand yields the quantity of energy displaced by the solar energy system. Dividing the quantity of energy displaced by the per-unit-area collector output and adjusting for field losses yields the required collector area. Finally, multiplying the storage fraction by the average daily demand yields the necessary storage capacity.

If estimates of storage costs and collector costs are available, total storage/collector subsystem capital costs can be approximated. The net results of the conceptual design are the displacement of fossil energy, the collector area and storage capacity needed to achieve this displacement, the approximate land area needed for collector deployment, and an estimate of the total capital costs.

Collector Output

System design begins with an examination of how the type of demand affects selection of the appropriate collector operating temperature. Two significantly different types of thermal energy demands are examined. Each strongly influences the solar energy system design. One type of demand is a sensible heating system in which the process heat transfer fluid experiences large temperature swings, and the second type of demand is a phase change system, such as steam, which tends to operate within rather narrow temperature limits.

A sensible heat demand, in which the temperature of the process fluid varies over a wide temperature range, is perhaps the type of demand most easily serviced by a parabolic trough collector. This type of demand, which may, for example, involve heating a heat transfer oil in an existing process heat system, closely matches the thermal characteristics of the solar collector field. The collector field collects thermal energy through a sensible heat mechanism and, as a result, undergoes large temperature swings. Thus, it is conceivable that the temperature in the collector field could be made to conform closely to the temperatures of the process heat transfer fluid. Conceptual design of the solar energy system can proceed in a rather straightforward manner because the average operating temperature of the collector field is approximately equal to the average process temperature. This is not the case with a latent heat demand such as a process steam system.

Process heat is most commonly delivered to an application in the form of steam. The design difficulty encountered in a process steam system is the interfacing of a sensible heat solar collection system with a latent heat (i.e., steam) process heat system. The problem is illustrated schematically in Figure 2 for a hypothetical case in which 200 psi saturated steam at 380°F is desired.

After condensation of the steam by the process, the hot water is returned to the boiler for revaporization. While the hot condensate may be used for preheating, this is not shown in order to simplify the discussion. The hot condensate is assumed to be saturated. The primary design problem is how to interface the relatively constant temperature process steam system with a solar energy collection system which operates best with large swings in temperature.

Sensible heat addition to the process steam generator is indicated on Figure 2 in the form of straight lines. As shown, several options are available with the constraint imposed by the second law of thermodynamics -- the temperature of the collector fluid must, at any given point, be greater than the corresponding temperature of the process fluid in order for heat transfer from the collector fluid to the process fluid to occur. The two different heat addition lines for the collector fluid (lines PA and PB) represent different ΔT's across the collector field.

At first consideration, heat addition line PA might appear best. This heat addition process would result in the lowest average collector temperature of the two situations and collector performance increases with decreasing operating temperature. There are, however, system considerations which can force a system design away from one in which the ΔT across the collector field is small and toward designs in which the ΔT is large, such as represented by line PB.

One system level consideration which favors a large collector field ΔT is storage. Most storage concepts developed to the point where they would be used in near-term solar energy systems employ sensible heat. The ΔT across the storage system is essentially the ΔT across the collector field. As the sensible heat storage ΔT increases (and thus the collector field ΔT increases), the volume of storage required to store a given quantity of energy decreases, resulting in decreased storage costs. The challenge for the designer is to find the conditions representing the most cost-effective system. Rules of thumb are presented in the handbook to address this tradeoff.

Once the collector operating temperatures are determined as in Figure 2, nomographs presented in the handbook can be used to determine collector output. The nomographs are presented such that all the designer need know about the collector under question is its efficiency vs temperature characteristics (i.e., the $\Delta T/I$ curve), its orientation, and its location. Nomographs for all TMY sites are presented. The impact of shadowing on an array of parabolic trough collectors is addressed for all TMY sites in the form of graphs such as that shown in Figure 3. Notice that in the case of Figure 3, a N/S oriented trough is shadowed more than an E/W trough. The Row Shadow Factor when multiplied by the collector output computed without considering shadowing is the collector output with shadowing considered.

The Role of Storage

The determination of the proper collector field size to service a defined demand is intimately tied to the amount of storage provided. As long as all of the thermal energy produced by a solar collector field can be effectively utilized to satisfy a demand, a solar energy system which employs no thermal energy storage will be the lowest cost system. Solar energy systems which have no thermal energy storage are usually capable of meeting only a rather small fraction of the total demand. If no storage is provided and the collector area is increased, the ability of the application to effectively use all the thermal energy produced by the collector field rapidly diminishes. This decrease in utilization of the collected solar energy results from mismatches between the demand profile of the application and the energy supply profile of the solar collector field. Increasing the utilization of the collected solar energy requires storage of some of the energy until periods when the demand by the application exceeds the collector field's ability to produce energy. Thus, a primary role of thermal energy storage is to allow increased displacement of fossil fuel energy while maintaining high utilization of collected solar energy.

Several different constant demand profiles are examined in the handbook. The first demand profile is a constant, 24-hour-per-day, 365-day-per-year demand. This profile is evaluated in some detail since it is one of the more common industrial demand profiles, and many of its characteristics which influence conceptual design (e.g., the significance of a Maximum Displacement Point) appear in other types of demands. Discussion of the 24-hour-per-day, 365-day-per-year demand profile is followed by examination of constant thermal energy demands, which occur only during the daytime (8 am to 5 pm). This allows determination of a chart which shows the proper quantity of storage for demands of any duration longer than daytime-only. Design of solar thermal energy systems which service demands which shut down on weekends are also evaluated. A final section addresses the design of solar energy systems for servicing applications whose thermal demands are not constant throughout an entire day but can be considered as combinations of constant demands.

To allow conceptual design with these different demand profiles, design tools were developed which examine the effect of variations in collector area and storage capacity on the utilization of the collected solar energy given that the demand for thermal energy is some fixed constant energy requirement. Figure 4 illustrates the use of the concept of energy utilization with a 24-hour demand profile.

As shown in Figure 4, if nominal displacement is small (i.e., the ratio of collector field output to the application demand is small), it would be anticipated that the utilization of the collected solar energy would be near 100%. In other words, if the quantity of energy produced by the collector field is small compared to the demand, the application can accept any energy produced by the collector field and, as a result, all the solar derived energy is utilized in displacing the fossil energy normally used to meet the application's thermal energy demand. As the size of the collector field is increased, the utilization of the collected solar energy starts to decrease due to mismatches between the energy demand profile of the application and the energy supply profile of the solar collector field. Increasing the utilization of the collected solar energy requires storage.

As seen in Figure 4, the maximum demand displacement with near 100% utilization of the collected solar energy is about 80%. This requires storage of approximately 75% of the solar energy collected during the day. Increasing storage capacity beyond this does little to increase demand displacement beyond the 80% level. This is due to the seasonal variation of the output from an E/W solar collector in Albuquerque. Due to the greater seasonal variation in output of a N/S collector, a N/S oriented collector can displace only about 60% of a constant year-round demand without significant waste of the collected solar energy. Nomographs are presented in the handbook which allow choice of the most cost-effective collector area/storage capacity combination.

References

1. R. W. Harrigan, Handbook for the Conceptual Design of Parabolic Trough Solar Energy Systems - Process Heat Applications - NTIS Report No. SAND81-0763 (Sandia National Laboratories, Albuquerque, July 1981.

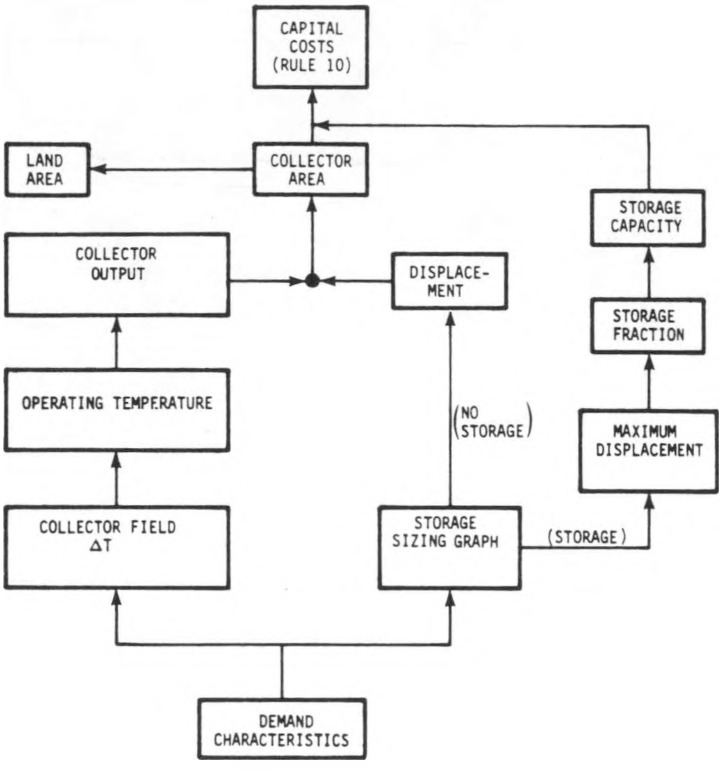

Figure 1. Logic Flow of Conceptual Design Process

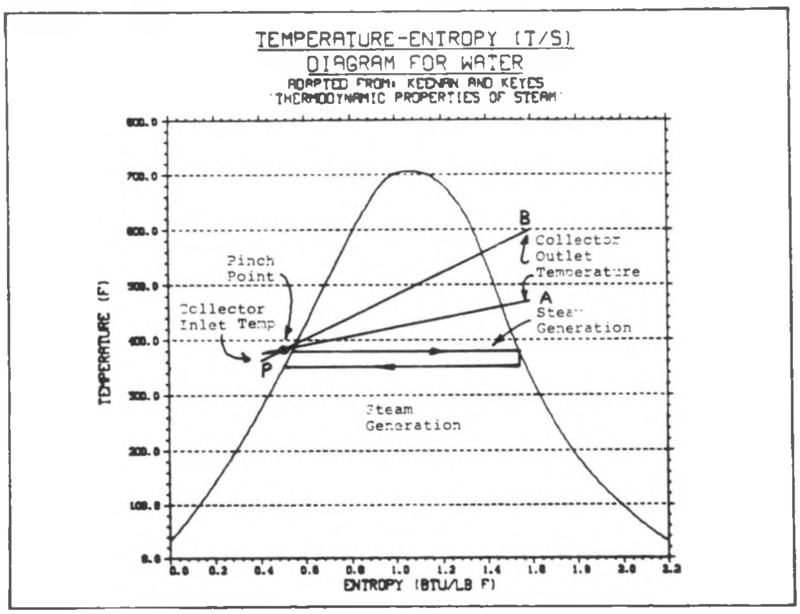

Figure 2. Temperature-Entropy (T/S) Diagram for Water

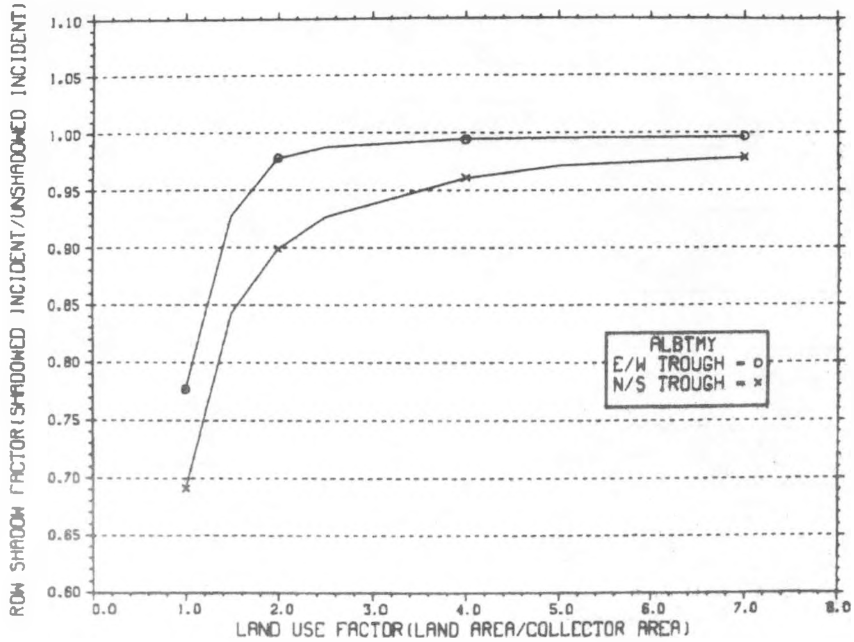

Figure 3. Shading of Annual Incident Direct Insolation

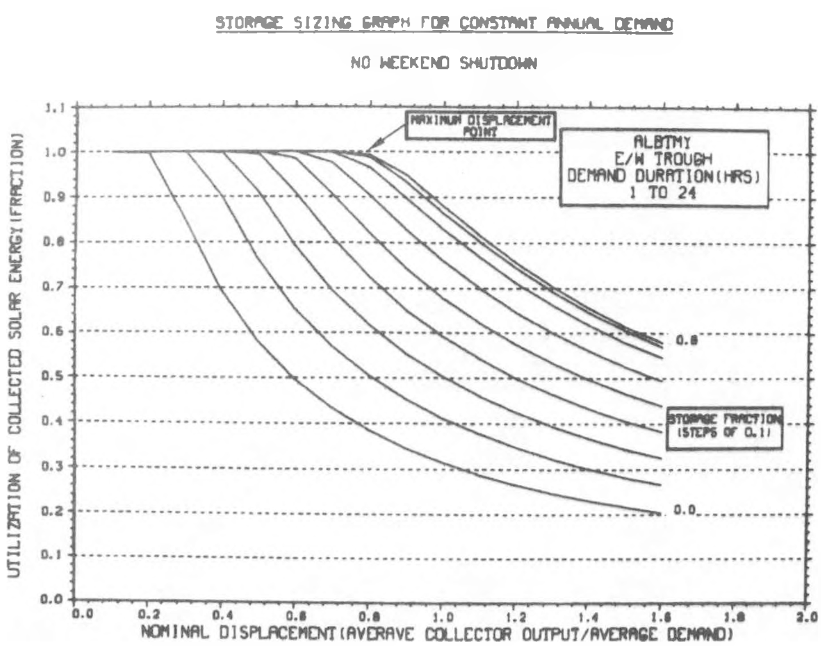

Figure 4. Storage Sizing Graph for E/W Trough--24 h/day

Performance Prototype Trough Test Results

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Introduction

The Performance Prototype Trough Development Project began in 1979 to apply information gained from the development of first-generation parabolic trough collectors. The goals were to improve peak performance to 60% (from the 40% to 50% achieved by first-generation troughs) and to improve durability and component life from less than 3 years to 20 years. First-generation designs did not lend themselves to mass production, a feature necessary for achieving low cost, so the new effort emphasized designs that use mass production materials and processes.

In 1980, an Engineering Prototype Trough which achieved 60% peak efficiency was developed. At the same time, different manufacturing concepts to adapt trough design to mass production processes were being investigated. Controls, drives, pylons, foundations, plating and four different basic structural designs were obtained from industry. Prototypes of the designs were fabricated from soft tooling and were tested. The final step in the Performance Prototype Trough Project was the assembly during FY82 of the four designs into 24-m (80-ft) drive strings, then integrating them in a ΔT string with a tracking and control system, and performing system tests.

System Description

The PPT system consists of four individual 80-ft long drive strings each designed so that the reflector structure fabrication is based on a different mass production technology. All other parts of the individual drive strings are identical. The four mass production technologies used for fabrication of the reflector structures are:

- Stamped Sheet Metal
- Sheet Molding Compound
- Sagged Glass/Steel Frame
- Honeycomb Sandwich

Prototypes of each reflector structure were fabricated and environmentally evaluated prior to fabrication of the PPT system.

Most of the critical components of the PPT collector system were fabricated by industrial sources. The primary role of SNLA was the specification, evaluation, integration and systems engineering of the industrially-fabricated components. Following is a list of the major component suppliers:

Reflector Structures Assembly	
Stamped Sheet Metal	Budd Co.
Sheet Molding Compound	Budd Co.
Sagged Glass/Steel Frame	Budd Co.
Honeycomb Sandwich	Parsons of California
Reflector Structure Mirrors	Corning Glass and Schott America Glass
Pylons	Bloomer-Fiske Inc.
Foundation	Applied Research Associates
Torque Tube	Budd Co.
Insulated Metal Hoses	Hydroflex Co.
Black Chrome Selective Coating	Highland Plating Co.
Drive	Cleveland Gear/Winsmith Inc.
System Control	Honeywell
Motor Control	Hampton Products Co.
Field Layout Design	Jacobs Engineering Group
Test Site Design	Black & Veatch Engineers
Wind Load Definition	Colorado State University
Receiver Glazing	Corning Glass Co.

Collector field layout studies during FY81 by the Jacobs Engineering Group resulted in a preliminary design for a 4645 m^2 (50,000 ft^2) parabolic trough collector field. The installation philosophy for the PPT collector test system was the installation of the system so that it would be representative of one of the ΔT strings in a complete 4645 m^2 field; particularly in the areas of pipe layout, electrical layout, foundations, control, and emergency power. Figure C82-1205 is a photo of the PPT collector ΔT string installed at the PPT test site. The ΔT string is 320 ft long and contains 192 m^2 of collector aperture area.

During the design of the PPT collector system, datums were incorporated to allow field assembly of all parts without a requirement for field adjustment to maximize performance. To evaluate this datum system the PPT collector was tested in the as-assembled condition.

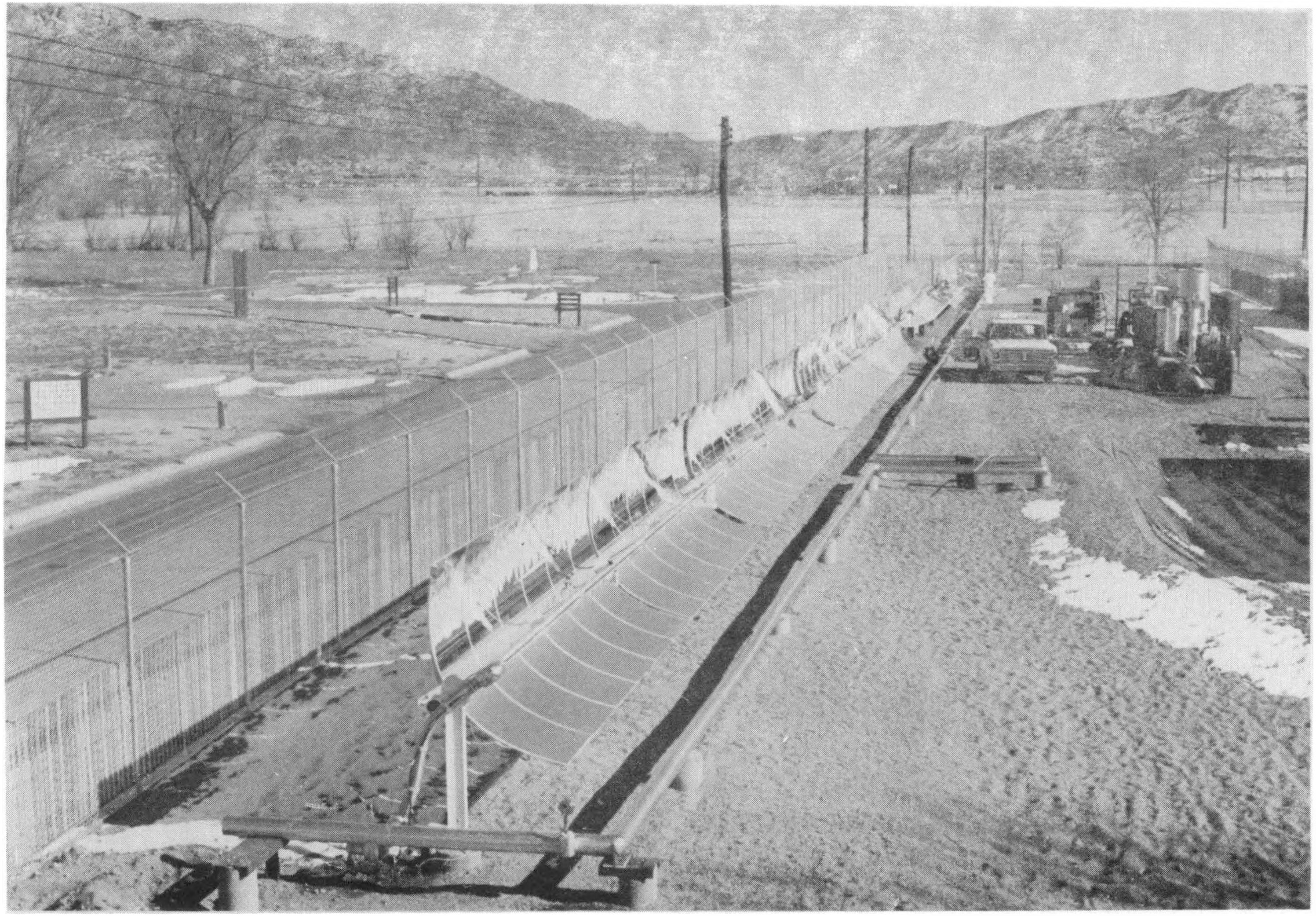
Test Results

Performance testing was conducted during FY82. Nominal design and test conditions for the PPT collector system were:

450°F input temperature
600°F output temperature
Therminol-66 heat transfer fluid
150°F temperature rise in 320 ft of active collector
E/W orientation
Antireflective receiver glazing; transmission = .98
Black chrome receiver; α = .97 ϵ = .25
2x96 meter active collector aperture
Mirror reflectivity = .93 $\longrightarrow$ .95

System testing was conducted in the following general areas:

- o Noontime Efficiency to 600°F
- o All-day Efficiency
  - Solstice
  - Equinox
- o Drive System Accuracy
- o Computer versus Shadow Band versus Integrating Wire Tracker
- o Automatic Control
  - fluid control
  - system software
  - emergency power
  - tracking
- o Best Focal Location
- o Receiver Tube Heat Loss to 600°F
- o Optimum Start Up/Shut Down Operating Philosophy
- o System Pressure Drop Tests



Production Prototype Trough
Collector Test Facility

A detailed presentation of the results is beyond the scope of this paper. Following is a selection of results which summarize the overall performance of the PPT system.

Table 1 presents the noontime system performance under nominal operating conditions.

Figure 1 presents the noontime efficiency versus operating temperature at a 1000 W/m^2 sun level for each individual 80-ft long drive string.

Table 2 presents the all-day performance for the system operating under typical process heat application conditions. The input temperature is constant at 350°F and the flow rate is held constant throughout the day resulting in a variable output temperature (flow rate calculated to nominally provide 500°F fluid at noon).

Table 3 presents the all-day performance for the system operating under constant output temperature conditions. Input temperature is 450°F and output temperature is 600°F. Flow rate is varied throughout the day to maintain a constant 600°F output. Testing was performed under equinox and solstice conditions.

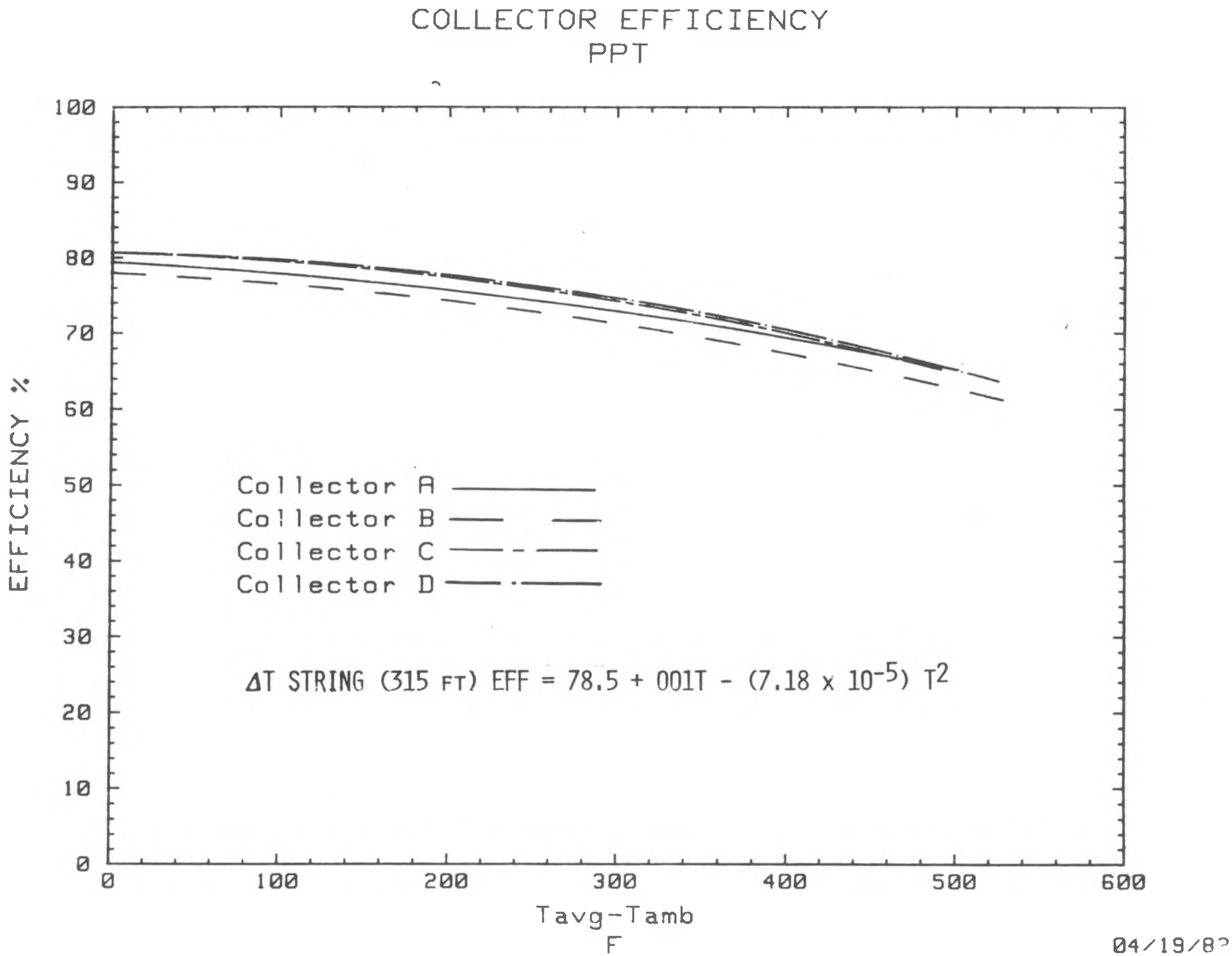


Figure 1. Efficiency vs Temperature, PPT Collector, E/W Orientation
Noon Efficiency at Solar Intensity of 1000 W/m^2

Table 1

Noontime Efficiency
PPT Collector

450°F in	600°F out	1000 W/m^2
Collector A (Sandwich)	67.3	450°F ⟶ 488°F
Collector B (SMC)	63.6	488°F ⟶ 525°F
Collector C (Glass/Truss)	65.3	525°F ⟶ 563°F
Collector D (Sheet Metal)	64.0	563°F ⟶ 600°F
Collector ABCD Average	65.1	450°F ⟶ 600°F
ΔT String Efficiency*	63.6	450°F ⟶ 600°F

*Includes losses of all flex hoses and lead in/out piping

Table 2

All-Day Performance (Equinox)
March 24, 1982
Constant Fluid Flow Rate Conditions
Solar Intensity at Noon = 1020 W/m^2

	Energy KW/hrs	Efficiency* %
Collector A (Sandwich)	224	64.9
Collector B (SMC)	213	61.3
Collector C (Glass/Truss)	212	61.0
Collector D (Sheet Metal)	211	60.7
Collector ABCD Average	860	61.9
ΔT String	835	60.1
Sun (Direct Normal Incident)	1799	--
Sun (Available to one-axis tracking E/W collector)	1390	--

*Efficiency based on 1390 KW/hrs available to PPT collector

Table 3

All-Day Performance
PPT Collector

	Spring Equinox 1982 $I_o = 1020\ W/m^2$		Summer Solstice 1982 $I_o = 920\ W/m^2$		Winter Solstice 1982 $I_o = 905\ W/m^2$	
	Energy KW/hrs	Efficiency[1] %	Energy KW/hrs	Efficiency[1] %	Energy KW/hrs	Efficiency[1] %
Collector A (Sandwich)	209	60.0	224	61.0	166	60.0
Collector B (SMC)	190	54.4	205	55.7	154	55.5
Collector C (Glass/Truss)	189	54.3	202	54.9	142	51.2
Collector D (Sheet Metal)	180	51.5	195	53.0	140	50.5
Collector ABCD Average	768	55.1	826	56.2	602	54.2
ΔT String[2]	743	53.2	796	54.2	579	52.2
Sun (Direct Normal Incident)	1842		1901		1280	
Sun (Available to E/W Collector)	1395		1470		1110	

1. Efficiency based on sun energy available to one-axis tracking E/W collector.

2. Includes losses of all flex hoses and ΔT string lead in/out piping.

3. I_o equals solar intensity at noon on day of test.

SESSION II

MISR SYSTEM & PLANT INTERFACE DESIGNS AND QUALIFICATION RESULTS

Session Chairman: J. A. Leonard

ACUREX MISR SYSTEM DESIGN AND APPLICATION

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Introduction

The Modular Industrial Solar Retrofit (MISR) project was established to develop a modular solar thermal line-focusing system which offers the industrial user a packaged system. A standardized system design offers proven reliability and performance, and reduced cost for the manufacturer. Acurex Corporation under contract to Sandia National Laboratories at Albuquerque (SNLA) has completed the design, construction, and evaluation test of a MISR system.

The system design uses 26,880 ft^2 of Acurex Model 3011 solar collectors to generate up to 5,450 lb/hr of steam at 250 psig in an unfired steam generator. System control is entirely automatic allowing unattended operation. The system components are packaged on two equipment skids with modularity also exhibited in the collector field. The Qualification Test System (QTS) installed at Sandia (figure 1) successfully demonstrated the modular concept, and provided a test bed for performance and reliability evaluation.

Two potential applications for the Acurex MISR system design were studied: Formica Corporation, Sunset/Whitney Ranch, California, and Lang & Gangnes Corporation, White City, Oregon. Engineering analyses of the mechanical, civil, electrical, and control interfaces for each plant indicated that both sites would be viable for the installation and operation of a solar system. A plot plan and interface drawings were generated to show the layout of the solar equipment at the sites.

MISR System Description

Process Description

The system configuration is illustrated in the process flow diagram, figure 2. Heat transfer oil is circulated through the collector field at a constant flowrate of 120 gpm. The heated oil from the collector field circulates through an unfired steam generator producing steam, and then passes through a feedwater heater. A centrifugal pump returns the oil to the collector field to be reheated. An expansion tank just upstream of the pump accommodates thermal expansion of the oil and provides the pump with the required net positive suction head. This tank also provides a convenient location for monitoring the oil level in the system and adding makeup oil if required.

Pressurized boiler feedwater is provided to the system at 300 psig, 230°F. The feedwater heater preheats the water as high as 404°F before it is sent to the steam generator. A level controller in the steam generator regulates feedwater flow with a level control valve. The steaming rate varies with the solar insolation level. Pressure in the steam generator matches the steam supply header, with a check valve provided to prevent backflow.

The system design includes all instrumentation and control hardware required for safe operation. A master control panel is provided with indicators and alarms to monitor system operation. An emergency power generator, fire protection system, and collector washing equipment are also provided. Table 1 summarizes the major equipment characteristics.

The system has a peak design output of 5,450 lb/hr of 250-psig saturated steam at an insolation level of 1,000 W/m^2. At these conditions, the oil temperature into the collector field is 394°F, with a 580°F outlet temperature. Each of the eight parallel ΔT strings has the same approximate flowrate (15 gpm) and temperature rise, varying slightly along the pipe manifold.

Collector Field

The collector field consists of 32 Acurex Model 3011 concentrating solar collector groups, as shown in figure 3. The Model 3011 collector is a reflecting parabolic trough with a glass reflector and a black-chrome-coated receiver tube inside a borosilicate glazing tube. Each reflector module has a 90° rim angle with a 7-ft wide aperture and is 20 ft long. A collector group has six modules bolted together, a single sun tracker, and an electromechanical drive located at the center of the group.

The 32 collector groups are arranged in eight parallel ΔT strings, with four collector groups per ΔT string. This collector field layout is the standard MISR design, but modularity and flexibility are inherent to the collector field design. The ΔT string is the basic building block with further flexibility provided by the collector group. This allows the collector field configuration to be easily tailored to the process condition, system size, or land constraints.

Equipment Skids

Most of the system components are assembled on the two equipment skids. The steam generator skid contains the unfired steam generator, feedwater heater and associated feedwater controls, instrumentation, and piping. Mounted on the main equipment skid are the oil pump, expansion tank, master controller, electric distribution equipment, emergency power generator, fire protection system, and associated piping and wiring. These equipment skids are an important part of the modular system concept. Individual components can be installed, checked out, and integrated at the factory. This reduces field installation time and minimizes expensive field labor. Standardizing the equipment skid reduces recurring engineering costs because new applications require only minor modifications to the existing design.

Operation and Control

The system will operate completely automatically with no operator intervention required under normal conditions. The master controller continuously monitors operating conditions to ensure safe operation. Before the system can start up, the master controller first checks all lockout conditions (e.g., loss of electric power or fire protection system discharged) and the system permissive signals such as safe wind speed or steam load present.

When adequate insolation is present, the master controller starts the collector field pump and instructs the collector groups to track the sun. The oil is heated by the collector field and circulates through the steam generator which heats up and then produces steam. Steam generation continues through the day varying with insolation level. Upon loss of insolation, the master controller instructs the collectors to maintain their present positions and stop the pump. The system will start up again when sufficient insolation returns, or will stow the collectors and place the system in a safe shutdown if insolation does not return after a user-selected interval.

The absence of a system permissive signal will shut down the system until the condition clears, at which time the master controller will initiate the startup sequence. When a lockout condition exists, the system will automatically shut down, sound an alarm, and remain locked out until the master controller is manually reset.

Manual operation of the collector field and pump can be initiated at the master controller. Local control of each collector group is possible using the group control box located at each collector drive. The emergency power generator, fire protection subsystem, and feedwater level control subsystem can also be manually operated or tested using controls located on the equipment skids.

Interface Designs

Formica Corporation

The Sierra Plant at Sunset/Whitney Ranch, California manufactures a full line of Formica products. Steam is used for process heating and steam presses. The steam load fluctuates between 50,000 and 25,000 lb/hr due to the cycling of the presses. The average load is 35,000 lb/hr at 210 psig, 390°F. The MISR system output can be easily integrated into current plant operating procedures to supplement the existing boilers.

Collector field siting at the Sierra Plant utilized a large plot of available land adjacent to the plant boundary near the boiler house. The main equipment skid is located at the collector field and the steam generator skid is located inside the waste incinerator building. The piping and conduit routing to the boiler house required some trenching under an existing road. The balance of the runs were abovegrade and used new or existing pipe racks. There were no difficulties interfacing with any of the process lines, electrical, or control functions.

Lang & Gangnes Corporation

The Med-Ply plant in White City, Oregon, produces plywood and uses process steam to dry the wood when it enters the plant. Steam load varies from 45,000 to 60,000 lb/hr of saturated steam at 285 psig, 417°F. The waste wood from the plant is used to fuel a 35,000-lb/hr boiler. The balance of the plant load is provided by a natural gas boiler. The steam produced by the MISR system is easily accommodated by turning down the gas-fired boiler.

The collector site for the Med-Ply Plant was on adjacent property, but was not an ideal site. The available land was smaller than required for a full MISR system. Consequently one ΔT string was eliminated, reducing the collector area to 23,520 ft^2, and derating output to 4,750 lb/hr. The other difficulty was a railroad siding between the plant and collector field which had to be bridged. A pipe bridge posed no technical problems, but was more costly and required approval of the local railroad.

The main equipment skid will be located at the collector field, with the steam generator skid inside the plant. The piping, electrical, and instrumentation interfaces are straightforward.

Conclusions

The modular concept of the MISR system greatly simplifies the design process. Interfaces are limited to steam, feedwater, blowdown, drain, electrical power, and an on/off switch in the plant control room. Discussions with plant personnel emphasized plant operation, to ensure that the solar system would not interfere with current boiler operations.

Despite the similarities of sites, variables will be encountered, particularly in the area of equipment skid layout and collector field layout. This does not affect system design, just the pipe and conduit routing that is engineered on a site-specific basis. The Med-Ply Plant's land availability problem exhibited the usefulness of the inherent modularity of a solar collector field.

In summary, both sites proved to be technically viable for installation of a MISR solar system. Modular equipment skids minimize recurring engineering costs and reduce the impact on plant operation during installation of the solar system.

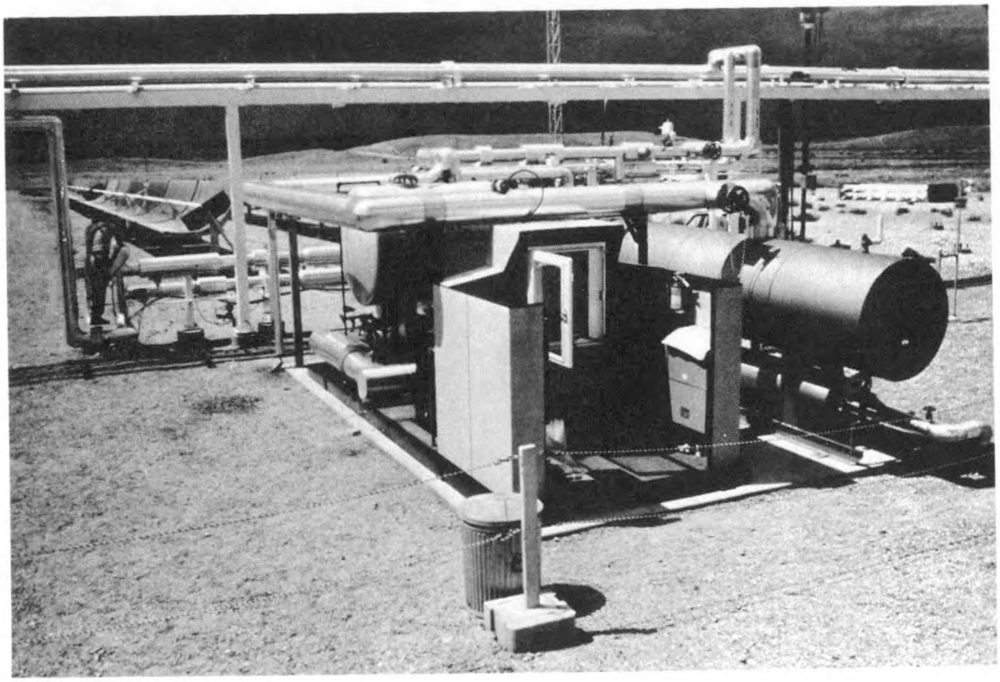

Figure 1. MISR Qualification Test System

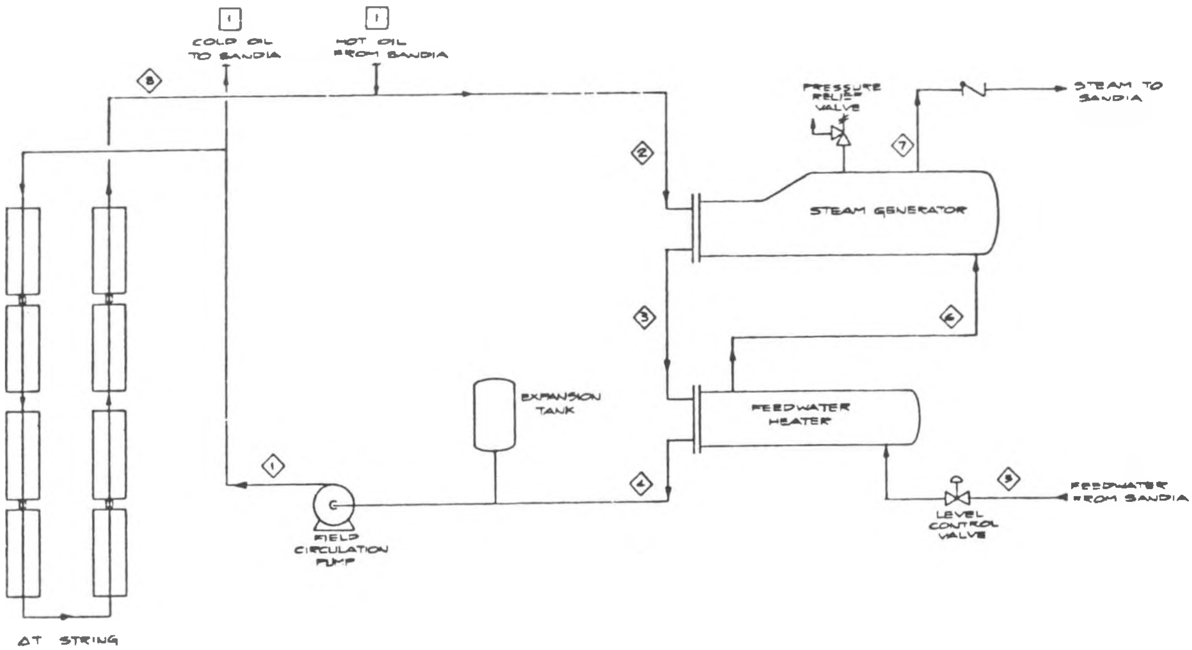

Figure 2. Process Flow Diagram

Table 1. Major Equipment Summary

Collectors	Acurex Corporation, Model 3011 Line focusing parabolic trough Glass reflector 26,880 ft^2 aperture area
Expansion Tank	Saracco Tank Co. Atmospheric API 650 625 gal
Unfired Steam Generator	Patterson-Kelley Co. Kettle type boiler 5,500 lb/hr, 4.5 million Btu/hr 250 psig (406°F) saturated steam
Collector Field Pump	SIHI, Inc., Model ZTNA-4020AN Centrifugal 120 gpm at 180 ft 15 hp motor
Feedwater Heater	Patterson-Kelley Co. Shell and tube, two-pass 0.85 million Btu/hr
Emergency Power Generator	Onan, Model 15.0RJC-10R 15 kW Gasoline

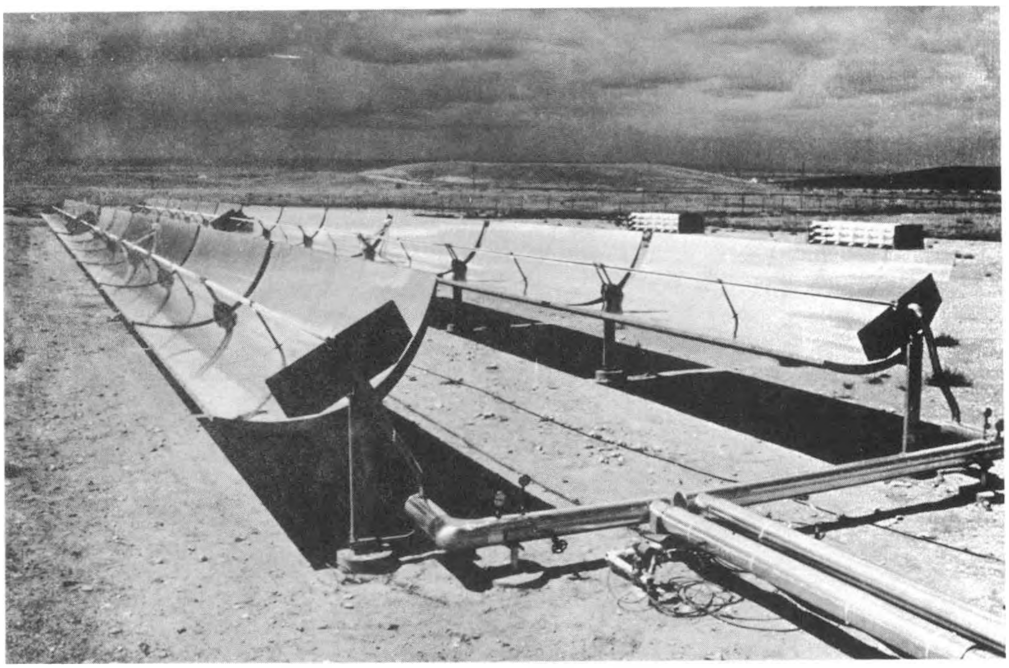

Figure 3. MISR Collector ΔT String

SOME REMARKS REGARDING SYSTEM QUALIFICATION TESTS AND RESULTS

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ABSTRACT

The goal of the MISR project is to assist solar system suppliers in the design, fabrication, and installation of modular line-focus solar thermal systems. These systems were evaluated to assist both the suppliers and potential buyers in removing any first-of-a-kind design problems as well as to determine how well they operated. Many of the evaluation items common to all the MISR systems are discussed in this paper.

INTRODUCTION

The goal of the MISR project is to assist five competitively selected solar system suppliers in the design, manufacture, and installation of a modular design solar thermal system. The modular design has the potential of reducing design and manufacturing costs of follow-on systems, reducing first-of-a-kind design problems, and increasing operational reliability. The first-of-a-kind designs were manufactured, installed at DOE sites, and evaluated. The objectives of this effort were to detect design problems and allow the designers to correct them, and to obtain operational and performance experience for designers and potential system buyers. This paper describes the methods used to evaluate the designs and the results obtained.

DESCRIPTION OF TEST SYSTEM

Due to project cost and schedule considerations, only minimum hardware systems representative of the full MISR designs were evaluated. For each of the five MISR designs, the qualification test system (QTS) consisted of a full complement of equipment with the exception that the solar collector field consisted of only one delta temperature collector loop. A propane fired heater simulated the balance of collector field. The heat transfer fluid (HTF) flows were proportioned as designed and a 3-way mixing valve allowed the balance of field simulator to follow the outlet temperature of the delta temperature collector loop. The QTS and the associated site equipment is shown in Figure 1. Conditioned feedwater and electrical power are supplied to the QTS, and pressure regulated steam is received from the QTS, condensed, and returned to the steam generator.

Suppliers installed the QTSs, checked them out, and trained site operators before turning the systems over for evaluation. The Foster Wheeler design was evaluated at SERI and the others were evaluated at SNLA. The SERI site is shown in Figure 2, the SNLA site in Figure 3. Each site was functionally identical to the description given in Figure 1. The data acquisition and data reduction systems were HP 9845 computers and the method for data reduction were identical. Only the effect of the different environments at the two locations should affect the data. This difference is small.

INSTRUMENTATION

The specific instrumentations used in the QTS evaluation were:

Type of Measurement	Instrument
Direct insolation	Epley Pyroheliometer
Pressure	Rosemont
Flow	Square edge orifice plate meters
Temperature	RTD's except for thermocouple in the steam line
Collector Tracking Angle	Inclinometer
Electric Power	Watt Transducers

Each instrument was checked before installation to determine the correct parameters to be used in data reduction. The accuracy goals are 5% on flow, 1% on temperature, 1% on insolation, and $\pm$ 0.03 degree on tracking. No errors due to the use of two separate sites were introduced because the data acquisition and data reduction methods were identical.

EVALUATION METHOD

The test sequence shown in Figure 4, was followed for each QTS. This test sequence was initiated after the system designer had installed, checked the system out, and trained the site operators in its operation and routine maintenance. The test sequence indicates that some tests may be repeated if satisfactory results were not obtained. These possible repeat tests represent design requirements. It should be noted that system performance is not a design requirement. It is the ratio of performance to cost that is important and cost data is only available from the system seller.

The function tests determine whether the required functions were incorporated into the designs and how the system responded to out-of-limit operating conditions. The satisfactory response for each is "fail safe." The safe condition for a MISR system is when the solar collectors are in their stow position and all other equipment is powered down. In each of the following situations the system must respond by the safe condition:

- Steam pressure is too high
- Low HTF flow
- Water level in steam generator too high or too low
- HTF at too high a temperature
- HTF level in expansion tank too low
- Loss of utility AC power
- Wind speed too high
- Insufficient insolation
- A fire is detected
- No steam generation desired

In addition, each collector delta temperature loop must safe itself if an over temperature in the receiver is detected. Each function is tested by simulating the out-of-limits condition or causing an out-of-limits to occur and observing the QTS response. The response must be a satisfactory one or the QTS is given back to the supplier for modification.

The 2-week continuous operation test determines if the system is capable of automatic operation with only routine maintenance being required. Of these 14 days, 7 days must have at least 4 kW/m^2 isolation each. Any repair or unscheduled maintenance required was performed by the system designer and the test was restarted.

The life test consisted of driving the solar collectors from the stow position to the maximum rotation angle and back 3000 times. This number of cycles is believed to be sufficient to find any design problems that exist. These tests were performed at near operating temperature.

The survival tests consisted of loading the collectors to the torque predicted for maximum design wind speed. Freezing weather is another survival test. These tests are scheduled last because of possible equipment damage.

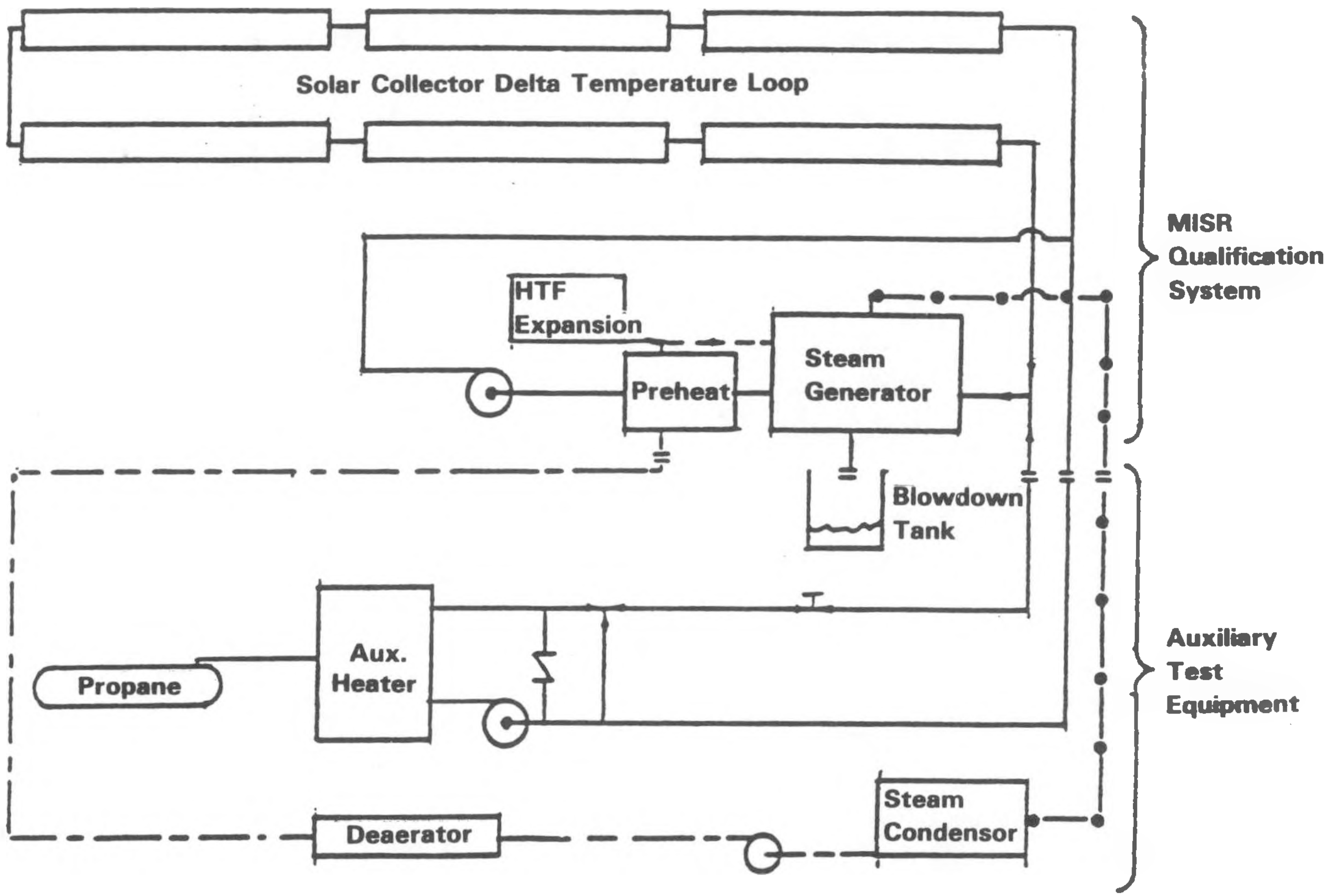
CONCLUSION

Essentially side by side evaluation of the MISR systems have been attempted. The evaluation is incomplete at this time, and I apologize for it. A final evaluation report will be prepared and should be available around July 1983. Caution is urged in comparing the different system data that will subsequently be presented. First, the evaluation is incomplete and the unavailable data may contain significant information. Secondly, a direct comparison of test results without system cost information can be misleading. Cost information is only available from the system suppliers. Problems will be discussed as the evaluation purpose was to discover them before they reached industrial use. Each problem will be corrected before the evaluation is satisfactorily completed. In general, the systems are more simple in design, yet more functionally capable than past systems.

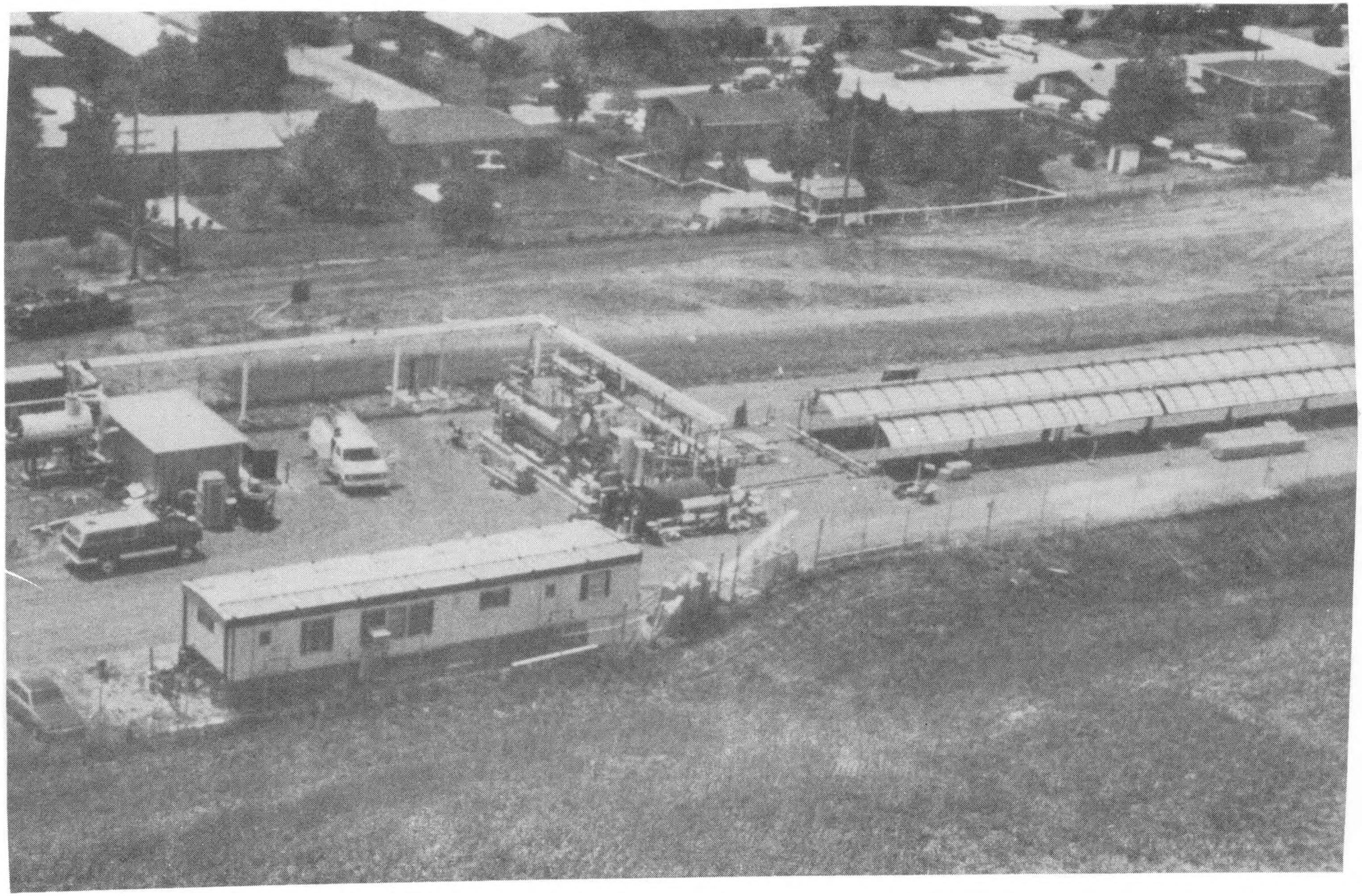
ACKNOWLEDGEMENT

A number of organizations and people have made significant contributions to this evaluation effort. Some are:

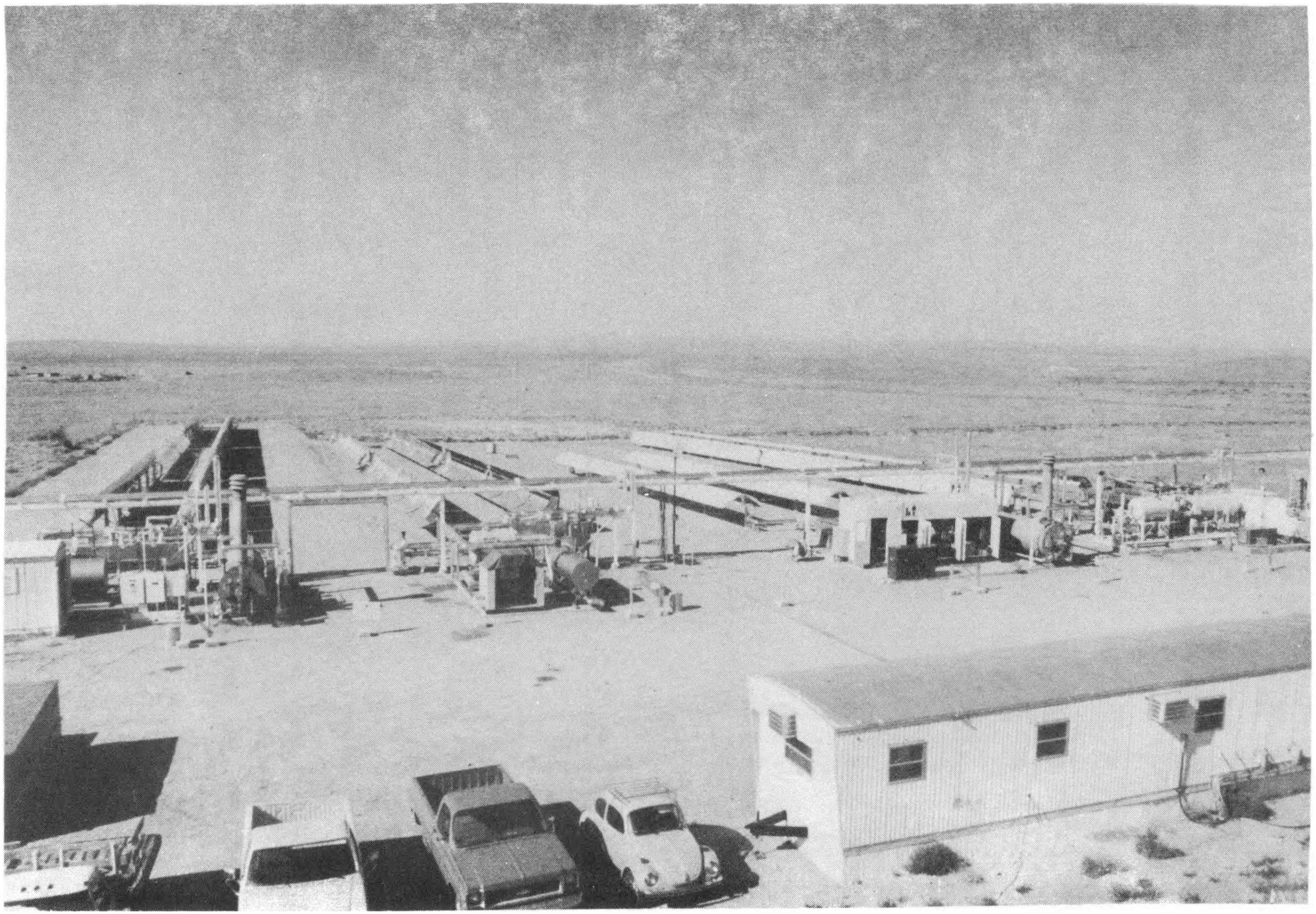
- SERI and A. Lewandowski
- Black & Veatch and B. Blesser
- EG&G, W. Einhorn and V. Dudley
- Several members of SNLA CRTF Division



MISR QUALIFICATION TEST SYSTEM
Figure 1



SERI MISR TEST SITE
Figure 2



SNLA MISR TEST SITE
Figure 3

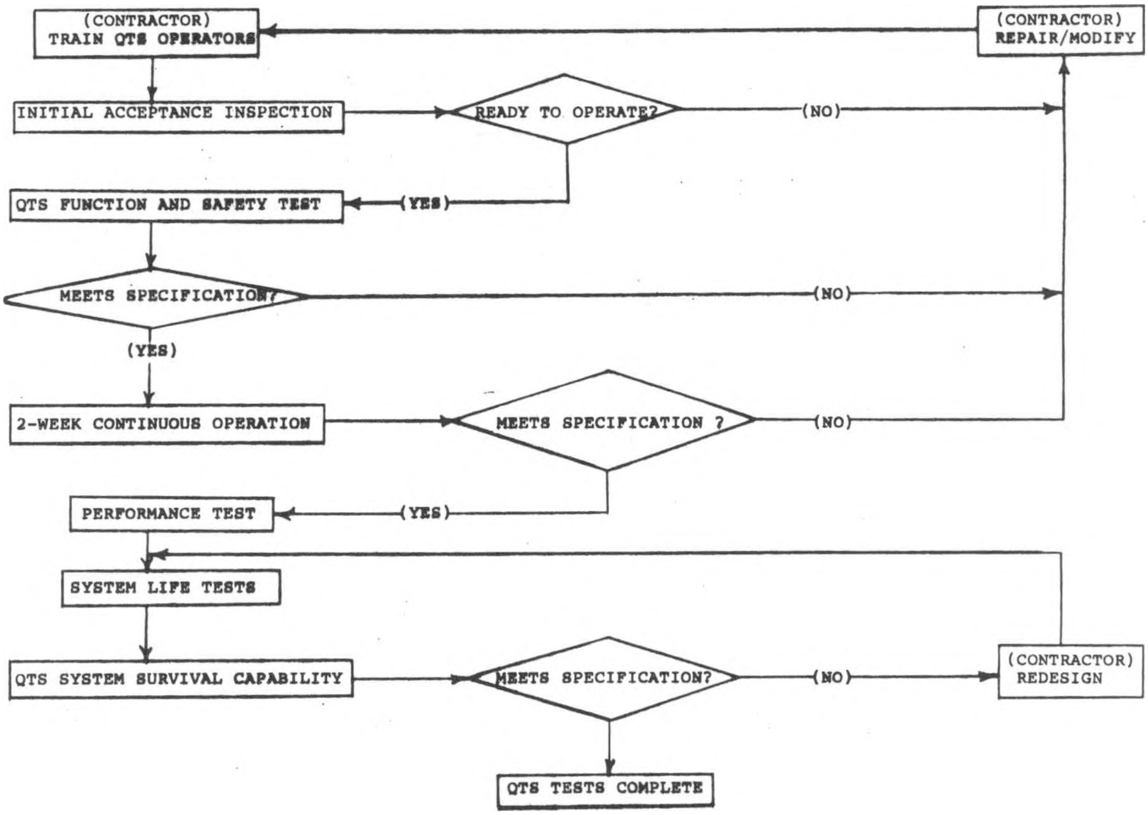


Figure 4 - Evaluation Test Sequence

ACUREX SOLAR CORPORATION
MISR System Qualification Results

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ABSTRACT

The Acurex Solar Corporation was one of five companies selected to design a Modular Industrial Solar Retrofit (MISR) system and to install at Sandia National Laboratories a minimum hardware system representative of a full modular design. Acurex installed and checked out the system at the MISR test park and then turned over the Qualification Test System (QTS) to Sandia Laboratories for testing and evaluation. The testing and evaluation consisted of testing the system to determine if the design requirements were satisfied, its operational characteristics and performance, and its long life operating capability. This paper presents the available evaluation results for the Acurex MISR design.

ACUREX SOLAR CORPORATION - MISR
SYSTEM QUALIFICATION RESULTS

QTS DESCRIPTION

The Qualification Test System (QTS) includes a full-size MISR equipment skid and one of the eight delta-temperature solar collector loops that would be in a full-size 2498m^2 (26,860 ft^2) MISR system. In the qualification testing, the remainder of the collector field was simulated by a propane-fired oil heater which is referred to as the balance-of-field simulator. Seven-eights of the flow from the MISR system flows through the balance-of-field simulator and is heated to the same temperature as the outlet of the Delta-T solar collector loop. The QTS is shown in Figure 1.

The Acurex MISR system is designed to use an organic heat transfer fluid. For the QTS Caloria HT-43 was used. The HTF is circulated at a constant flow rate. After being heated by the solar collectors, the HTF is piped to the tube bundle of an unfired steam generator and then past the expansion tank to a 11kW (15 hp) centrifugal pump and back again to the collector field. Feedwater is supplied to the steam generator through a proportional pneumatically-operated valve that is controlled by the level controller on the steam generator. The steam is generated and flows through a check valve to an existing plant steam line.

The solar collectors, Shown in Figure 2, used at the QTS are four 36m (120 ft) drive groups manufactured by Acurex Solar Corporation. These collectors use a thin glass silvered mirror - sheet metal laminate mirror assembly. The glass/metal laminated are edge clamped onto the collector module frame of a galvanized torque tube and ribs structure. The Acurex receiver assembly consists of a 6m (20 ft) long, black chrome steel tube inside of an anti-reflective coated glass tube. The receiver sections are joined together using a Swagelo k type tube connector. The receiver assembly is then connected to the HTF piping with a braided stainless steel flex hose. The flex hose has a strip-wound stainless steel outer jacket to limit the radius of curvature and to protect fiberglass insulation from the weather.

Collector tracking is by an Acurex designed tracking head that is mounted on the collectors at each drive pylon. A light sensor detector, the Solar Tracking Angle Reference (STAR), is mounted on an adjacent weather tower. The STAR senses direct sun insolation and sun position. This position information is used by the collector control to coarsely position the collectors sun position. The tracking head then assumes control for fine tracking.

The sensors in the STAR are long photocells that are oriented in the same direction as the collectors. At the test site, the collector orientation is east-west. The long cells cause the output to depend on incident angle as well as direct normal insolation, and thus is closely related to potential collector thermal output. A setpoint of 300 W/m^2 at normal incidence (solar noon for an east-west field) is equivalent to about 470 W/m^2 at a 50° incident angle.

The Acurex collector design has a very useful function that allows the collectors to de-steer 5° from focus. The collectors will always de-steer when the tracker sees the sun unless the master controller is sending an auto-track signal that indicates HTF flow through the collectors. Any other scenario will de-steer the collectors, including overdriving the manual position if left inadvertently in focus. The de-steer function allows the HTF circulating pump to be shut down two minutes after a cloud covers the light sensor. This saves considerable heat loss from the system and pump power that would occur if the circulating pump was left on until the collectors are stowed.

The Acurex method of connecting the expansion tank to the HTF pump suction piping is unique in that only small, rather than full-size piping and valves are required. A 1.9 cm (0.75 in.) gas vent pipe from an expanded section of piping near the pump inlet allows gasses to escape to the top of the expansion tank before entering the pump suction. A 3.8 cm (1.5 in) liquid line connects the bottom of this section to a standpipe in the expansion tank, and allows thermal expansion of HTF into the expansion tank without providing a large conduction path for loss of heat. The standpipe prevents water that collects in the bottom of the expansion tank from being drawn back into the circulating HTF. The vent line provides for removal of entrained gasses both during start-up and normal operation. There is no requirement for flowing through the expansion tank, thus minimizing system heat loss.

A separate, gasoline fueled, motor generator serves as an emergency backup electrical power system. In the event utility power is lost the emergency generator automatically supplies power to stow the collectors.

Unique Design Features

The Acurex MISR design has several unique design features. The main ones are briefly described below.

Two Skid Design - The design incorporates two skids, Shown in Figure 3. One consists of the steam generator with its associated controls and accessories. It was manufactured by Patterson-Kelly and drop shipped to the site. The second skid contains the HTF circulation pump, HTF expansion tank, electrical switchgear, master control panel, and emergency generator. This design approach allows the steam generator to be installed in or next to an existing boiler house with the equipment skid being next to the collector field. They may also be installed side by side as they are at the MISR test site. The skid design is flexible and can be easily resized for different applications.

HTF Pump - The HTF circulation pump is designed in such a way that can use a Viton seal rather than a more expensive metal seal. This is accomplished by extending the pump shaft to a distance that the Viton labyrinth seal is sufficiently self cooled. The design also reduces the risk of catastrophic seal failure. It has performed without any problems during the evaluation.

Microprocessor Control System - The control system is built around the Master Controller, a product proprietary to Acurex, which furnishes ample system status information to the operator. At a glance one can learn the status, if any subsystem is out of limits, and if it is caused by the environment or is strictly system related.

Self Purging System for vapors in the HTF - The design incorporates an expanded section in the HTF pipe that allows the entrained vapors to be collected and vented to the expansion tank. This is a simple system that operates all the time the system is running to purge itself of air or vapors from the HTF fluid.

QTS FUNCTIONS

The Acurex master controller monitors insolation, wind speed, and system safety status. The system will start the HTF pump and rotate the collectors out of stow after 2.5 minutes of adequate insolation. Forty seconds is allowed to achieve adequate HTF flow. When insolation falls below the set point of the STAR for two minutes, the pump is shut down and the collectors are placed in de-steer. After 2.5 minutes of adequate insolation again, the system will automatically restart. If adequate insolation does not occur within thirty minutes, the collectors are stowed. These times are all field adjustable.

The master controller also allows the collectors to be placed in manual hold, manual de-steer, or wash position. There is also a manual position control with which the collectors can be oriented to any position by setting a control knob on the control panel to the same position. In this manual mode, the collectors will automatically stow in case of high wind or will de-steer if they should approach focus. This control is also used to position the collectors for rain-wash.

EVALUATION RESULTS

The QTS was accepted for testing in November, 1982. The first set of tests to be performed were function and safety tests. The purpose of these tests was to determine that all safety systems operated as designed and that the system was fully operational. In as much as practical, all operating configurations were examined to determine how the system responded in all cases. During these tests, it was found that the low flow switch malfunctioned, was replaced and the 2-week unattended operation test was initiated. This test requires a minimum of two weeks continuous automatic, unattended operation. The test site was set up to simulate a plant with a 1.7 MPa (250 psig) steam main and the balance of field simulator was operated as described earlier. No maintenance of the QTS system, other than scheduled maintenance, was allowed. During the first day of this test, the feedwater check valve jammed closed and had to be disassembled and repaired. Subsequently, a collector control cable snagged on a portion of the drive and had to be repaired. Because of these maintenance items, the two week test was restarted. A minimum of seven days of total insolation above 4 kWh/m^2 (1272 Btu/ft^2) per day was required during the test period or it was to be extended as long as was necessary. Due to inclement weather, twenty-three days were required to complete this test. The system successfully completed this test.

Life cycle tests are being performed on each QTS to evaluate the life of collector components, in particular the drive systems and flexible hoses. During this test, the collectors are cycled from stow to the north horizon and back with stops at six angles in between in each direction. One complete cycle requires about forty minutes with the drive system operating at a fifty percent duty cycle.

During the first twenty-four hours of life cycling, the elbows on the receiver end of two flexible hoses were bent. Subsequent investigation showed that when the collectors were driven to their limit at the north horizon, the radius-limiting strip-wound cover of the flexible hose had exceeded its limit in its S-shaped configuration and was causing the elbows to be bent. These two flexible hoses were replaced and the collector rotation was limited to ten degrees above the north horizon which is adequate and within the design requirement for tracking even in a north-south field. During subsequent life cycling, another control cable snagged and now requires replacement. However, at this writing, the other three collector drive groups have completed 499 cycles without incident.

The QTS evaluation is near completion. The design contains many state-of-the-art subsystems and several unique features. Some first-of-a-kind problems have been discovered, but one of the purposes of the MISR evaluation was to find them. Solutions have been found. The control system and solar collector design are believed to be exceptionally good. The system design is clean and is a good example of state-of-the-art line-focus system technology.

PERFORMANCE

Performance measurements are being made on each QTS. Normal incidence efficiency measurements are being made at inlet temperatures from 121 to 204° C (250 to 400° F) corresponding to steam pressures of .4 to 1.7 MPa (67 to 250 psig). Thermal loss measurements are being made over the same temperature range with the collector oriented towards the clear north sky so that the reciever is shaded by the collector. Measurement of incident angle modifiers and peak noon efficiency at ambient temperature are being made using tap water as a once-through heat transfer fluid. The heat capacity of the mechanical equipment skids and collectors are being determined by heating them as rapidly as possible from ambient with the balance of field simulator while measuring the heat required. Thermal efficiency of the mechanical equipment skids, overnight cooldown and parasitic electrical use are also being measured.

The measurements completed to date are summarized in Table 1. The preliminary values obtained, when compared to line-focus technology status, appear to be very good. These basic parameters may be used to project performance of the system in various applications. Such simulations as well as the results of the uncompleted measurements and life cycle tests will be included in the final MISR project report.

TABLE 1

PERFORMANCE RESULTS*

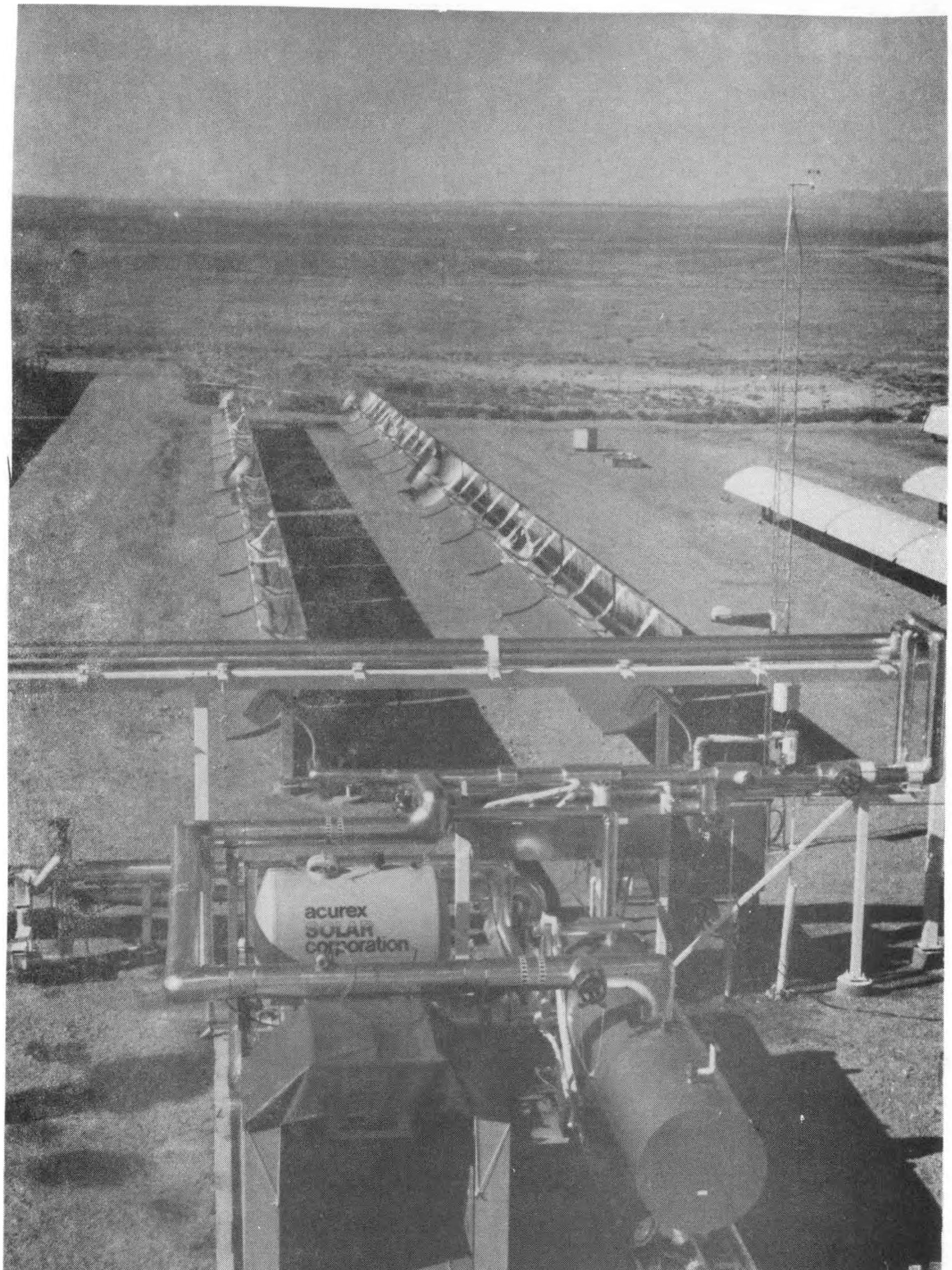
Collector Efficiency at Normal Incidence

Average Temperature (°C)	Average Temperature (°F)	Ambient Temperature (°C)	Ambient Temperature (°F)	Direct Normal Insolation (W/m^2)	Direct Normal Insolation ($BTU/hr-ft^2$)	Efficiency (%)
248	478	8	47	949	301	68
212	413	3	37	867	275	70
197	387	0	32	890	282	71
175	348	8	47	934	296	73

Collector Heat Loss

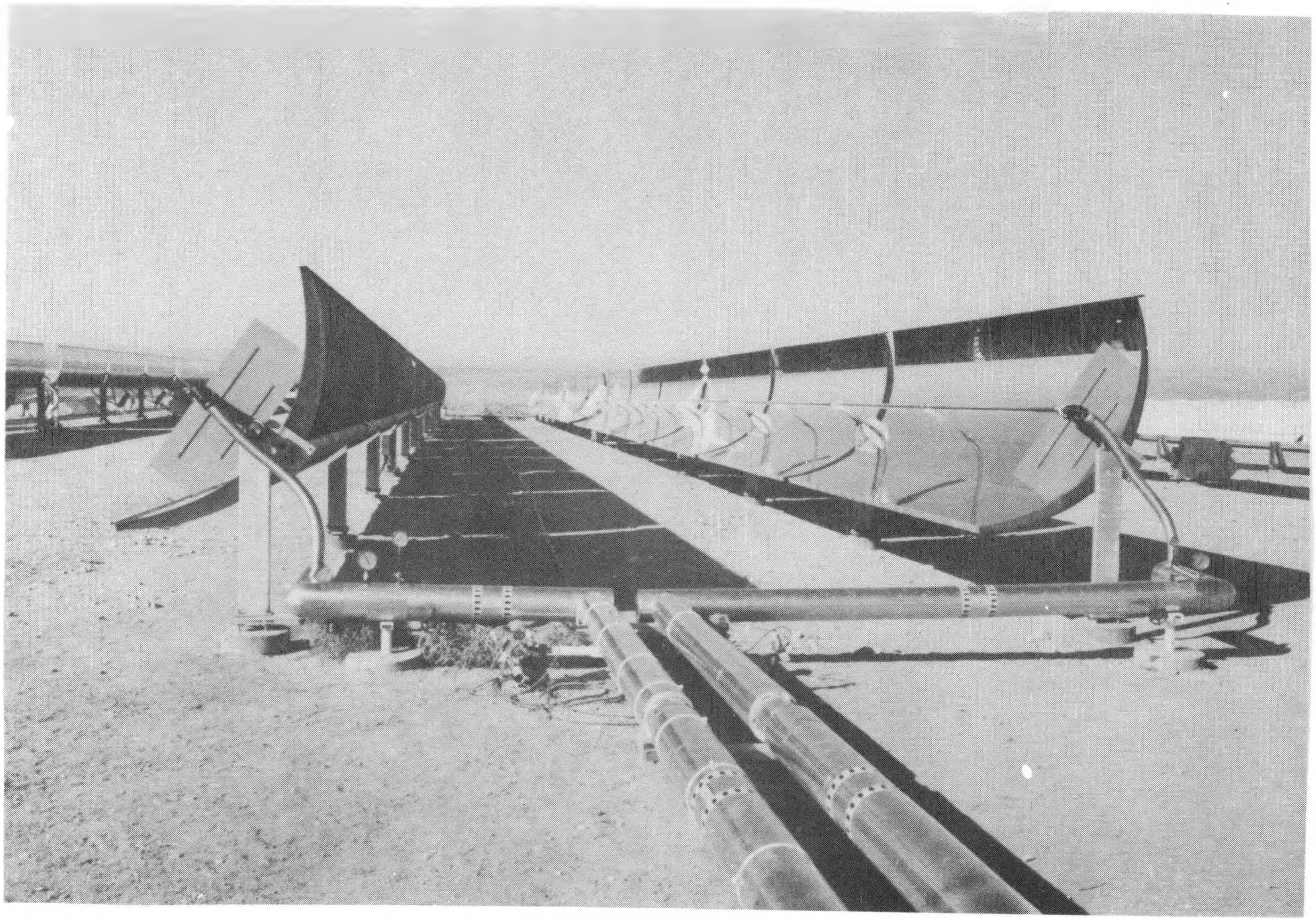
Average Temperature (°C)	Average Temperature (°F)	Ambient Temperature (°C)	Ambient Temperature (°F)	Wind Speed (m/s)	Wind Speed (mph)	Heat Loss (W/m^2)	Heat Loss ($BTU/hr-ft^2$)
280	536	10	49	5	11	132	42
195	384	11	51	2	4	69	22
170	337	9	48	5	11	53	17
167	332	5	40	1	3	53	17
147	297	3	37	1	3	44	14
120	249	12	53	2	5	32	10
69	156	1	34	3	7	17	5

*Collector efficiency and heat loss were measured from the inlet to outlet of the delta temperature loop; thus, heat loss from the flexible hoses and and interconnecting piping are included.

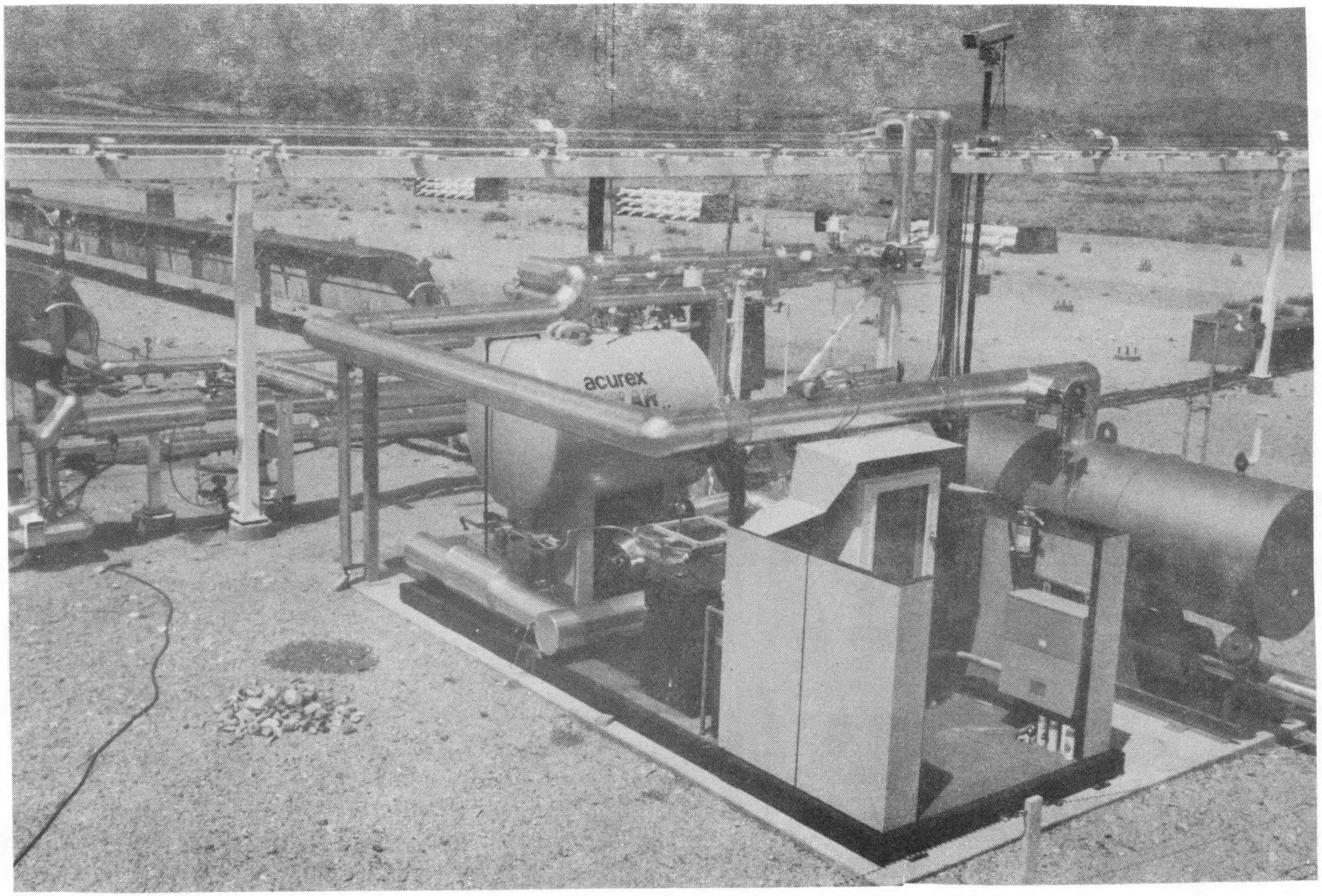


ACUREX MISR QUALIFICATION TEST SYSTEM

Figure 1



ACUREX COLLECTORS
Figure 2



ACUREX MISR EQUIPMENT SKIDS
Figure 3

TIM REYNOLDS
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MISR SYSTEM DESIGN

A. CONCEPT SUMMARY

BDM has designed a MISR system that is cost-effective and reliable using standard commercial products with emphasis on standard fabrication and installation techniques. This design is based on experience gained by BDM in previous solar IPH programs.

The BDM MISR design is a packaged, augmentary solar industrial steam generator featuring automatic or manual override control of the constant flow, modular array field, and mechanical and electrical skids. The MISR contains 25,200 square feet of Solar Kinetics T-700 linear parabolic trough collectors. The collector field is configured in five delta-T loops each containing 36 T-700 collectors and totaling 5,040 square feet. End manifolding is provided as the most cost-effective and functional piping configuration. The BDM MISR system can be configured in either north/south, east/west or intermediate orientations, depending on the profile of the demand and other site specific constraints. The mechanical skid contains an expansion tank, pump, fire protection system, piping, and valving. The smaller electrical skid contains the hazard panel, central master controller, backup power generator transfer switch, and utility electrical interfaces. It is located near the mechanical skid at a sufficient distance to satisfy fire safety codes. Also located near the mechanical skid is the nonfired steam generator skid.

The array field design and skids have been arranged to allow easy access to all valves, controls, and major piping systems for easy installation and maintenance. This system has been designed for production of the commercial packaged system, in that the majority of the system subassemblies are fabricated and shipped to the field as completed units. This allows cost reductions in the production of MISR systems and improves quality control and assurance.

The collector/array, heat transport, electrical and control subsystems will now be discussed in detail.

B. SOLAR COLLECTOR/ARRAY FIELD

1. Solar Collector Subsystem Selection

The T-700 linear parabolic trough (LPT) was selected for the MISR design because of its wide spread use, cost competitiveness, and state-of-the-art design that is supported by a continuous product development program at Solar Kinetics.

The T-700 is a 20-foot long LPT of 7-foot aperature that is highly modular in construction. Mirror modules are joined in a drive string consisting of 6 mirrors with a drive pylon in the center. The drive pylon is a self-contained unit requiring only control and power wiring. The T-700 is constructed using a monocoque principle in which an aluminum skin is stretched over precision cast aluminum ribs that are attached to an aluminum torque tube. The surface is then coated with FEK-244. The standard T-700 was selected for the MISR design primarily because it is a proven, reliable product with over 300,000 ft^2 produced.

The T-700 collector system uses a proven design which consists of a drive pylon activated by a two speed dc motor. This drive pylon provides 270^0 of rotation to allow use in both east/west and north/south orientations, and an inverted stow position. The two speed dc motor tracking system provides good tracking accuracy, minimizes the effects of backlash, and allows rapid stow of collectors when adverse conditions are detected.

2. Array Operating Configuration Selection

The selected array layout and operating configuration consists of a constant flow, self-balancing, low parasitic system. This system uses end-manifolding and a minimum number of piping connections, valves, and control components to provide ease of installation and maintenance, increased reliability, and reduced cost. The reduced number of components is directly related to the relatively long delta-T loop configuration. The rationale for the selected array configuration is as follows:

a. Fluid Flow Design

A constant flow configuration was selected to maximize net annual efficiency and simplify system control. With constant flow, the outlet temperature of the collectors will vary with daily insolation between the maximum and minimum operating temperatures. This allows lower average fluid temperatures which result in higher efficiency. With constant flow, temperature control valves are not needed, thereby reducing costs, simplifying control, and increasing reliability. A self-balancing system results since each ΔT loop has the same flow without need for throttling. This reduces requirements for fluid control valves and eliminates requirements for rebalancing the system after temporary alterations for collector maintenance.

b. Orientation

The BDM MISR can be oriented in the direction required for a specific application. The concept has been developed so that no additional design is required for altering orientations between the two extremes of east/west and north/south. East/west orientations will be required where uniform daily output is desirable. If a summer peaking demand exists or if the MISR system is used as an augmentary system supplying a small fraction of the total demand, total thermal energy output can be maximized with a north/south orientation.

c. Delta-T Loop Length

BDM has selected a delta-T loop which contains 36 T-700 collectors that provide 5,040 square feet of aperture. Five delta-T units are required for the MISR array field.

In selecting a delta-T loop, several factors must be considered. First, the loop must contain even multiples of tracking units so as not to unnecessarily increase tracking system cost. Second, it is desirable to minimize cost by reducing the number of valves, piping connections, and control components required for assembly and installation. Third, parasitic head loss must not become prohibitive. Fourth, the loop size must be selected so as to yield modularity and reasonable field geometries.

Six discrete delta-T loop sizes were considered for the BDM MISR design. These delta-T loops ranged from 2 tracking units (12 collectors) to 12 tracking units (72 collectors). The total cost and number of controls, manifold connections, piping manufacturing, and field labor decreases as the loop length increases. This characteristic causes the longer loop to be attractive. Longer loops are permitted by virtue of the larger receiver diameter (1-5/8 in) of the T-700. Nonetheless, the pumping head loss for each loop increases with length increasing parasitic pumping power requirements. Therefore, a tradeoff exists which must be resolved for final system optimization. In addition, as the loops become very large, the concept of the modular array field disappers and system reliability is affected in that larger fractions of the total array field are lost if one loop is inoperative for maintenance or repair.

d. Delta-T Loop Manifold Interface and Manifold Location

The BDM MISR is an end-manifold design with individual delta-T loop/manifold connections. This configuration was selected with a six tracking unit configuration after tradeoff studies had been made with center manifold designs. The end-manifold configuration was selected for four reasons. First, it allows easy access for manifold installation maintenance and safety during emergency conditions, thereby reducing system installation and maintenance cost. Second, the field geometry works very well with long delta-T loops. Third, it provides marginally interrupted access to all collectors for cleaning and maintenance whereas the center manifold encumbers intra-array access. Finally, the end-manifold concept supports a self-balancing fluid flow design. In previous analysis, BDM has determined that center manifold taps with short delta-T loops can yield variances from minimum to maximum flow rates of 77 percent in different loops. End-manifold concepts, relatively long delta-T loops, and a uniform manifold diameter yield a self-balancing system with a maximum of 5 percent variance from the minimum loop flow rates. Therefore, the end-manifold system provides the most balanced fluid flow design, installation, and operational capabilities.

C. HEAT TRANSPORT SUBSYSTEM (HTS) DESCRIPTION

The flow of heat transfer oil can be traced starting from the discharge side of the heat transfer oil pump located on the mechanical skid. The total pump volume flow rate is 125 gpm (55,550 lb/hr). Isolation valving is provided for the pump. The main oil stream continues through the master flow meter into the main inlet manifold. From the manifold, oil is distributed to the five delta-T units with flow self-balanced at 25 gpm. Flow goes through each of the delta-T loops and returns to the outlet manifold increasing in temperature 85^{o}F for 650 W/m^2 insolation. The 1^{o}F drops in fluid temperature to and from the mechanical skid and collector field represent heat losses in the manifolds. The outlet manifold returns hot oil to the steam generator where the solar energy is removed in the form of steam. Oil then flows by the heat transfer fluid expansion tank which is in parallel with the main stream back to the pump. The expansion tank is sized to contain the full drain volume of the manifold. The ullage space is filled with nitrogen to minimize fluid oxidation and to cause the expansion tank to act as an accumulator thereby improving cold pump starts.

Gross steam production at 650 W/m^2 is 2,550 lbs/hr with a collector efficiency of 50.4 percent. Full sun (1,000 W/m^2) production is 3,840 lbs/hr at a collector efficiency of 55 percent.

Instrumentation is provided for control and monitoring of system performance. A total of 30 temperature switches (1 at each drive pylon) monitor the system for overtemperature. Pressure relief valves (PRV) are located in the steam generator and heat transfer fluid expansion tank and in each delta-T loop. A PRV will respond to any tube breakage in the steam generator which would immediately manifest itself in a pressure increase because of the high saturation pressure of steam at approximately 500^{o}F. Activation of the flow switch in the steam generator PRV line would result, causing system shutdown.

D. MECHANICAL SKID

The mechanical skid is an enclosed, stand alone unit fabricated from off-the-shelf equipment and provides safe economical generation of steam from heated thermal fluid. It measures 10 ft x 12 ft to allow safe transportation to sites without requiring expensive vehicles, permitting and escorts. The size of the mechanical skid was also determined from structural dynamic considerations as it was felt this size would act most like a rigid-body thus minimizing the eventuality of damage to insulated HTF piping occurring during handling. The skid supports the heat transfer fluid expansion tank and ullage maintenance unit, the collector circulation pump, and Halon 1301 fire protection unit. Flanged connections are located at the perimeter to interface with plant piping. All hardware is weatherproof, available in cataloged incremental sizes, and has been proven in field applications.

E. Steam Generator (SG) SKID

The Patterson-Kelly packaged SG is designed for an operating pressure of 250 psig and is sized with the collector circulation flow rate to result in optimum net energy output. The system is operated at a constant HTF flow rate and the inlet/outlet temperatures of the steam generator are allowed to "float" and seek their respective equilibrium points in the system. This philosophy of operation greatly simplifies the controls of the system and reduces pumping parasitics. The shell is amply proportioned to store a large volume of water at saturated steam pressure. Intermittent feedwater injection has minimum effect on steam output and the large thermal capacitance reduces the effects of intermittant cloud cover. The internal moisture separator utilizes inertia forces at sharp changes of flow direction to remove entrained water from the emerging steam.

F. ELECTRICAL SUBSYSTEM

1. Electrical Distribution Subsystem Description and Requirements

The electrical distribution subsystem consists of standard commercial equipment which conforms to NEMA and NEC safety and performance standards. Its function is to provide power for all pumping, tracking, control and ancillary functions of the MISR with a standard interface to industrial site utility connections.

The electrical subsystem load is divided into two areas. The first is the ac system power which includes the heat transport subsystem, main pumping power, the control valve electrical requirements, and 110V ac to the drive pylons. Each drive pylon then converts and rectifies the ac voltage to satisfy the dc voltage requirements of the drive motor and controls. Other elements are the ac power for the safety and the fire control systems and convenience outlets that are placed in the field. The second load area consists of emergency power and emergency controls. This is provided by a packaged 15 kw motor generator with transfer switch.

2. Electrical Skid

The electrical skid for the MISR system is a self-contained unit that will be transported by truck to the industrial site. The only requirement from the site will be a utility drop sized for 50 KVA, 480 volts, three-phase. All switch gear protective equipment and metering will be on the skid. Other interfaces on the skid are designed to mate with the mechanical skid emergency generator and the collector array on the branch junction boxes which will be in place.

The major pieces of equipment located on the skid are the 480 volt three-phase switch gear, the generator transfer switch, the 120 volt ac main distribution and switch gear panel boxes, the central master controller and the hazard panel. The ac power is distributed to the system subelements and the phases balanced by equal loading. The hazard panel contains status indicators for the system's temperature, pressures, and fluid levels, as well as providing power to the fire detection and control systems on the mechanical and electrical skids. The central master controller contains the rain and light sensors and microprocessor for central control.

3. Emergency Power System

Power failure, phase reversal, phase loss or low voltage are monitored by the hazard panel. When any of the above conditions occur the transfer switch restores power by starting the 15 kw emergency generator and placing it on line. When normal line power returns, the transfer switch returns normal power after a set delay and the engine/generator set is turned off automatically. The engine/generator also features an automatic exercise circuit to insure engine/battery reliability.

G. CONTROL SUBSYSTEM

The MISR Master Control System provides automatic, unattended operation under normal conditions as defined by meteorological inputs and system temperature and flow data.

The control system for the MISR operates on an on/off relay control philosophy. The control system hardware uses standard relays and gives simple fail-safe operations in its interconnections. Proportional and integrating or differentiating controls are not used anywhere in the MISR system because of their inherent complexities. All control output is in the form of on/off levels rather than analog levels. Critical temperature readings corresponding to loop over-temperature or heat transfer fluid manifold over-temperature are in the form of snap switches. The use of relay controls, as opposed to computer controls, hardens the system against the adverse effects of near-hit lightning strikes and power line voltage dips. The system is capable of automatic unattended operation or manual operation. Under emergency shutdown, automatic controls are overridden, and all subsystems shutdown. Additionally system alarms would be activated. System alarms include annunciators, lights, and notification of local emergency personnel.

H. MISR INTERFACE DESIGN

In consonance with one of the key objectives of the MISR program BDM was awarded a contract by Sandia National Laboratories to develop interface designs of BDM's MISR system with two industrial users: A. E. Stanley Mfg. Co., a potato starch manufacturing plant located in Monte Vista, Colorado, and Prepared Foods, Inc., a meat packing plant located in Santa Teresa, New Mexico. These designs were completed to a level sufficient to permit construction bidding for all site preparation work, utility service, feedwater, steam line with associated hardware, and interface controls that are required for safe and reliable operation of the solar system and the connected plant. The designs optimized the performance of the existing MISR design with respect to installation cost, system operational performance, and site limitations. Cost estimates for construction of the interfaces were also developed.

THE BDM CORPORATION
MISR - QTS Description and Test Results

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ABSTRACT

The BDM Corporation Modular Industrial Solar Retrofit (MISR) Qualification Test System (QTS) was installed at Sandia National Laboratories for qualification testing and performance evaluation. The QTS consists of all of the non-solar equipment and one of the five delta temperature solar collector loops that would be in full-size MISR system. Installation of the system was completed and testing begun in September, 1982. Function and operational testing of the QTS were completed in October, 1982. Completion of performance measurements and life cycle testing has been interrupted due to damage to some of the collectors collectors and failures of flexible hoses that occurred during life cycle testing. Operational experience and performance data are summarized and some unique design features are discussed.

THE BDM CORPORATION
Modular Industrial Solar Retrofit Project
Qualification Test System
Description and Test Results

INTRODUCTION

The BDM Corporation was one of five companies selected to design a Modular Industrial Solar Retrofit (MISR) system and to install and complete operational checkout of a Qualification Test System (QTS) under contract to Sandia National Laboratories. The QTS was installed and tested at Sandia National Laboratories.

The qualification test system consists of all of the non-solar equipment and one of the five solar collector delta-temperature strings that would be in a full-size 7626 M^2 (25,020 ft^2) MISR system. In the qualification testing, the remainder of the collector field was simulated by a propane-fired heater which is referred to as the balance-of-field simulator. Four-fifths of the flow from the skid flows through the balance-of-field simulator and is heated to the same outlet temperature as the delta T-string.

QTS DESCRIPTION

An overview of the QTS is shown in Figure 1. The collectors, shown in Figure 2, include six drive groups of T-700 collectors manufactured by Solar Kinetics, Inc. (SKI). Each drive group is 37 m (120 ft) long and has an aperture of 2.1 m (7 ft). The collectors are an aluminum monocoque design with FEK-244 reflective surfaces. Each collector drive incorporates a ball-screw mechanism and 90 Vdc motor and is controlled by a light sensor mounted on the edge of the collector. The collectors are rotated about the vertex of the parabola and thus include counterweights for rotational balance.

The non-solar equipment is mounted on four skids which are on four separate concrete pads, as shown in Figure 3. The equipment includes an Onan gasoline-powered engine generator, a Patterson-Kelly packaged steam generator, a mechanical equipment skid, and an electrical skid. The mechanical equipment skid includes a Dean Brothers pump, an insulated expansion tank, a nitrogen ullage system, and a Halon 1301 fire suppression system. The electrical skid includes the backup power transfer switch and exerciser, power distribution panels, pump motor starter, collector master controls and weather instrumentation, and a hazard enclosure.

UNIQUE DESIGN FEATURES

The following features of this design are of special interest due to their uniqueness:

- This system incorporates straight-forward hazard controls based only on switch closures and relay logic. Feedwater delivery to the steam generator is also controlled by switch closures. When a magnetic float detects low level, a solenoid-powered feedwater valve is opened until high level occurs.

- The mechanical equipment skid, including the HTF pump and the expansion tank, is enclosed in a small structure to assist fire protection.

- The SKI receivers use an internal elastometric O-ring to seal the space between the black-chrome plated tubing and the glass annulus. The receivers are joined together with a Marmon clamp and a compression seal. A flexible hose with a corrugated metal cover is used to connect the receivers to the manifold.

- A portion of the field manifold was installed in the QTS for proof of concept. The field supply line is mounted above the return line, and each delta-T string is connected to the manifold with two flexible hoses to allow for thermal expansion.

QTS FUNCTIONS

The Solar Kinetics Master Controller monitors sunlight, rain, and wind conditions. The setpoint of the sun sensor is field adjustable. Five minutes of continuous sun is required before the pump will start and the collectors will rotate out of stow. An additional five minutes of continuous sun is required for acquisition of the sun by the collectors. If satisfactory pump flow is not established in ten minutes, the system will shutdown. At the end of the day, fifteen continuous minutes of low insolation will cause the system to be shut down. The pump is operated throughout this fifteen minute period. A five minute period is allowed for shutdown following any stow command before the system will begin monitoring the sun again. All of these parameters are field adjustable.

A rainwash feature has been incorporated in the master controller. A single remote switch, which could be located inside the user's industrial plant, places the system in the rainwash mode. The system must first detect rain, then it waits for the rainwash switch to be turned on. The collectors are then rotated to an approximately vertical position as determined by a field-adjustable time delay. Rainwash is terminated either when the rain sensor no longer detects rain, or when the sun is detected, or when the rainwash switch is turned off, or following detection of a hazard, or after a maximum field-adjustable time, nominally eight hours.

EVALUATION RESULTS

The BDM QTS, which was the first to become operational, was accepted for testing in August, 1982. The first set of tests to be performed were function and safety tests. The purpose of these tests was to determine that all safety systems operated as designed and that the system was fully operational. In as much as possible, all operating configurations were examined to determine how the system responded in all cases, even those which may not have occurred to the designer. During these tests, some leaks developed in the receiver joints. All receivers were originally joined with a one-bolt Marmon clamp and elastomeric O-rings. During BDM's checkout of the system, those installed in the higher temperature areas of the delta-T string began to leak. These were replaced with metal C-rings and two bolt clamps. During this phase of testing, the remainder of the elastomeric seals also began to leak and thus all joints were retrofitted with metal C-rings. Since that time, some joints have been fitted with graphfoil seals that seems to be leak resistant and are manifestly easier to install than the metal C-rings.

The next test to be performed was an unattended operations test. This test requires a minimum of two weeks continuous automatic, unattended operation. The test site set up to simulate a plant with a 1.7MPa (250 psig) steam main and the balance of field simulator was operated as described earlier. No maintenance of the QTS system other than scheduled maintenance was allowed. A minimum of seven days of total insolation above 4 kWh/m^2 (1272 Btu/ft^2) per day was required or the test period was extended as long as was necessary. This test was completed with no problems in October, 1982.

Life cycle tests are being performed on each QTS to evaluate the life of collector components, in particular the drive systems and flexible hoses. During this test, the T-700 collectors are cycled from stow to the north horizon and back with stops at six angles in between in each direction. One complete cycle requires about fifteen minutes with the drive system operating at a fifty percent duty cycle.

During life cycling an apparently inoperative wind switch allowed the collectors to operate in gusts of up to 22 m/s (50mph). During those gusts one drive group jumped ahead two links on the chain drive, apparently because of the combination of high wind and a loose turnbuckle which tensions the chain. Since the limit switches and mechanical stops are part of the drive chain and not the collector structure, the collectors were driven into the non-drive pylons and substantial damage resulted. At some time, several other reflectors in the south row, which is most exposed to winds, were also damaged.

Life cycle testing has been temporarily suspended after 875 cycles due to inexplicable failures of flexible hoses. These hoses are being used in a different configuration than most previous applications by SKI. The cause of failure is presently under investigation.

PERFORMANCE

Performance measurements are being made on each QTS. Peak (normal incidence) efficiency measurements are being made at inlet temperatures from 121 to 204°C (250 to 400°F) corresponding to steam pressures of 0.5 to 1.7 MPa (67 to 250 psig). Thermal loss measurements are being made over the same temperature range with the collector oriented towards clear sky with the receiver shaded by the collector to maximize radiative effects. Measurement of incident angle modifiers and peak efficiency at ambient temperature are being made using tap water as a once-through heat transfer fluid. The heat capacity of the mechanical equipment skids and collectors are being determined by heating them as rapidly as possible from ambient with the balance of field simulator while measuring the heat input. Thermal efficiency of the mechanical equipment skids, overnight cooldown and parasitic electrical use are also being measured.

Collector efficiency measurements had not been made before the mirrors were damaged during life cycling. These mirrors are to be replaced by SKI and these measurements will then be made.

The measurements completed to date are summarized in Table 1. These basic parameters may be used to estimate performance of the system in various applications. Such simulations as well as the results of the uncompleted measurements and life cycle tests will be included in the final MISR project report.

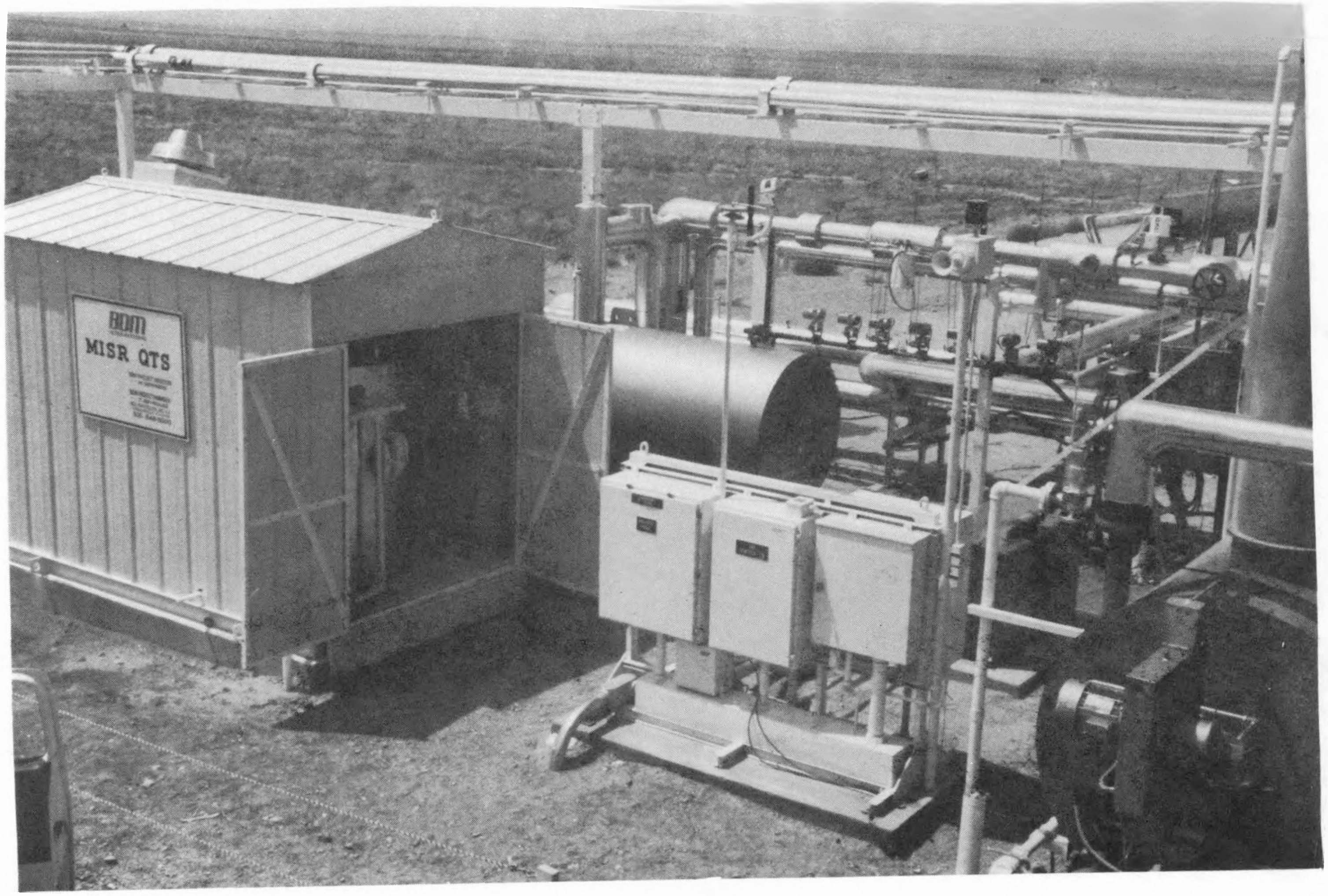
TABLE 1

PERFORMANCE RESULTS*

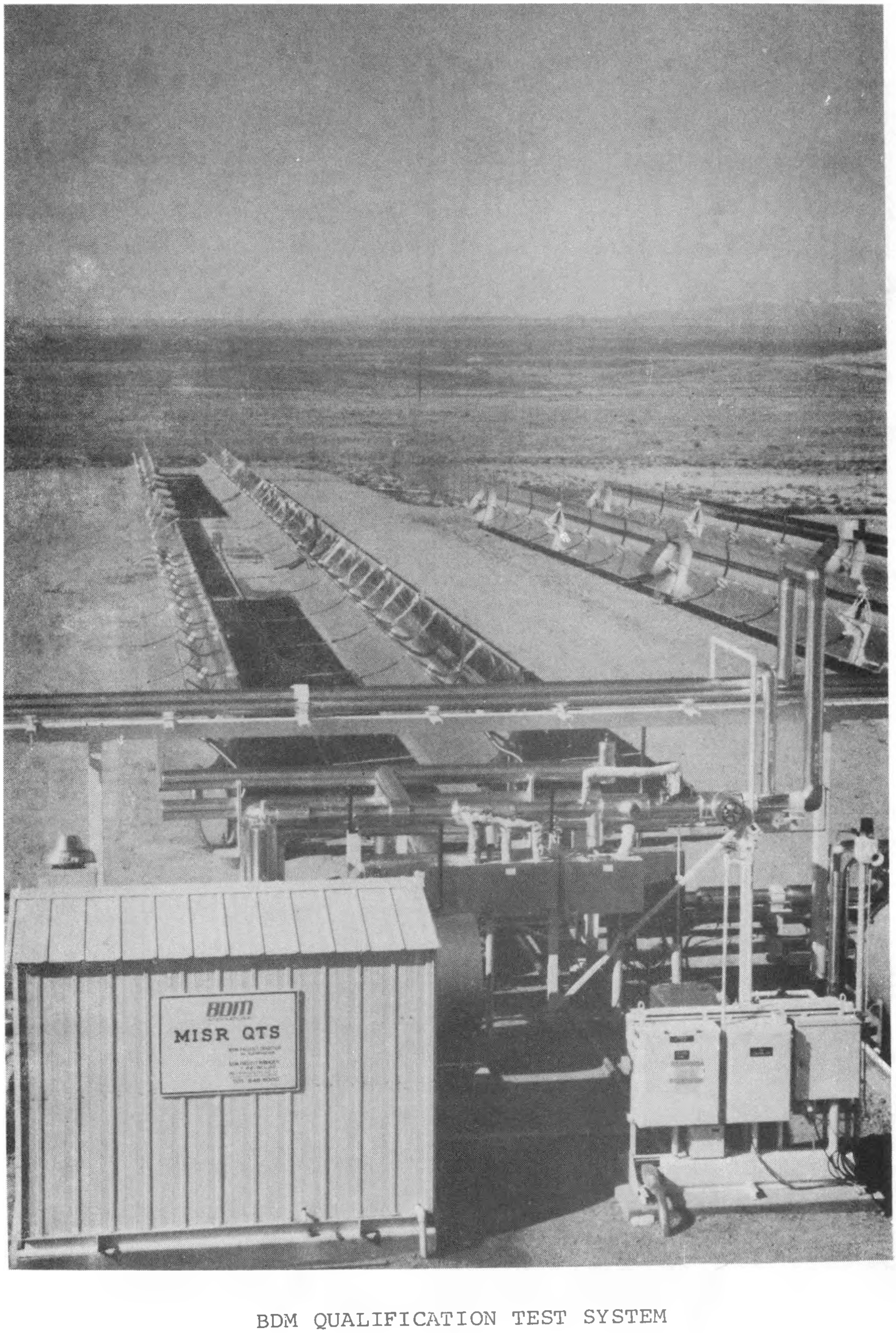
Collector Heat Loss

Average Temperture (°C)	Average Temperture (°F)	Ambient Temperature (°C)	Ambient Temperature (°F)	Wind Speed (m/s)	Wind Speed (mph)	Heat Loss W/m^2)	Heat Loss (BTU/hr-ft^2)
191	376	6	43	3	7	114	36
144	291	5	41	1	3	60	19
87	188	9	48	3	7	33	11
46	115	3	38	1	3	9	3

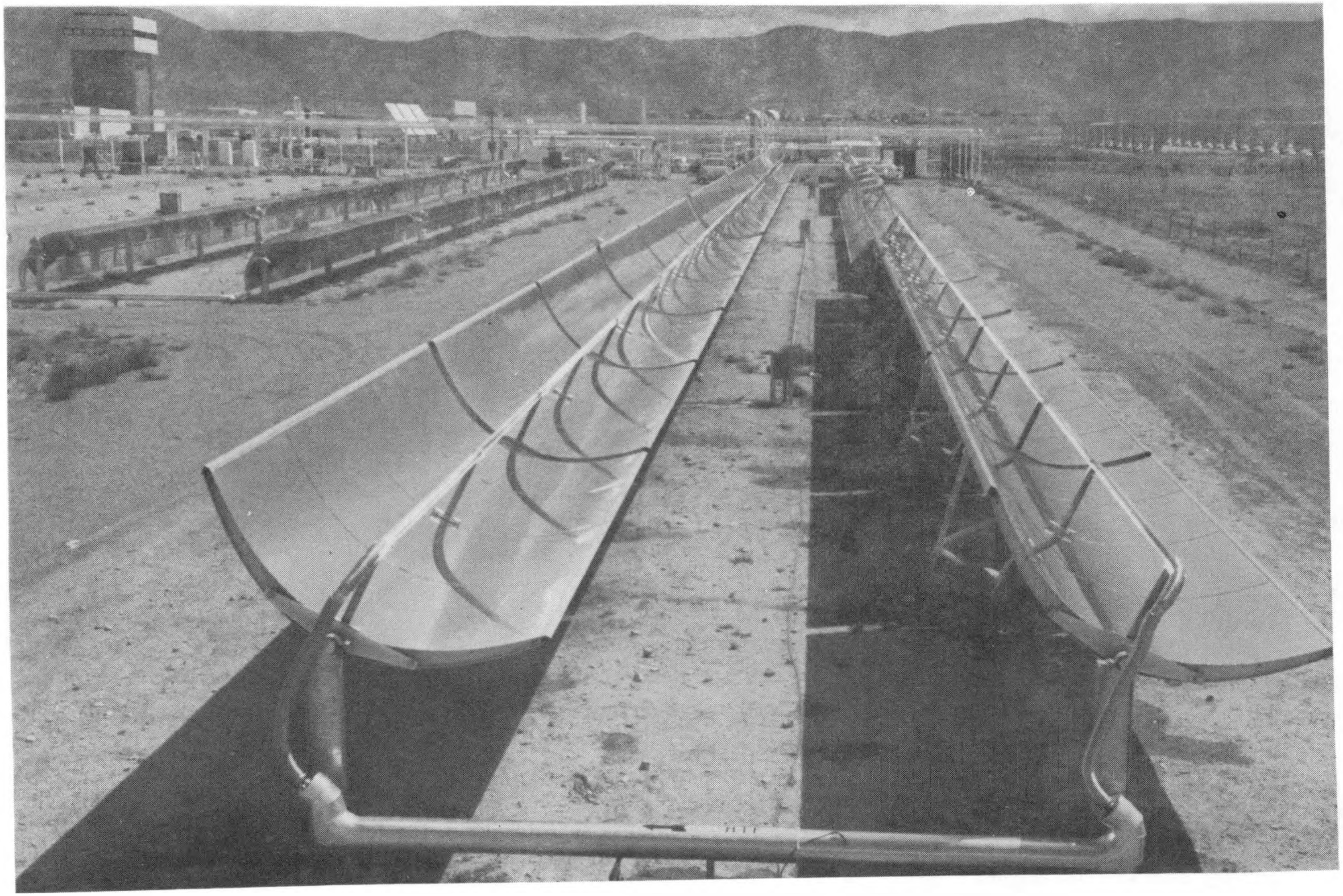
*Collector heat loss was measured from the inlet to the outlet of the delta-temperature string; thus, heat loss from flexible hoses and interconnecting piping are included in the results.



BDM EQUIPMENT SKIDS
Figure 2



BDM QUALIFICATION TEST SYSTEM
Figure 1



SOLAR KINETICS T-700 COLLECTORS IN BDM MISR QTS
Figure 3

MISR
CUSTOM ENGINEERING, INC.
by Clyde Castle, P.E.

The CUSTOM ENGINEERING MISR SYSTEM has a collector field of approximately 25,000 square feet of 2x6 meter silvered glass collectors. Six collectors are driven by one drive motor to form a drive string. Four drive strings form a ΔT loop and eight ΔT loops make up the collector field. Collector rows are 16.5 feet center to center, and with allowance around the perimeter for vehicle access, the total area required for the system is approximately two acres. The equipment skid is positioned to supply a central manifold for the HTF to the eight ΔT loops. Figure 1 shows the system layout.

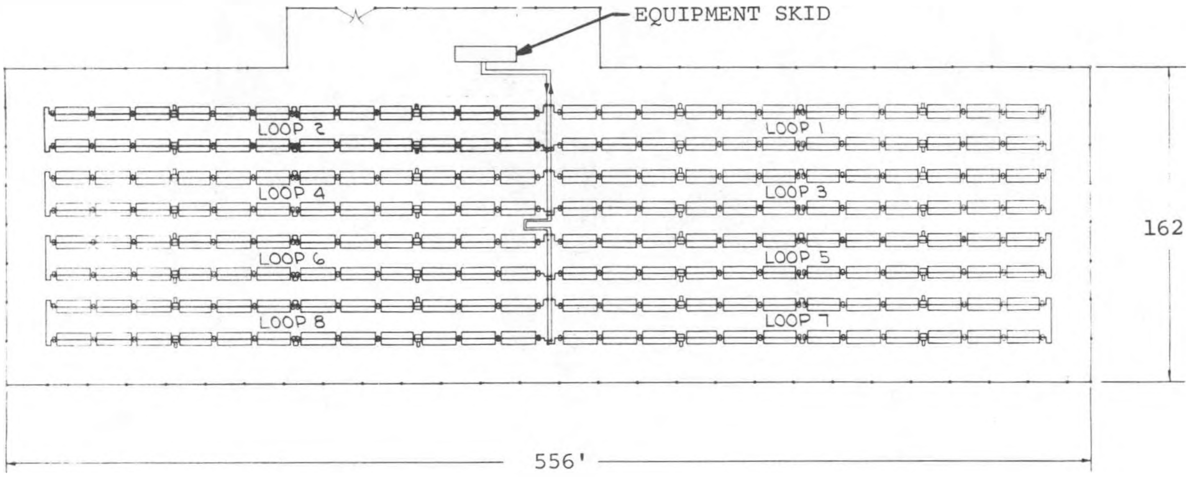


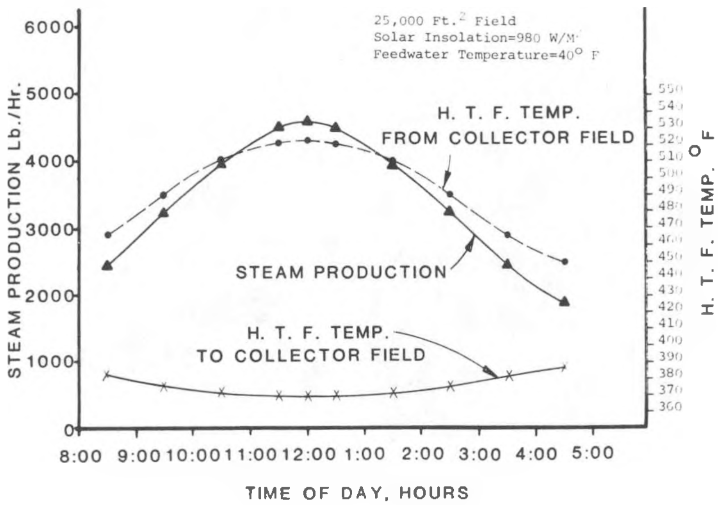
FIGURE 1

The critical operating parameters of the system are:

HTF	-	Therminol 60
HTF Flow	-	60,000 pounds per hour maximum
Typical Operating Temperature	-	HTF Flow, 360-390° F; HTF Return, 455-550° F
Steam Generator	-	Kettle Type-"U" Tubes
Steam Pressure	-	100 to 250 psig
Maximum Steam Production	-	6,000 pounds per hour

The combination of these factors results in the system performance as shown in Figures 2 and 3.

FIGURE 2



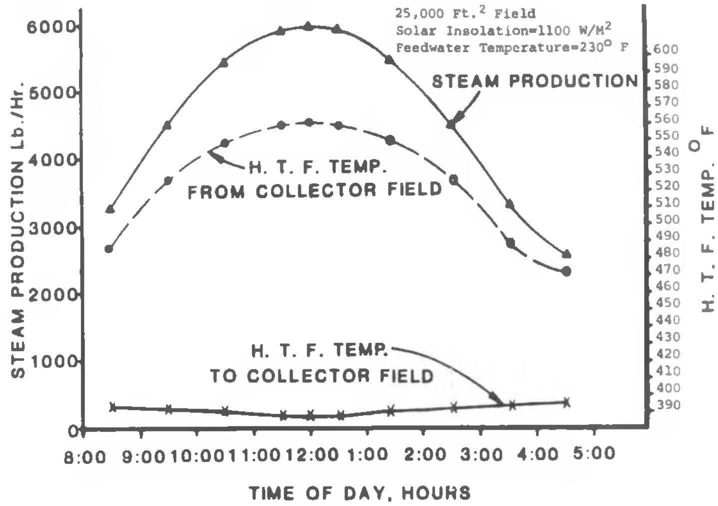


FIGURE 3

The above gives an overall description of the system. The following identifies the subsystems that are of special interest because they represent interesting applications of existing technology:

CONTROL SYSTEM

The MISR Control System, shown in Figure 4, is designed to meet the following criteria:

- o Operate unattended
- o Highly reliable
- o Accurate and fail safe sun pointing
- o Low cost
- o Easy to service

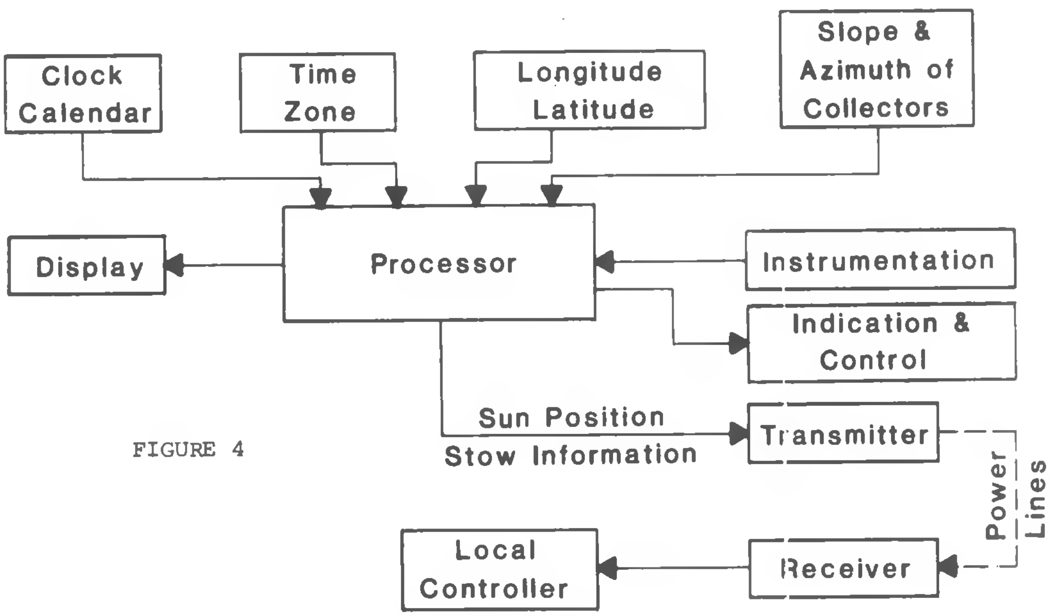


FIGURE 4

The system is a Microprocessor-Based Power Cable Carrier Control sun pointing system (SUNPOINT), developed by Custom Engineering, Inc., based upon research conducted by Sandia National Laboratories.

SUNPOINT has an FM transmitter which transmits the sun angle information over the existing power cabling to the local receiver-controllers. The sun angle information is generated by the master controller, which is a microcomputer.

The control system is designed with the capability of two receiver-controller addresses. These are used to stow adjacent rows of collectors in opposite rotation directions for maximum protection from wind and dust. It can also be used to rotate adjacent rows of collectors to face each other for washing purposes.

The microcomputer used in the master controller system is based upon a Z-80 microprocessor. The master controller serves two purposes:

1) To supply the local controller with the desired collector position. This information is derived from a set of equations solved by the master controller while using the inputs of a crystal-controlled clock.

2) To supervise the total system by continuously testing it to a set of logic instructions.

The master controller has a battery-backed RAM memory and a battery-backed clock which retains information particular to the locality and time of the installation; i.e., longitude, latitude, time zone, year, and collector azimuth and slope.

The master controller automatically starts executing the logic program immediately after power-up or after reset. The master controller can be reset by means of the reset key on its twenty-five key panel, or from the control cabinet panel. A special key can be depressed on the front of the master controller which will put it in the monitor mode after reset. This enables the user to put in or change RAM constants, and gives him access to service subroutines.

The logic subroutines in their natural sequence are:

a) Initialization
b) Idle
c) Wake-up
d) Operational

The shutdown modes are:

e) Nominal Shutdown
f) Out-of-Nominal Shutdown
g) Emergency

In addition, there is the rainwash mode: a service subroutine which can be entered from the idle mode (by means of the master controller keyboard), or from the operational mode via the nominal shutdown. Finally, there is the interrupt subroutine. The master controller repeats this routine every quarter second, regardless of where the main program is executing. The subroutine constantly watches:

a) Emergency and Out-of-Nominal conditions
b) Wind speed
c) Insolation
d) Temperature
e) Watch Dog Timer: This is a solid state circuit which must be continuously pulsed by the interrupt routine, otherwise the circuit will produce a fail signal. The purpose of this circuit is to avoid system shutdown due to an aberration on the power line which can cause a temporary malfunction of the computer.

f) The routine also increments a number of timers at each pass, for time out purposes; for example, the user-determined duration of the rainwash period. Figure 5 shows the main elements of the control system logic.

Local Controller
The local receiver-controllers receive the FM signal from the power cabling. After decoding, a sixteen-bit word message is obtained, containing sun angle and address information. The receiver-controller compares this with the position feedback information of a potentiometer attached to the collector axis. It will then send out a polarized signal to the drive motor to align the axis according to the new information. If no information (or garbled information) is received, the controller will automatically put the collectors in stow.

High-Temperature Protection
The control system is designed so that a ΔT loop will be stowed if an over-temperature signal is received from either the expansion switch or the temperature sensor at the return end of the loop. In order to avoid the necessity of running additional circuits from the over-temperature devices to each of the four drive motors of the ΔT loop, the sensors activate an FM signal trap that removes the FM signal from the local controller power circuits. When this signal is interrupted, the local controllers drive the collectors to the stow position where they will remain until the control for the loop is reset.

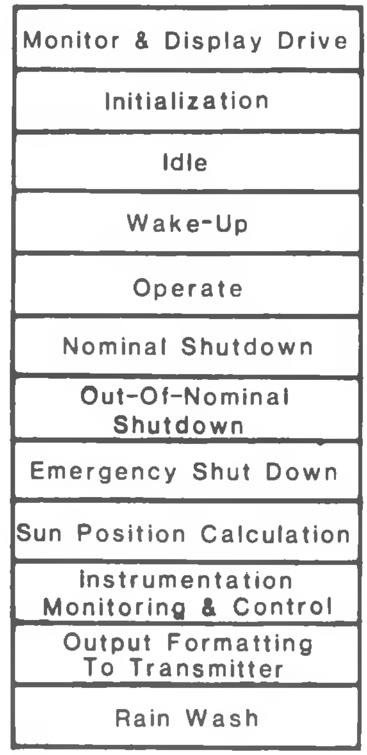


FIGURE 5

The over-temperature signal is generated by one of two sensors: The first is a thermocouple measuring the temperature of the HTF fluid leaving the ΔT loop. The second is a microswitch in the same location which generates an over-temperature signal when the receiver tube length expands beyond a preset amount. This signal activates a relay that energizes a filter coil. The coil is on the power cable that carries the FM signal to the controllers for the drive motors of the four drive strings. When the filter coil is energized, it suppresses the FM signal from the microprocessor. The loss of the FM signal is sensed by the drive motor controller, and the drive string is rotated to the stow position. The ΔT loop will then be in a safe condition while the cause of the problem, usually a flow restriction, is being investigated. Thus, only one-eighth of the collector fields' production is lost as a result of the local high-temperature condition.

Receiver Tube
The detail design of the receiver tubes and associated hardware has been a continuing problem for parabolic line focusing collectors. Custom Engineering reviewed the work completed by SNLA in this area, and with that background, developed an approach proven to be effective.

The receiver tube assembly, shown in Figure 6, consists of a Pyrex jacket around a black chrome-finished steel tube. This jacket is a 60mm diameter (2.36-inch) Pyrex tube with a 2.39mm (0.094-inch) wall thickness with an anti-reflective coating applied. The tubes are approximately 3-meters (9-3/4 feet) long with two required for each 6-meter (19-3/4 feet) collector.

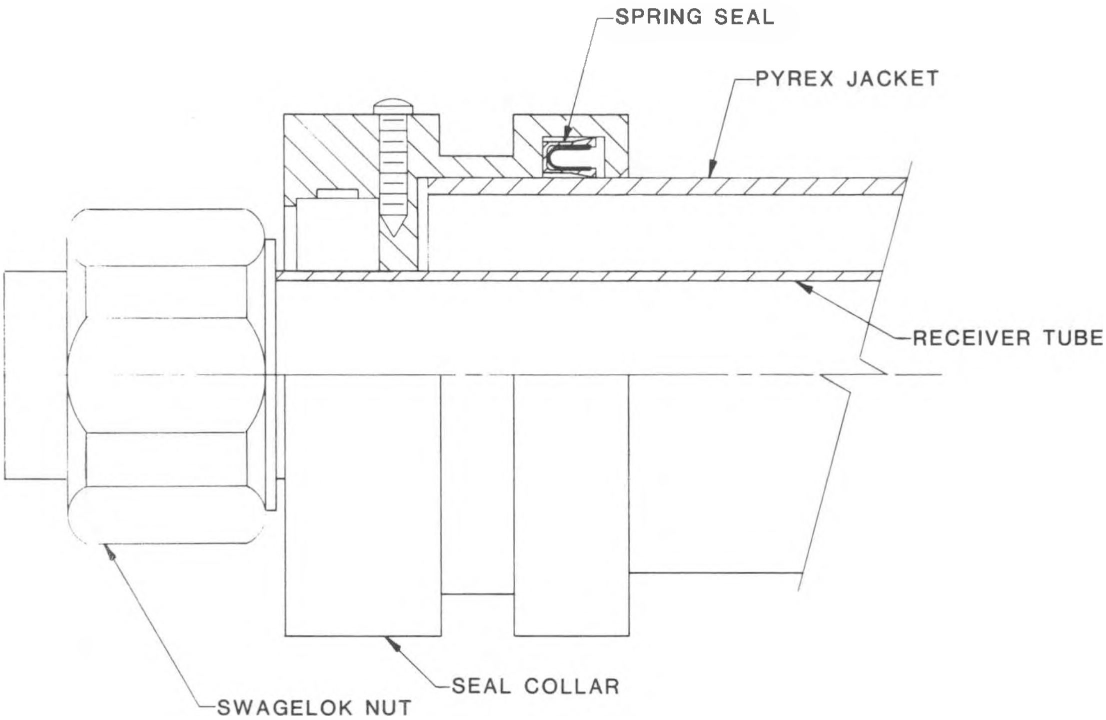


FIGURE 6

Because of previous studies, CEI decided it was not cost-effective to attempt to evacuate the space between the jacket and the receiver tube. Rather, the effort was directed toward designing a water and dust tight seal between the two tubes. The approach was to design the seal fitting so that the Pyrex tube would not require special forming at the ends and that the seal would be on the outside of the Pyrex jacket. This location of the seal takes advantage of about a 10:1 factor in terms of the load that a Pyrex tube can withstand when applied radially from the outside, versus a similar load applied from the inside surfaces.

Plant Interface Design

Under contract with SNLA, Custom Engineering, Inc. developed the Plant Interface Design for Cyprus Industrial Minerals Company, Three Forks, Montana, and Wayne Poultry, Pendergrass, Georgia.

The Cyprus requirements were unique in that the company was phasing out their requirements for steam and using only hot air in their talc drying process. Because of this the steam generator was eliminated and the HTF was piped to two heating coils in the user's facility. Blowers force air through the coils and supply 320 to 450^{o} F air for the talc drying process.

At the Cyprus facility, the optimum collector field orientation was in a northeast/ southwest direction, and the distance from the equipment skid was about 750 feet. There were no special grading problems but it was necessary to route the piping and conduit under a rail spur.

The Wayne Poultry installation is more conventional in that their requirement is for steam. From our proposed equipment skid location there is approximately 150 feet of steam pipe required between the skid and the tie-in to the steam system.

The collector field will be located in a northeast/southwest direction and will have a slope of 3% after grading. Except for the amount of grading required, the MISR Plant Interface is an ideal one because of the close proximity of the plant and field location.

Figure 7 shows a schematic for a typical industrial installation for Custom Engineering's MISR system.

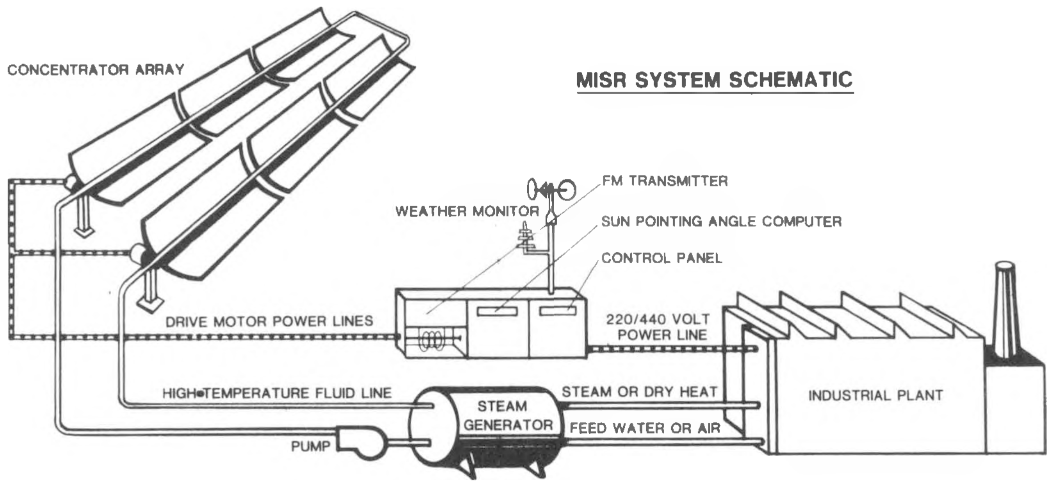


FIGURE 7

Custom Engineering, Inc.

MISR QTS DESCRIPTION AND TEST RESULTS

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ABSTRACT

This paper describes the Custom Engineering, Inc. (CEI) MISR qualification test system (QTS) and the available design evaluation results. The QTS consists of a full complement of equipment with the exception that the solar collector field consisted of only one delta temperature collector loop. The evaluation has progressed through to the performance tests. Some unique design features are also discussed.

INTRODUCTION

The CEI MISR QTS is one of the five designs developed by industry under the MISR project. It was the latest contract to be awarded (12/5/81), which was about 3-months after the other four, and CEI completed their installation on November 24, 1982. Some bad weather, checkout problems, and year end holidays, delayed the start of evaluation testing until January 3, 1983. This paper discusses the QTS design, available results, and some unique design features.

QTS DESCRIPTION

The CEI MISR QTS installlation at the SNLA test site is shown in Figure 1. The equipment, exclusive of the solar collectors and the emergency engine-generator, is all located on one skid. On the right side of the figure (north side) is the control enclosure. It has a double roof painted white for summer heat reflectance and an enclosed electric heater for maintaining an acceptable internal temperature during the winter. Immediately to the left of the control cabinet is the steam generator and preheater. In front of the steam generator is located an electric powered modulating feedwater control valve - a a unique feature. To the left of the generator is the uninsulated heat transfer fluid (HTF) expansion tank. Next to it is the vertical mounted 11 kW (15 hp) HTF circulation motor/pump. The pump is a centrifugal type. In the foreground is located the propane fueled engine-generator to supply power to stow the solar collectors when utility power is lost. The collector loops in the background are oriented with their axis of rotation, East/West. The collectors are installed to follow the slope of the ground which slopes 2.82% westward. The collector delta temperature loop contains 4-drive strings and 288 m^2 of aperture area of mirrors. This represents 1/8 of the MISR collector field design. The collectors are the PPT type design and were manufactured by the Budd Company.

The collector drive strings are powered by a 0.37 kW (1/2 hp) dc motor through a gearbox. The collector orientation is controlled by a directed tracking system. Figure 2 shows the main structure of the collector, and Figure 3 shows the receiver assembly. Black chrome selective coating, AR coated glass, an external omni type seal, and a "hair-pin" hinge are used in this receiver assembly. The system control is built around a microprocessor. It is programmed to operate the QTS while monitoring all the system functions and calculating the sun position and directing the collectors to the focus orientation. It communicates with the collector field through the use of the Power Cable Carrier Control (PC^3) system. No additional control wiring is required for the PC^3 system. The front of the control cabinet is shown in Figure 4.

UNIQUE DESIGN FEATURES

Several features of the design are unique in that they have not been used before or have worked exceptionally well:

- The Microprocessor and PC^3 system offer a high degree of system operational flexibility in the areas of collector orientation, field slope, function and parameter monitoring, and alarm initiation. Most of these can be accomplished by a programming change. This system also allows the collector rows in a loop to stow toward each other eliminating the

- An electronic filter in each collector delta temperature loop power cable allows the total loop to be stowed when an over-temperature is detected while allowing the rest of the loops potential of wind damage to the external rows.
  to continue operating normally.

- The collector receiver glass tube holder with its external omni seal allows large enough seals to be used to accommodate the tube manufacturers tolerances, the seal operates at low temperature, is shaded from the UV radiation, and applies stress to the glass in a way the glass is strongest.

- The electric powered modulating feedwater control valve provides precise control of the feedwater without the potential problems associated with air powered systems. It is an electric over hydraulic system and with loss of electrical power the valve automatically closes.

- The fire protection system is a water spray system that derives its supply from the utility. This system, however, was not used at the QTS site.

EVALUATION RESULTS

In the preliminary operation of the QTS, some observations were made that could affect follow-on designs:

HTF Expansion Tank: This was specified in the design requirements to be an ASME pressure vessel. It now appears that an API vessel, with at least one 5 cm (2 in.) diameter vent rated at 0.3 Pa (50 psi) is sufficient. The outlet of this tank should be a few centimeters above the bottom to allow water to collect and be easily drained.

HTF Expansion Tank Piping: The CEI QTS was designed so that the tank could be in series, in parallel, or be out of the HTF flow circuit. It was determined that the tank operating in the parallel mode with a vapor exhaust line from the HTF line to the top of the tank was most satisfactory.

Ullage System: The system was designed with a nitrogen blanket on the HTF in the expansion tank to pressurize the pump inlet and inhibit HTF oxidation. The tank operates cool enough in the parallel mode that no nitrogen blanket is necessary.

Function testing consisted of determining whether the required system controls were included in the design and to determine how they responded to an out-of-limits condition. Each function was simulated and the response observed. The CEI system had been accepted without proper adjustments of all the functions so that some were observed as they were adjusted. One function design requires some additional design effort to operate properly - the insolation level detector. Probably some blinders on the pyronometers will solve the problem and this will be tried as soon as time permits. Otherwise, all the functions were present and operated satisfactorily. The function sequence and timing are controlled by the Microprocessor program. This is easily changed whenever a different control approach is desired.

Other test results are listed below in Table 1. Performance testing was initiated and the results indicated a lower efficiency than expected for the PPT collectors. Laser ray trace of several collector mirror modules was conducted. The focal length was found to be approximately 1 1/2 centimeter longer than designed. Hardware is being fabricated to correct this. Tracking accuracy testing determined that approximately 1 degree of hysterious existed in the system. This was determined to be the result of backlash in the feedback potentiometer gear train. A small spring is being designed into this gear train to eliminate the backlash. It is believed that the backlash is the problem as the electronics are accurate to $\pm$ 0.01 degree.

CONCLUSION

The QTS evaluation is continuing and final conclusions at this point are impossible. The design contains many state-of-the-art subsystems and several unique design features. Some first-of-a-kind problems have been discovered, but one of the purposes of the MISR evaluation was to find them. Solutions are being investigated and in a short time they will be resolved. The control system and collector receiver design are believed to be exceptionally good. The system design is clean and some of the items discussed indicate the design can be simplified further. Some mirror breakage has occurred and is apparently due to imperfections in the original glass. With the items mentioned corrected, the design is a fine example of the progress being made in line-focus collector system technology.

TABLE 1

COLLECTOR PERFORMANCE*

String No. 2:

Avg. HTF Temperature 226°C (440°F)
Hand Track - Efficiency = 59%
Auto Track - Efficiency = 49%

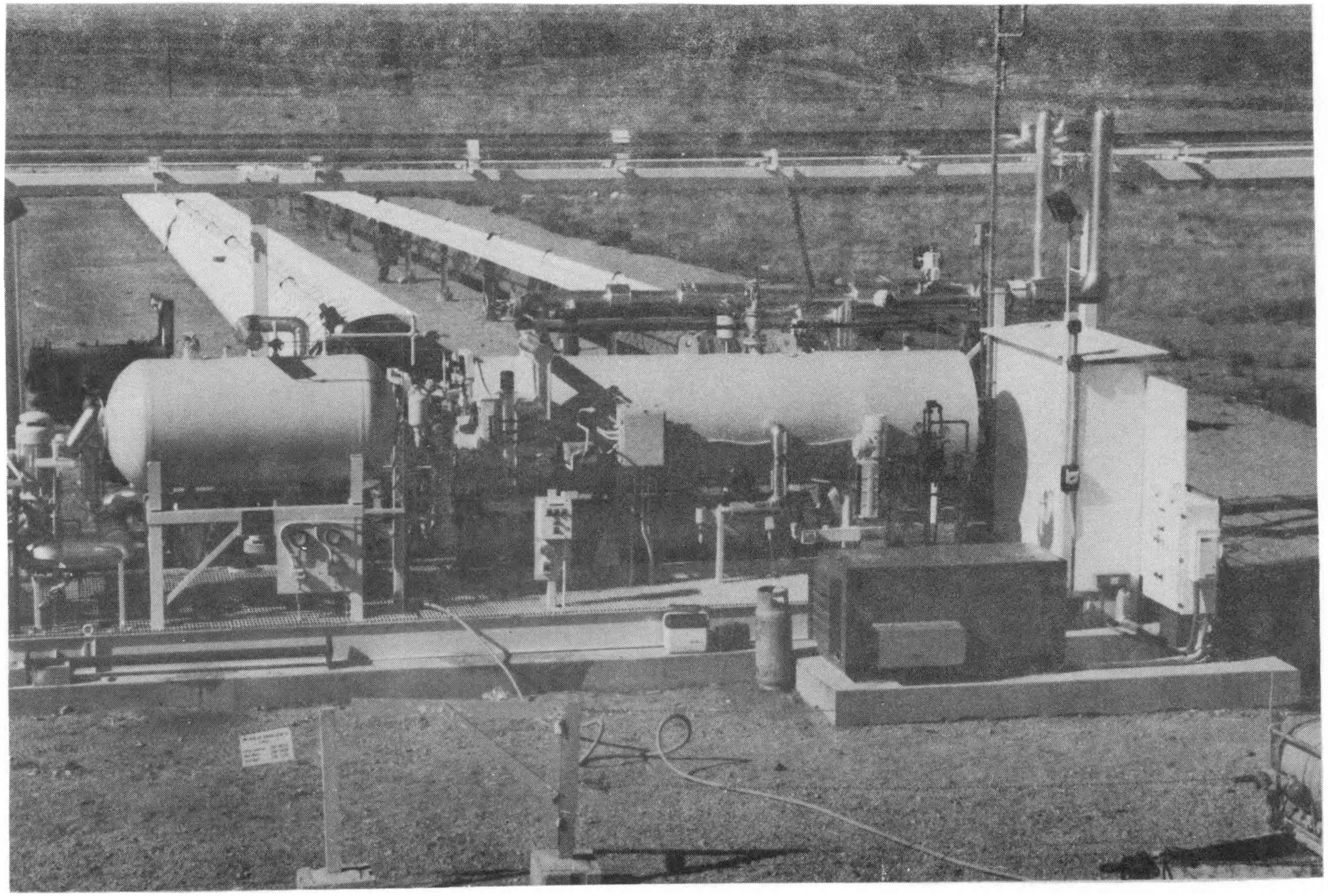
Loop:

Avg. HTF Temperature 238°C (460°F)
Hand Track - Efficiency 53%
Auto Track - Efficiency 40%

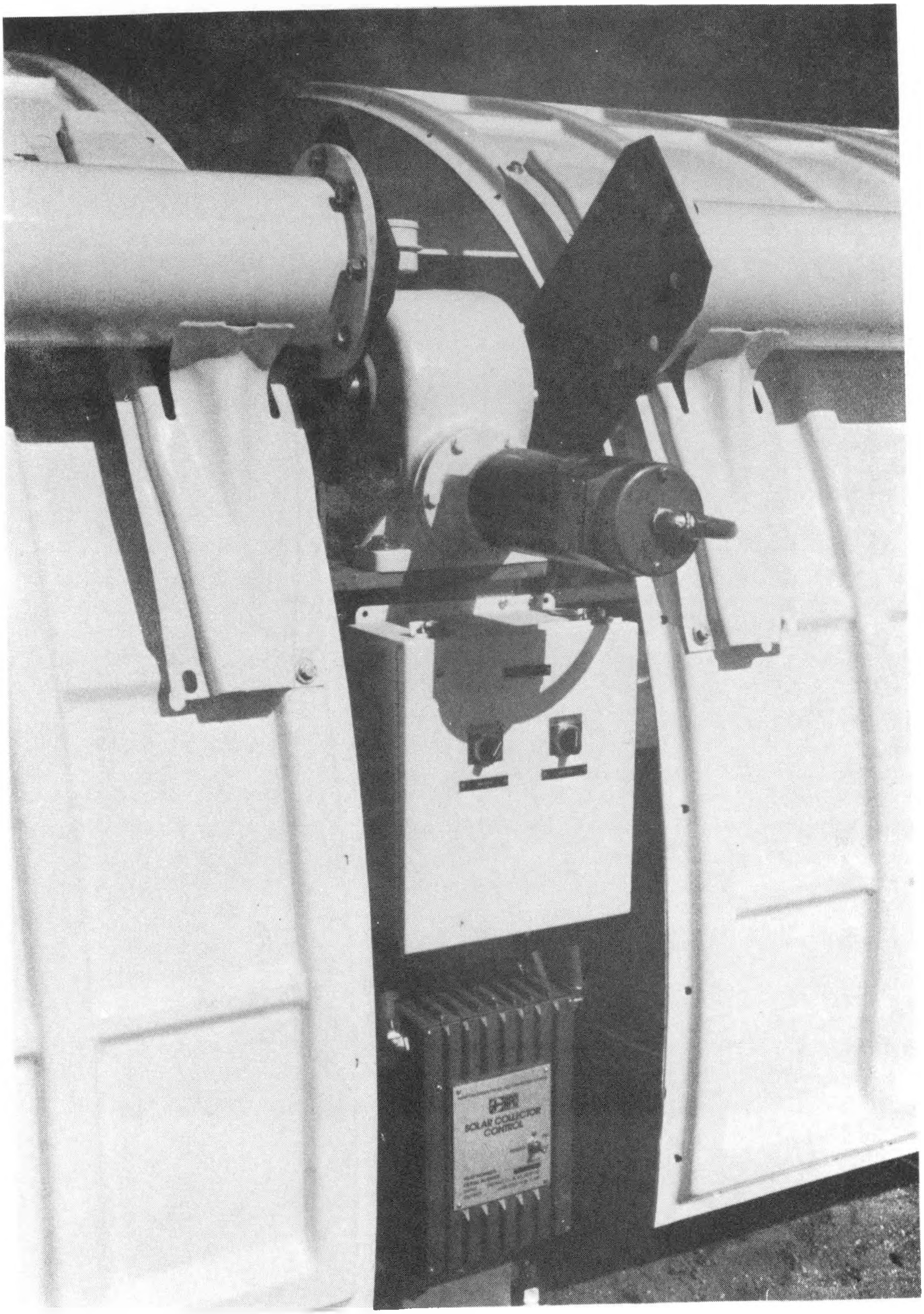
Heat Loss

Avg. HTF Temperature	182°C (360°C)
Ambient Temperature	7°C (44°F)
Wind Speed	4 M/S (9 mph)
Thermal Loss	11 W/M^2 (33 $BTU/hr\ ft^2$)

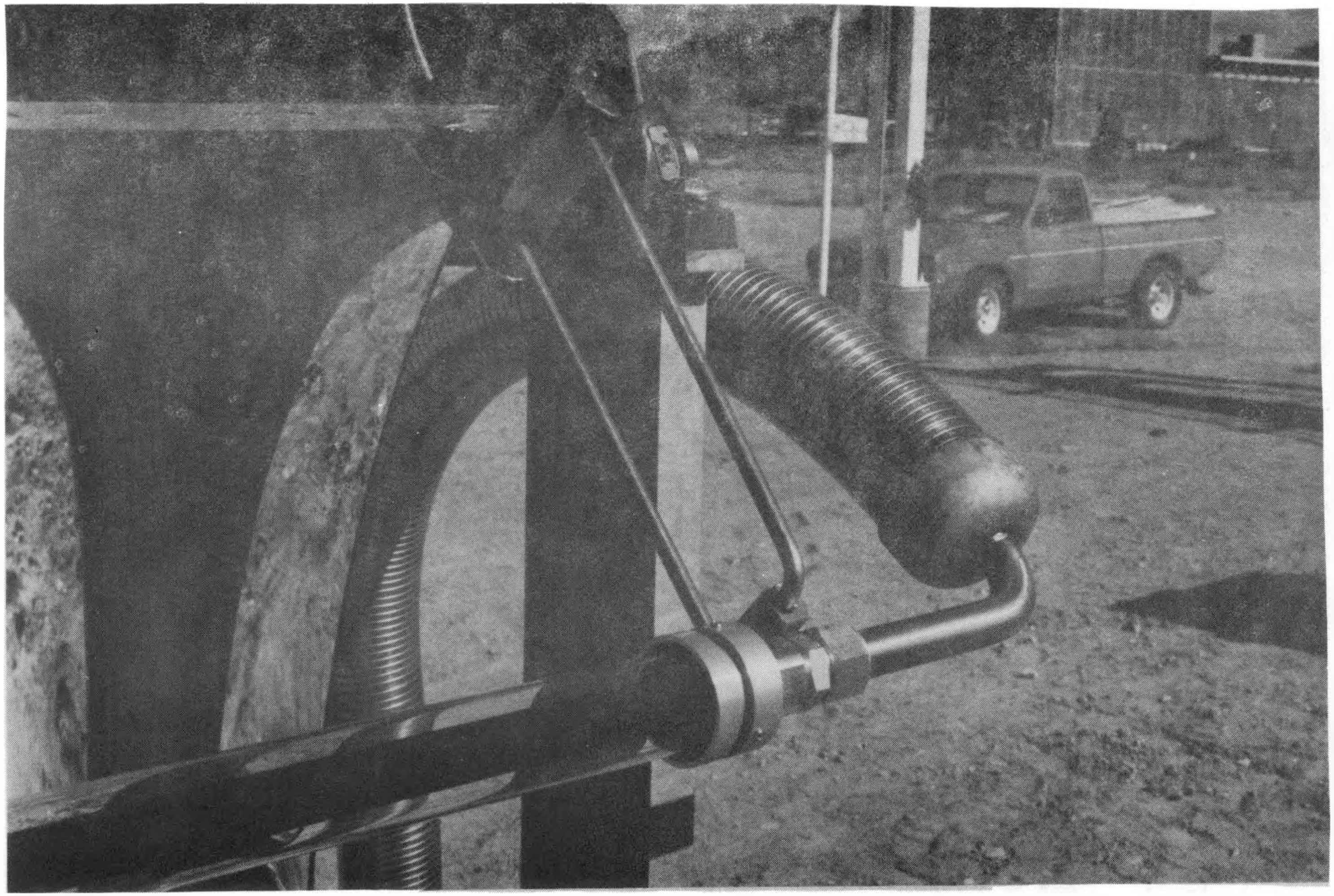
* Collector efficiency and heat loss were measured from the inlet to outlet of the delta temperature loop; thus, heat loss from the flexible hoses and interconnecting piping are included.



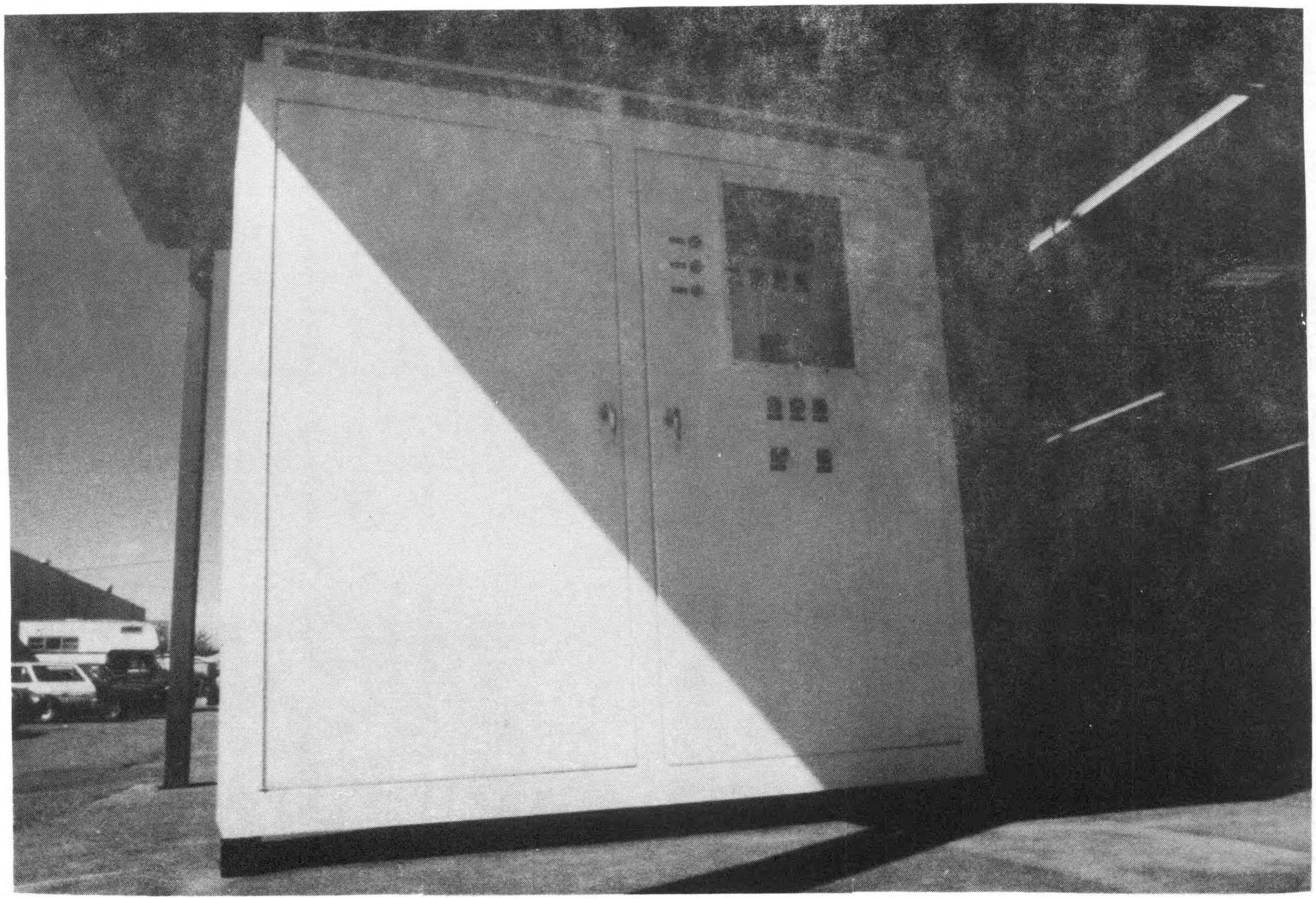
CEI MISR QTS INSTALLATION
Figure 1



CEI QTS COLLECTOR STRUCTURE AND DRIVE
Figure 2



CEI QTS COLLECTOR RECEIVER ASSEMBLY
Figure 3



CEI QTS CONTROL CABINET
Figure 4

FOSTER WHEELER'S MODULAR INDUSTRIAL SOLAR RETROFIT SYSTEM

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Abstract

Foster Wheeler has designed a Modular Industrial Solar Retrofit (MISR) System that uses pressurized water to carry heat from solar collectors to a steam generator. The essential components of this design have been tested. This paper outlines the system design, details the lessons learned from the tests, and describes two designs prepared for the installation of MISR systems at specific industrial sites.

Introduction

Of all solar thermal systems, those utilizing line-focus single-axis aperture tracking collectors are of particular interest to industrial users. Their advantages are threefold:

- They can provide heat at temperatures that meet over 80 percent of industrial requirements.
- They have been extensively developed, demonstrated, and tested.
- Small systems can be installed with costs per unit area of collector similar to those estimated for large systems.

To ensure the greatest possible penetration of the potential industrial market for such solar thermal systems, cost-effective, reliable systems must be offered to possible users. To this end, the development of proven modular designs will greatly enhance the likelihood of commercial success. Accordingly, as part of a program funded and directed by Sandia National Laboratories, Albuquerque (SNLA), Foster Wheeler has designed a modular solar thermal system using parabolic trough collectors. Based upon this design, a test system has been installed at the Solar Energy Research Institute's (SERI's) site in Golden, Colorado, and tested by SERI and SNLA personnel.

In this paper, we will discuss both the design of the modular solar thermal system and the performance of the test system. In addition, we will briefly describe designs prepared for two potential users of modular solar thermal systems, emphasizing the interface between the solar thermal system and the existing plant facilities.

Design of a Modular Solar Thermal System

The design concept espoused by Foster Wheeler has one feature that distinguishes it from all the other designs prepared as part of the Modular Industrial Solar Retrofit (MISR) System Development Program: It uses pressurized water as the heat-transfer fluid that, circulating in a closed loop, transfers energy from the solar collectors to a steam generator.

Water has several advantages over organic heat-transfer fluids in line-focus solar thermal systems. Some of these advantages, such as its superior heat-transfer and friction-loss characteristics, are commonplace; others, such as the elimination of the cost of fire protection systems, are less widely recognized. The advantages can be summarized as follows:

- The heat-transfer and friction-loss characteristics of water are markedly superior to those of organic heat-transfer fluids. Therefore, the system can operate at lower temperatures or with lower flow rates and smaller pipe diameters when water is used, resulting in lower heat losses, capital costs, and parasitic power consumption.
- The release of organic heat-transfer fluids can cause fire or environmental hazards. No such risks are posed by water.
- When organic heat-transfer fluids are used, capital costs are increased because of the need to install fire protection systems, headers to collect the discharge from relief valves, and additional heat-transfer surface to heat the boiler feedwater and generate steam.
- Overheating and water that leaks into an organic heat-transfer fluid degrade the fluid.
- Initial and replacement costs of the organic heat-transfer fluid are avoided if water is used.

The major disadvantages of using water are that a high pressure is required to prevent boiling in the closed loop, particularly in and downstream of the collectors, and that freeze protection has to be provided, should the system be installed in a location where subfreezing temperatures are encountered.

In our system, freeze protection has been provided by allowing for the circulation of warm water through the collector field. Accommodation of the high pressures required to prevent boiling within the collectors has proved to be a more interesting task. We must ensure that the pressure within the closed loop always prevents boiling and that the integrity of the connections between the rotating solar collector receiver tubes and the fixed manifold piping is maintained at the high pressures.

To prevent boiling, we pressurize the accumulator, through which all the water in the closed loop is circulated after emerging from the steam generator. Before start-up the vapor space of this accumulator is filled with nitrogen. Then as the water heats in the loop, it expands, gradually filling the accumulator and compressing and warming the nitrogen. Through an appropriate choice of initial nitrogen pressure and water level, we can ensure that the sum of the partial pressures of nitrogen and water vapor in the accumulator will always be such that boiling is precluded within the closed loop.

The integrity of the receiver-to-manifold connections has not yet been fully achieved; leaks were found in the rotary joints initially installed. This subject will be discussed later.

Other than the choice of water as the heat-transfer fluid, our design is similar to the other designs for MISR systems (Figure 1). It comprises a parabolic-trough collector field with a skid-mounted kettle-type steam generator, through-flow accumulator, and pump. When insolation is sufficient, water is circulated through the collector field to an unfired boiler in which steam is generated. At peak insolation, water will leave the collectors at 260°C (500°F) if 1.71 MPa gage (250 lb/in^{2}g) steam is being generated; if insolation or the required steam pressure is lower, this exit temperature will be lower. The water flow rate is fixed--no attempt is made to control the water temperature other than by heat transfer in the boiler.

The collectors we used are Suntec line-focusing parabolic-trough collectors with tracking receivers and reflectors. The collectors are 36 m (120 ft) long with a 3-m (10-ft) aperture. Water passes through the receiver tubes of two collectors in series before being returned to the steam generator. The axis-to-axis separation

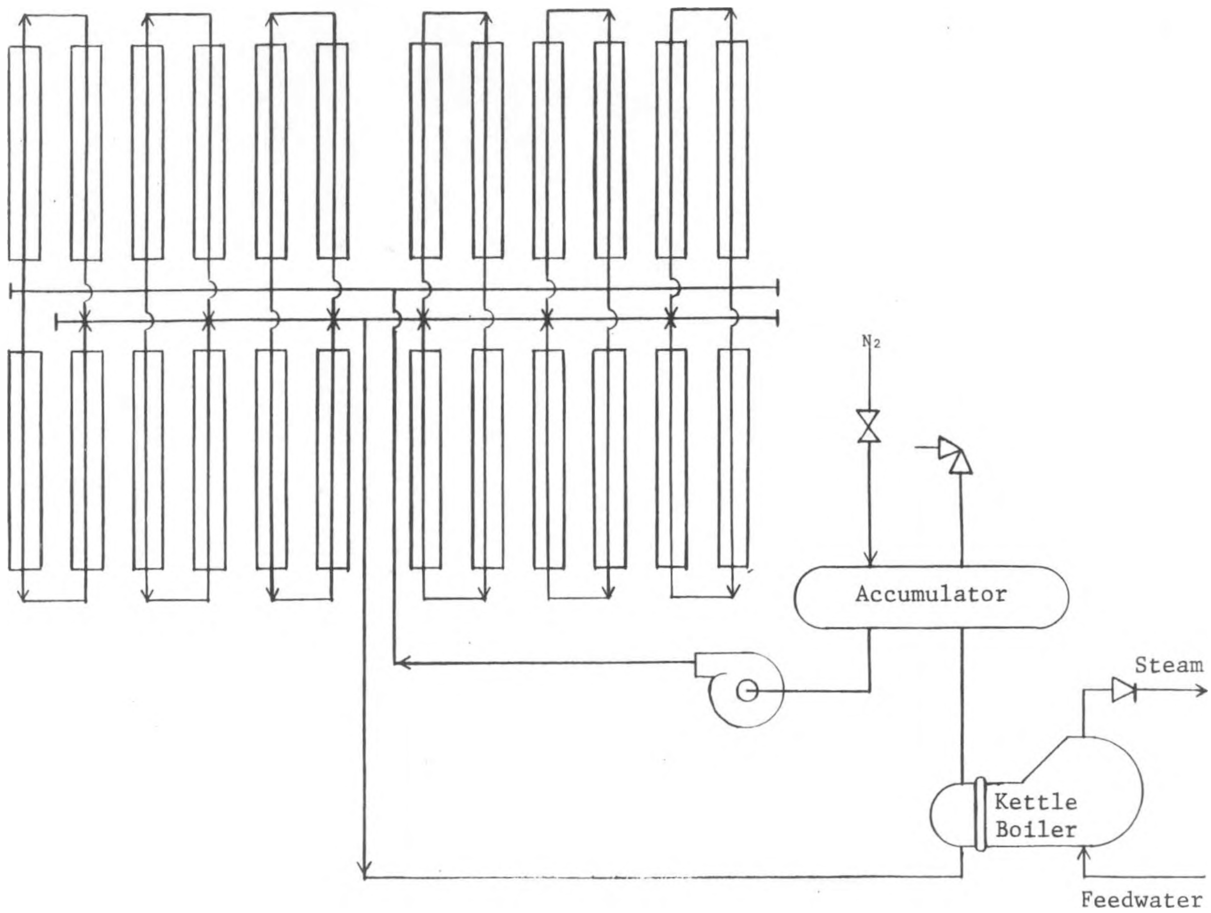

Figure 1 Schematic of MISR System

is set at 6 m (20 ft), allowing easy access for maintenance while minimizing the delivered cost of solar thermal energy. Collector positions are controlled by the highly distributed Honeywell Flux-Line Suntracker System.

Problems Encountered and their Resolution

In the course of operating the test system, evaluating its performance, and reviewing the design, several design changes have been found necessary or desirable.

The principal problem encountered in the operation of the Qualification Test System at SERI has been the failure of the rotary joints installed between the manifold piping and the collector receiver tubes after 4 months of intermittent operation. The arrangement shown in Figure 2 was chosen as an inexpensive means of using

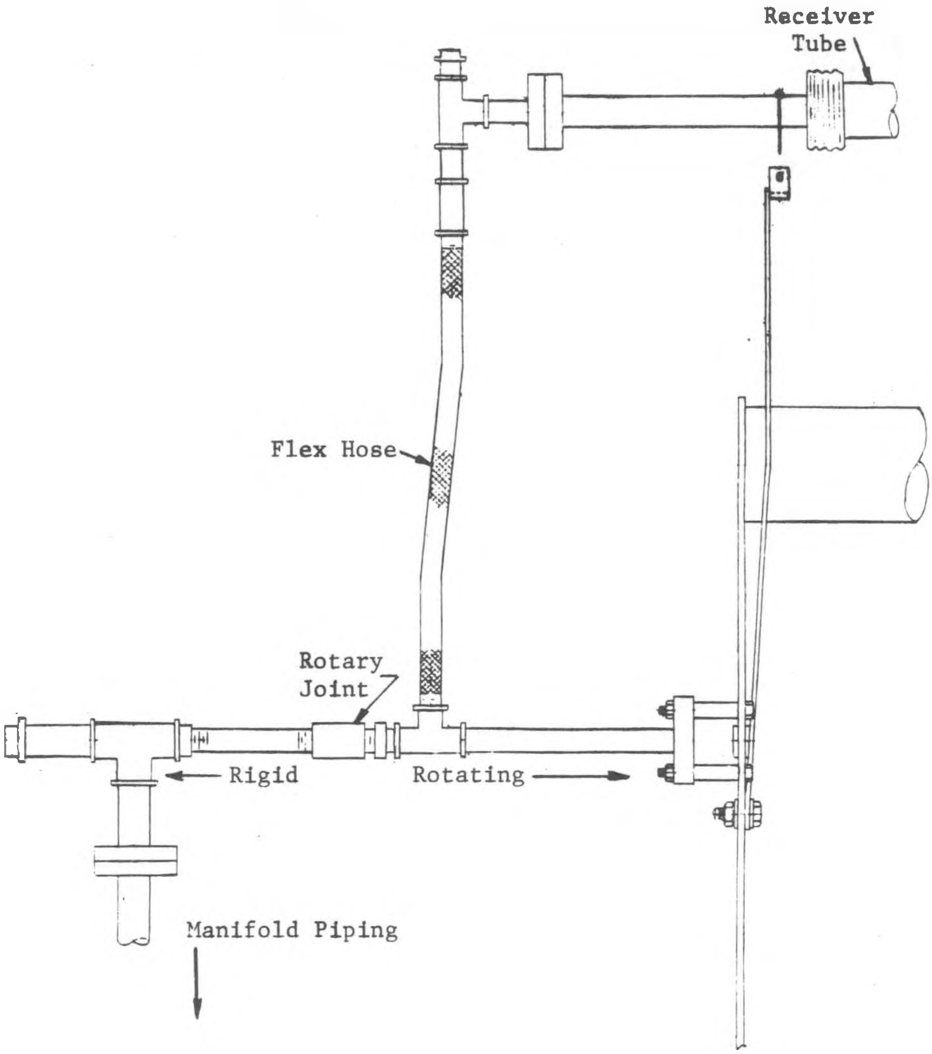

Figure 2 Rotary Joint Arrangement

standard, commercially available components to avoid the use of flexible hoses and the accompanying problems of contraflection and torque. With the rotary joint arrangement, thermal expansion and contraction in the receiver tube is accommodated by a flexible hose placed between the joint and the receiver tube; thermal expansion and contraction in the manifold piping is accommodated by allowing the pipe supports freedom to move within a slide. From an examination of the joints after their failure, we have determined the following: As a result of misalignment of the joint, thermal expansion within the manifold, and pressure-induced axial thrusts, excessive wear occurred on the rotary joint bearings. As the annular gap in the joint widened, the "O" ring was extruded into it and was eaten away as the gap width fluctuated with rotation. The rotary joint assembly can be redesigned to eliminate these problems. Such a redesign would entail:

- Anchoring of the manifold side of the rotary joint to the collector pylon
- Insertion of a flexible hose on the manifold side of this anchor point to accommodate any misalignment or remaining thermal expansion in the manifold pipes
- Provision of a back-up seal to help prevent extrusion of the O ring
- Lengthening of the male portion of the joint together with the use of a second bearing.

This design would, however, necessitate the use of a nonstandard joint which is not immediately available for the MISR System Development Program. Instead, we have resolved to use a flexible hose that is maintained under tension by the manifold piping when fully elongated (Figure 3). By this means we hope to avoid the problem of contraflection as the receiver tube rotates. This hose is currently being installed and tested at the SERI test site.

Other design changes, although desirable, are of lesser importance. In large part they stem from a resolve to eliminate some of the conservatism, redundancy, and complexity within the initial design. In particular we recognize that because there are no heat sources within the closed loop piping other than the collectors, there is no need to install relief valves other than on the collector strings. We can thus eliminate the relief valve on the hot pressurized water return line.

In the initial design, freeze protection was provided by circulating warm water through the collector field, allowing steam from the main plant to condense in the MISR System steam generator and maintain a minimum temperature within the loop. Simulations of system performance, however, indicate that steam condensation will seldom be required at sites within the continental United States. Accordingly, we

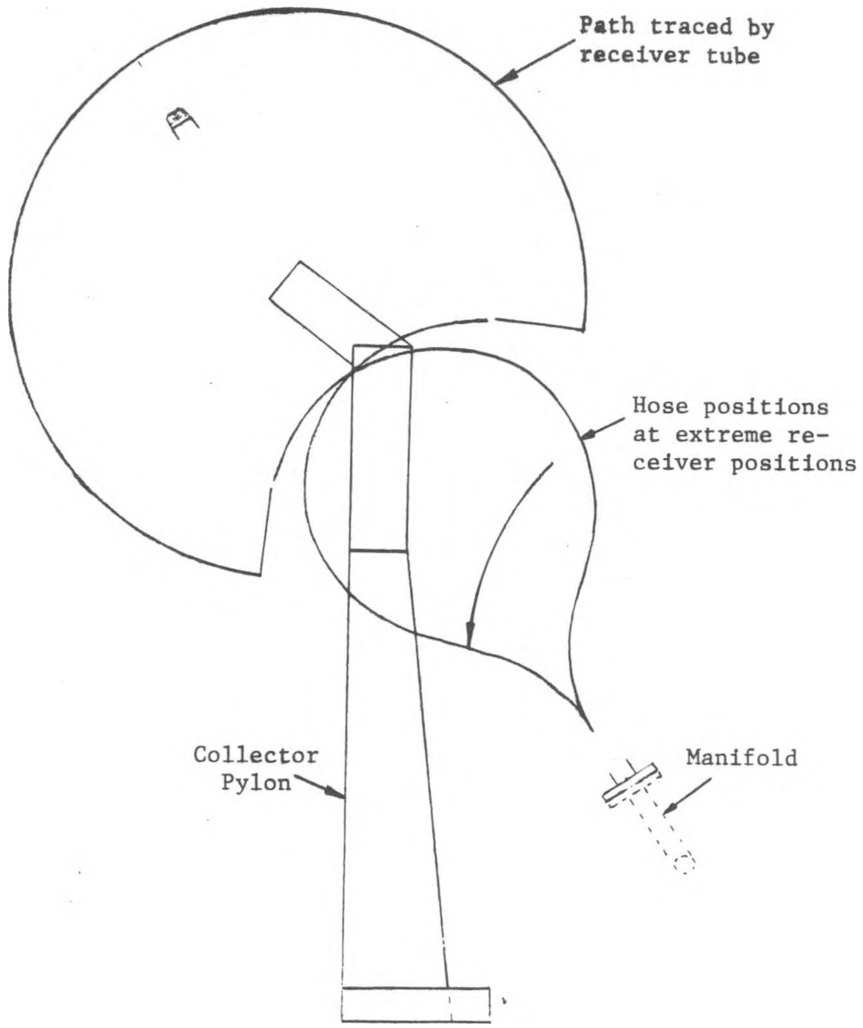

Figure 3 Flex Hose Arrangement

believe a simpler, less expensive means of maintaining a minimum temperature within the closed water loop is a thermostatically controlled electric heater installed in the accumulator.

To further simplify our MISR design, we also propose the elimination of all duplicate instruments and the use of hand-operated valves on the accumulator to control the initial nitrogen filling and purging of the vapor space. As a final measure we would also replace the cascaded feedwater flow control to the steam generator with a simple level control.

By these steps we not only reduce the initial capital cost of the MISR system, but also ensure easier operation and reduced maintenance without impairing the safety of the system in any significant way.

Interface Designs

Designs have been prepared for the installation of MISR systems to generate steam at the facilities of Davis & Geck in Manati, Puerto Rico, and Western Electric in Norcross, Georgia. In both cases the intent was to allow for system installation with the minimum of changes from the generic MISR design, while eliminating any extraneous instrumentation or components so as to reduce capital and operating costs.

At Western Electric's facility, where the MISR system's peak supply rate is less than 15 percent of the average demand, our approach was simple. We tied the steam supply from the MISR system into the plant's main steam line and accommodated any variations in steam demand and solar thermal system supply by modulating the supply of steam from one of the two boilers maintained on line at all times. This operating strategy is merely an extension of that currently in use. The resultant system design has the collectors on a north-south axis, thereby generating the most steam on an annual basis. A change in the field layout was required to fit the MISR system in the space available (Figure 4). The balance of the system was identical to that proposed in the generic MISR system design, with the exception that the skid-mounted air compressor was deleted, and plant instrument air was used in its place. The anticipated performance of the system, utilizing 258 m^2 (27,840 ft^2) of collectors, is depicted in Figure 5.

At Davis & Geck's facility, the operating strategy differed somewhat in that the solar thermal system was tied into two independent steam supply systems, although differences in the pressures with which the systems operate allow us to preferentially substitute for steam supplied in one of these systems. This strategy requires some manual operation. Should this be judged unacceptable, a more sophisticated control system has been devised. The system design again calls for collectors aligned on a north-south axis in an elongated field. The balance of the system

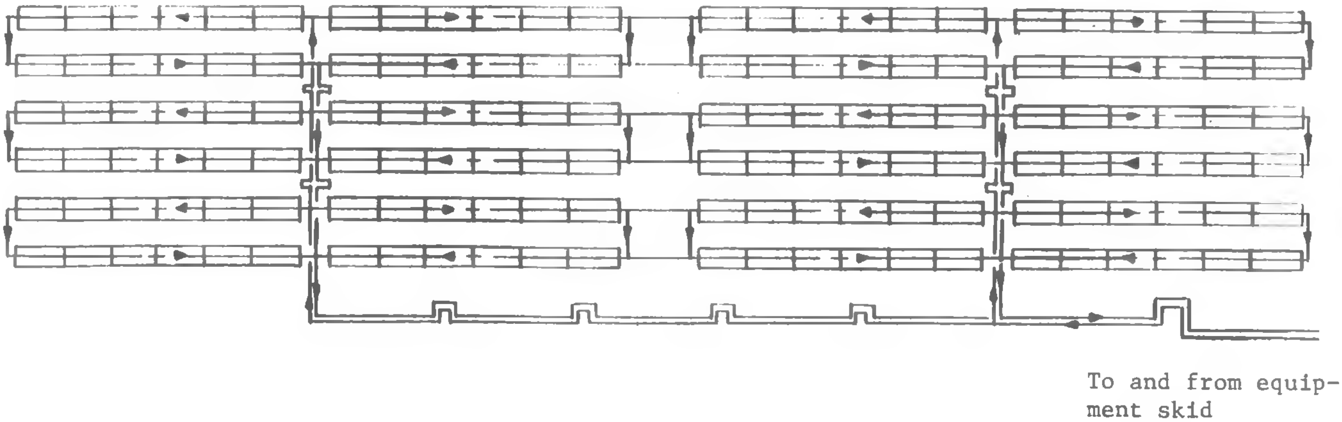

Figure 4 MISR Field Layout for Davis & Geck and Western Electric

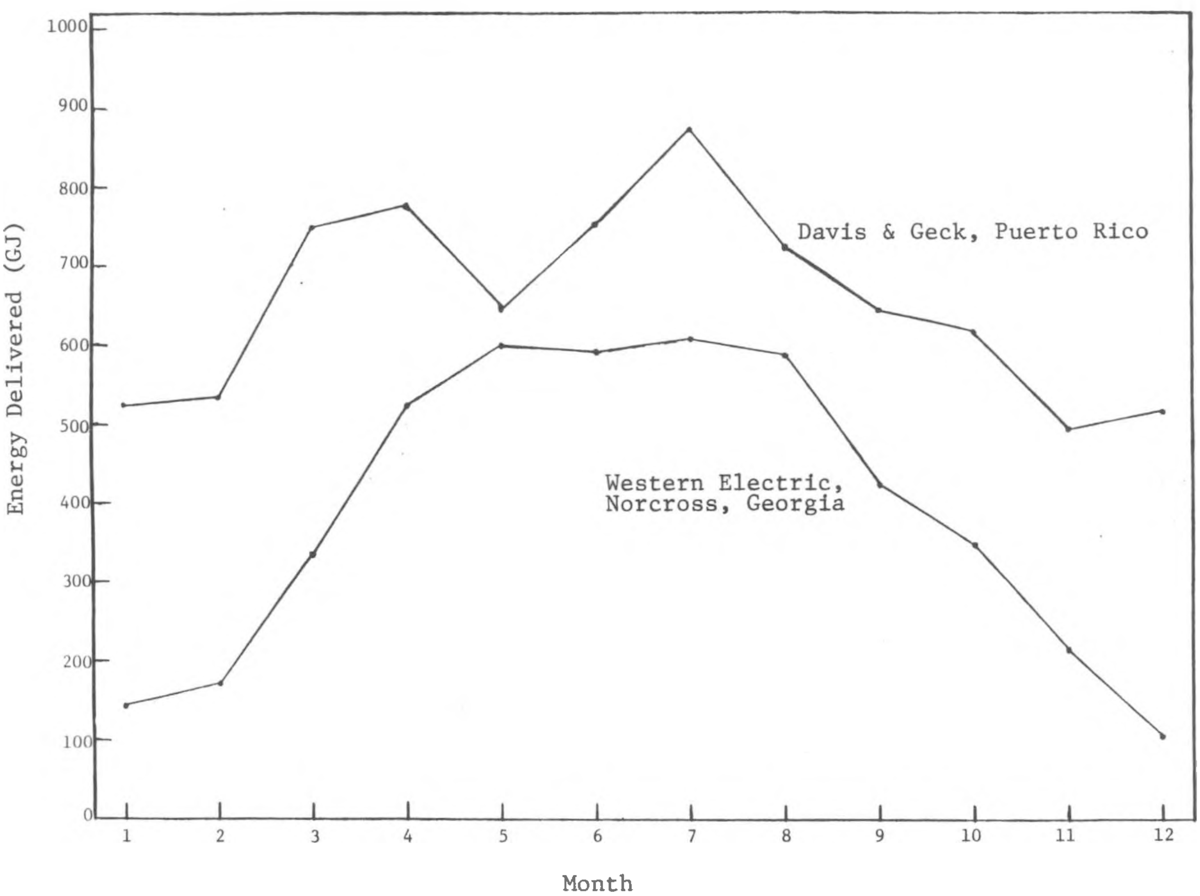

Figure 5 MISR System Performance (N-S Collectr Orientation)

is considerably simpler than that proposed elsewhere because of the elimination of all requirements for freeze protection. The anticipated performance of the system is shown in Figure 5.

No attempt was made to address the economic viability of the MISR system to each of the plants. However, current oil prices and economic conditions do not favor the installation of such systems at this time.

Conclusions

A modular industrial solar retrofit system using water as the heat-transfer fluid has been designed and tested. Additional designs have been prepared to show how these systems would interface with the plants of two prospective users of solar thermal energy. As a result of the tests and design reviews, design changes have been made or recommended. With these changes we believe that the reliable and efficient collection of solar thermal energy is possible.

ACKNOWLEDGMENTS

The authors thank R. Alvis and C. P. Cameron of Sandia National Laboratories and W. Hunt and A. Lewandowski of the Solar Energy Research Institute for their support and guidance during the project. We also thank the staff at Suntec Systems, Incorporated, and our colleagues at Foster Wheeler for their invaluable contributions.

FOSTER WHEELER SOLAR DEVELOPMENT CORPORATION

MISR - QTS DESCRIPTION AND TEST RESULTS

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ABSTRACT

The Foster Wheeler Solar Development Corporation Modular Industrial Solar Retrofit (MISR) Qualification Test System (QTS) was installed at the Solar Energy Research Institute for qualification testing and performance evaluation. The QTS consists of one solar collector delta temperature loop (1/12 of the design) and a full-size equipment skid. Installation of the system was completed and testing begun in September, 1982. Function and performance testing of the QTS is essentially complete. Operational and life testing have been delayed due to some problems with the rotary joints used to connect the collector receivers to the manifold. The rotary joints are being replaced with flexible hoses. Operational experience and performance data are summarized and some unique design features are discussed.

Foster Wheeler Solar Development Corporation
Modular Industrial solar Retrofit Project
Qualification Test System
Description and Test Results

INTRODUCTION

Foster Wheeler Solar Development Corporation was one of five companies selected to design a Modular Industrial Solar Retrofit (MISR) system and to install and complete operational checkout of a Qualification Test System (QTS) under contract to Sandia National Laboratories (SNLA). The QTS was installed at the Solar Energy Research Institute (SERI) at Golden, Colorado. Testing of the QTS was performed by SERI under the direction of SNLA using test equipment and test procedures which were essentially identical to that used for testing of the other MISR qualification test systems at SNLA.

The qualification test system includes a full-size MISR equipment skid and one of the twelve delta-temperature solar collector strings that would be in a full-size 2586 M^2 (27,840 ft^2) MISR system. In the qualification testing, the remainder of the collector field was simulated by a heat exchanger and propane-fired heater which collectively are referred to as the balance-of-field simulator. Eleven-twelfths of the fluid from the skid flows through the balance-of-field simulator and is heated to the same outlet temperature as the delta-T string.

QTS DESCRIPTION

An overview of the QTS is shown in Figure 1. The collector delta-T string, manufactured by Suntec Systems, Inc., is shown in Figure 2, and the equipment skid is in Figure 3. The delta-T string includes two drive groups each of which is 37 m (120 ft) long and has an aperture of 3 m (10 ft). The collector reflective surface is back-silvered sagged glass mounted on a space frame. Four panels of glass are mounted rim to rim allowing the collector to fold at the torque tube for shipment, although for the QTS, the glass was shipped separately. Each collector drive incorporates a Honeywell DC motor and a Eurodrive gearbox and is controlled by a Honeywell Flux Line Sun Tracker Control System.

Mounted on the equipment skid are the heat exchanger, accumulator, a 4 kW (5 hp) centrifugal pump, a 2 kW (3 hp) instrument air compressor, skid controls and instrumentation, a Honeywell Solar Field Master Controller and associated weather instrumentation, a power distribution panel, and nitrogen gas supply. The Foster Wheeler MISR system is unique in that the heat transfer fluid is pressurized water. Pressurized water is circulated through the solar collectors and the balance-of-field simulator where it is heated to a maximum outlet temperature of 270 °C (520°F). The water then flows to the heat exchanger and through the accumulator tank to the centrifugal pump and back again to the collectors and simulator.

UNIQUE DESIGN FEATURES

Adequate pressurization of the circulating water must be maintained at all times to prevent boiling in the collector receivers. In this system, pressure control is completely passive. The accumulator both accommodates the expansion of the pressurized water and maintains sufficient pressure (up to 6 MPa (880 psig)) so that boiling does not occur. Pressure control is passive in that the accumulator is initially pressurized with nitrogen and this pressure increases as increasing system temperature causes nitrogen pressurization and water expansion into the accumulator.

Unlike some other solar steam systems which use water as a heat transfer fluid, this system uses a heat exchanger rather than a flash tank for steam generation. This has the benefit of greatly reducing parasitic power requirements for operation of the heat transfer fluid pump. Feedwater is delivered to the heat exchanger through a pneumatically-operated valve which is proportionally controlled by a cascade control system which measures both feedwater flow and level. Steam which is generated in the heat exchanger flows through a check valve to the plant steam main.

A critical requirement for water systems is freeze protection of the collector field piping. In this system, water is periodically circulated through the system by the centrifugal pump when required. Stored heat is drawn from the heat exchanger and the accumulator. When the accumulator temperature falls below a preset minimum, steam from the plant steam main is allowed to blanket the heat exchanger. High level resulting from the condensation of the steam blanket causes an automatic drain valve to open. A temperature recorder monitors two sensors mounted on the receivers and an ambient air temperature sensor. The recorder starts the circulating pump when any two of the three sensors fall below 4° C (40° F) and stops the pump when both of the receiver sensors reach 38° C (100 ° F). This voting system of sensors provides redundancy; however, if the temperature recorder fails, as occurred in testing, no vote is taken and the freeze protection system is not energized.

Another unique feature of this system is the extensive use of pneumatic instrumentation throughout the system. Pneumatic instrumentation is used to control feedwater delivery, steam blanketing during freeze protection, and most system safeties. Pneumatic systems also drive a flow rate gauge and a three pen recorder that displays steam generator level and pressure as well as the pressure of the circulating water.

Backup power for stowing the collectors in case of power failure is provided by a battery box located in the collector field. No backup power is provided for freeze protection; however, capped drains are provided which can be opened if necessary to drain the collector field to prevent freezing.

Several unique features are associated with the collector receivers. Stainless steel bellows are used to seal the space between the black-chrome plated tubing and the glass annulus allowing for differential expansion of the tubing and the glass. The receiver is fastened to thin supports which bend as the receiver expands. The 3 m (10 ft) receiver sections are shop-welded together into twenty foot segments which were then field-welded together into 6 m (120 ft) lengths on the collectors.

As originally installed, a rotary joint was used to connect the rotating piping on the collectors to the stationary manifold. As shown in Figure 4, a short flexible hose connected the end of the receiver to piping at the center of rotation of the collector. At that point, a Swagelok quick-connect served as a rotary joint connecting the rotating collector piping to the stationary manifold. During testing of the QTS, several failures of the O-ring seal in these joints occurred. An improved O-ring material was then tried, but also failed. Subsequent analysis has indicated that wear of the bearing surfaces in the joint allowed the O-ring to be extruded out of position where it was quickly shredded. Since it appears that extensive modification or redesign of the joint would be required, Foster Wheeler has decided to install flexible hoses in the QTS; however, the high cost of flexible hoses for high pressure water systems provides an economic incentive for pursuing the application of rotary joints.

QTS FUNCTIONS

A Honeywell Solar Field Master Controller monitors sunlight and wind conditions. The set point of the sun sensor is field adjustable and the sensor also incorporates blinders which may be set to control startup and shutdown times. Five minutes of continuous sun are required before the system will start up. Twenty minutes of no sun will cause the system to be shut down. The shutdown timer is only reset if there is five minutes of sun during the twenty minute period. The pump is operated throughout the twenty minute period. The collectors will search for the sun once every twenty minutes while they are authorized to track.

The system will shutdown the circulation pump and stow the collectors if any of the following conditions occur: high wind, no flow, high or low fluid level in the accumulator, high or low fluid level in the heat exchanger, high heat exchanger pressure, high-high pressurized water pressure or loss of any phase of electrical power. An alarm without shutdown will be generated in response to low nitrogen supply pressure or high pressurized water pressure. In addition, the collectors will stow if a high temperature condition is detected by the local controller or if the battery power supply detects loss of AC power.

A rainwash feature has been incorporated in the master controller. To rainwash the collectors, the operator switches the master controller to manual authorization which starts the system and the pump as if sun conditions were satisfactory. When the collectors rise in their search mode to the desired position, the operator moves a switch which leaves them in that position until he resets the switch, or wind or a safety hazard shuts the system down. The master controller is placed in the back of the main control cabinet, but could be mounted inside the user's industrial plant if so desired.

EVALUATION RESULTS

The QTS was accepted for testing in September, 1982. The first set of tests to be performed were function and safety tests. The purpose of these tests was to determine that all safety systems operated as designed and that the system was fully operational. To the extent possible, all operating configurations were examined to determine how the system responded in all cases. During these tests, it was found that the annunciator system did not retain transient alarms and allowed the system to be started without a manual reset. In addition, the loss of flow alarm was found to occur after normal shutdowns. Further, the freeze protection system did not operate correctly. All of these items were corrected with fairly simple control wiring changes, and upon successful completion of these tests the system was placed in the unattended operations test.

The unattended operations test consists of a minimum of two weeks continuous automatic, unattended operation. The test site was set up to simulate a plant with a 1.7 MPa (250 psig) steam main, and the balance of field simulator was operated as described earlier. No maintenance of the QTS system other than scheduled maintenance was allowed. A minimum of seven days of total insolation above 4 kWh/m^2 (1272 Btu/ft^2) each was required or the test period was extended as long as necessary to achieve this requirement. The system was operated for the required time in the first attempt to complete this test; however, leaks developed in the rotary joints and a steady loss of nitrogen pressure from the system was observed which allowed boiling to occur in the receivers. The nitrogen leak has since been repaired by capping an automatic vent valve on the accumulator and relying on the safety relief valve for pressure relief in case of high system pressure. At this writing, procurement of the flexible hoses to replace the rotary joints is currently underway. It is expected that the unattended operation test will be repeated in March, 1983.

Life cycle tests are being performed on each QTS to evaluate the life of collector components, in particular the drive systems and flexible hoses/rotating joints. The rotary joints continued to experience failures during life cycling; however, the drive systems have completed 1161 cycles with no problems. A cycle is rotation from stow to the far horizon with stops at six angles in between each way. One cycle requires twenty minutes with the drive motor operating at a 60 percent duty cycle.

PERFORMANCE

Performance measurements are being made on each QTS. Peak (normal incidence) efficiency measurements are being made at inlet temperatures from 120 to 200° C (250 to 400° F) corresponding to steam pressures of 0.5 to 1.7 MPa (67 to 250 psig). Thermal loss measurements are being made over the same temperature range with the collector oriented towards clear sky so that the receiver is shaded by the collector. Measurement of incident angle modifiers and peak efficiency at ambient temperature are being made using tap water as a once-through heat transfer fluid. The heat capacity of the mechanical equipment skid and collectors are being determined by heating them as rapidly as possible from ambient with the balance-of-field simulator while measuring the heat input. Mechanical equipment skid thermal efficiency, overnight cooldown and parasitic electrical use are also being measured. The measurements completed and analyzed to date are summarized in Table 1. These basic parameters may be used to projected performance of the system in various applications. Such simulations as well as the results of the yet to be completed measurements and life cycle tests will be included in the final MISR project report.

ACKNOWLEDGMENT

I wish to thank Allen Lewandowski of SERI for his excellent work in directing the testing of the Foster Wheeler QTS and to thank as well William Hunt, John Anderson, Carl Bingham, Jim Pruett, and Walter Peters, also of SERI, for their assistance in testing.

TABLE 1

PERFORMANCE RESULTS*
Collector Efficiency At Normal Incidence

Average Temperature (°C)	Average Temperature (°F)	Ambient Temperature (°C)	Ambient Temperature (°F)	Direct Normal Insolation (W/m^2)	Direct Normal Insolation (BTU/hr-ft^2)	Efficiency (%)
224	435	15	59	887	282	59
178	353	10	50	903	287	63
117	243	12	54	877	279	67
24	75	14	57	836	266	75

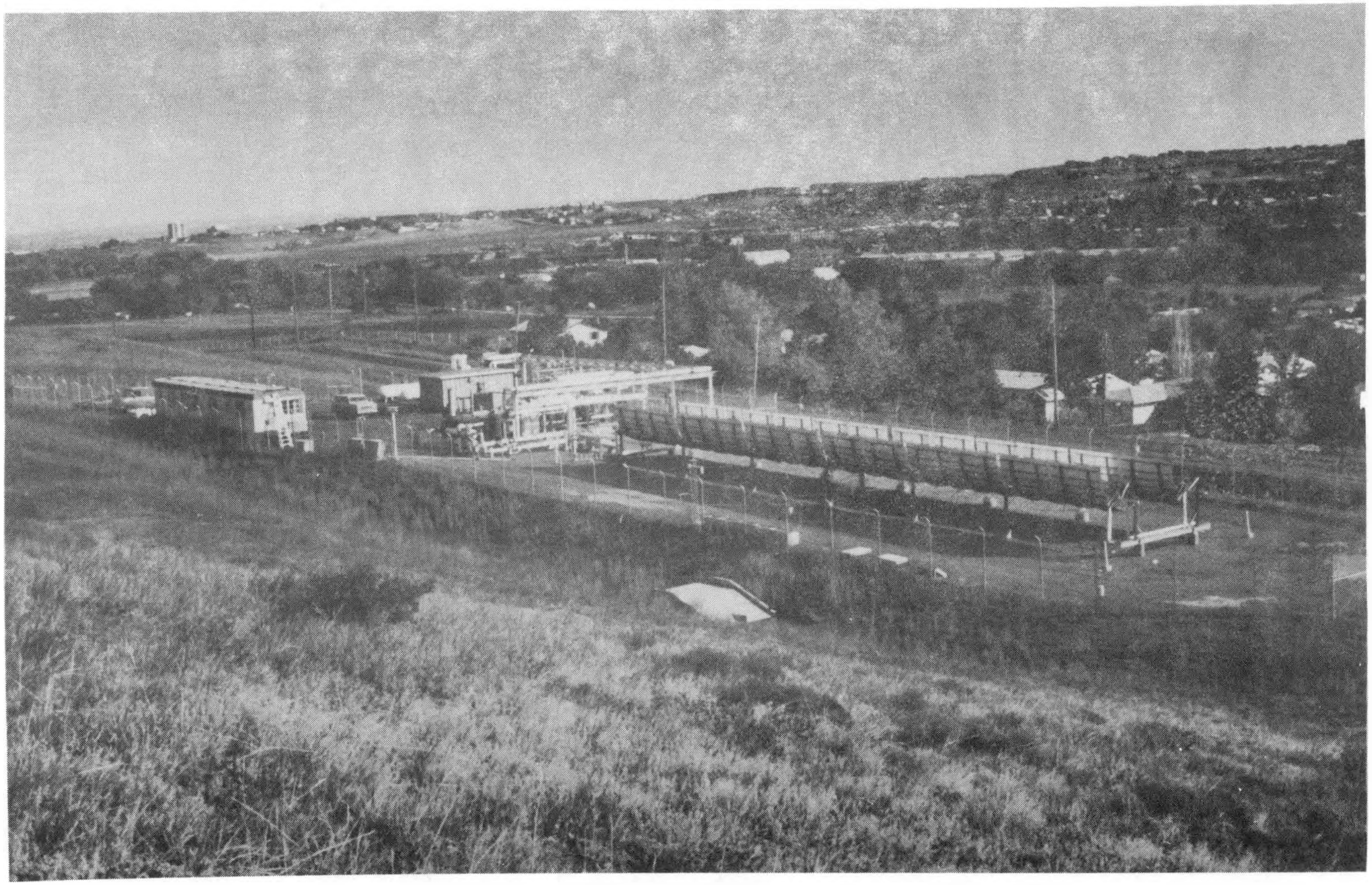
Collector Heat Loss

Average Temperature (°C)	Average Temperature (°F)	Ambient Temperature (°C)	Ambient Temperature (°F)	Wind Speed (m/s)	Wind Speed (mph)	Heat Loss (W/m^2)	Heat Loss (BTU/hr-ft^2)
202	395	11	52	4	9	113	36
201	394	5	40	2	5	98	31
174	346	3	37	1	3	79	25
153	307	10	51	8	18	78	25
144	291	3	37	1	3	60	19
121	250	2	35	2	4	44	14
97	207	9	49	6	14	33	10
96	205	2	36	2	4	31	10

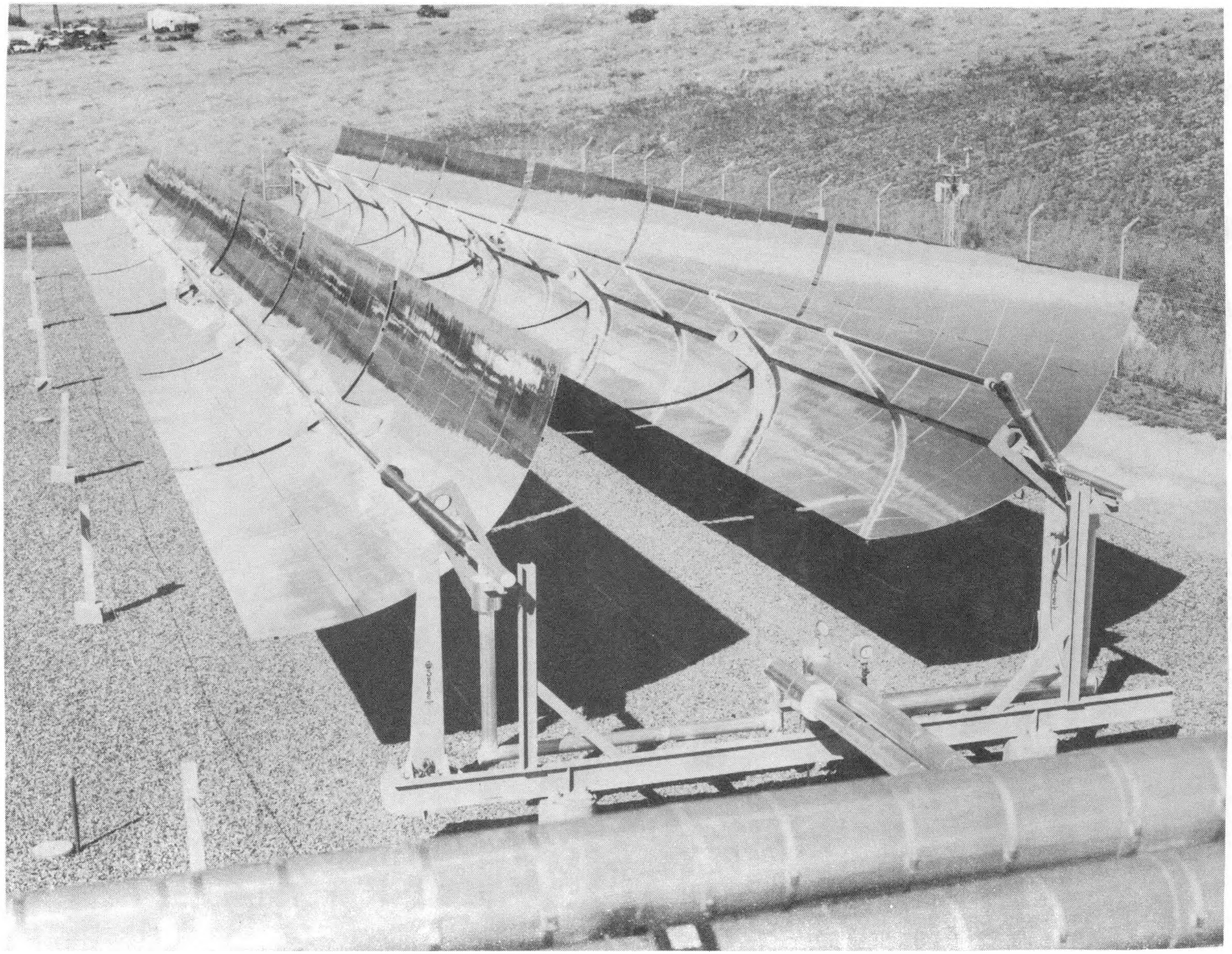
Collector Incident Angle Modifier

Average Temperature (°C)	Average Temperature (°F)	Ambient Temperature (°C)	Ambient Temperature (°F)	Direct Normal Insolation (W/m^2)	Direct Normal Insolation (BTU/hr-ft^2)	Incident Angle (°)	Incident Angle Modifier
21	70	9	48	745	237	1.9	1.0
20	68	9	47	711	226	19.0	0.94
18	65	9	48	657	209	31.2	0.91
17	62	9	48	575	183	40.9	0.89
14	58	9	47	418	418	52.2	0.80

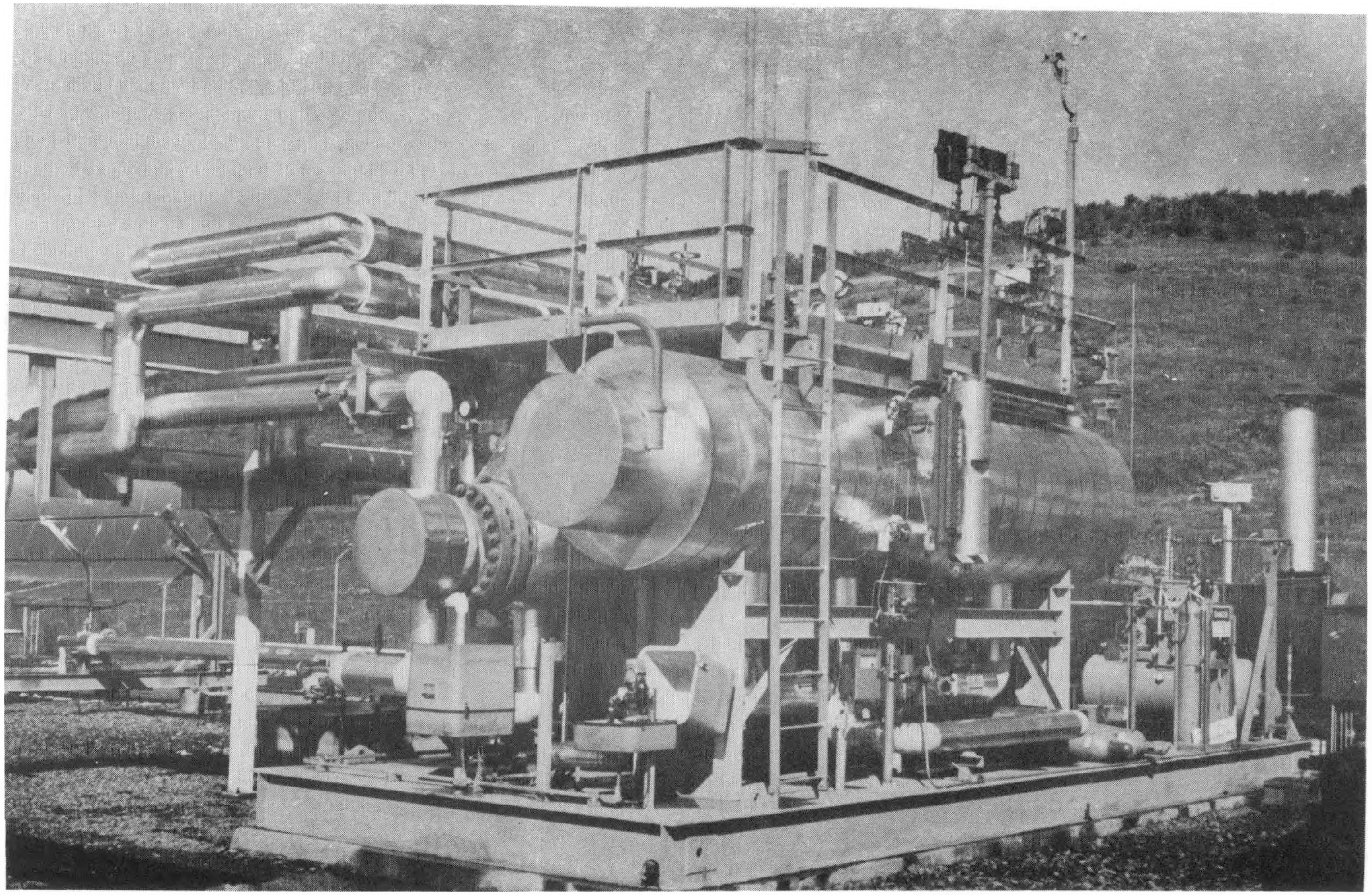
*Collector efficiency and heat loss were measured from the inlet to the outlet of the delta-temperature string; thus, heat loss from flexible hoses rotary joints, and interconnecting piping are included in the results.



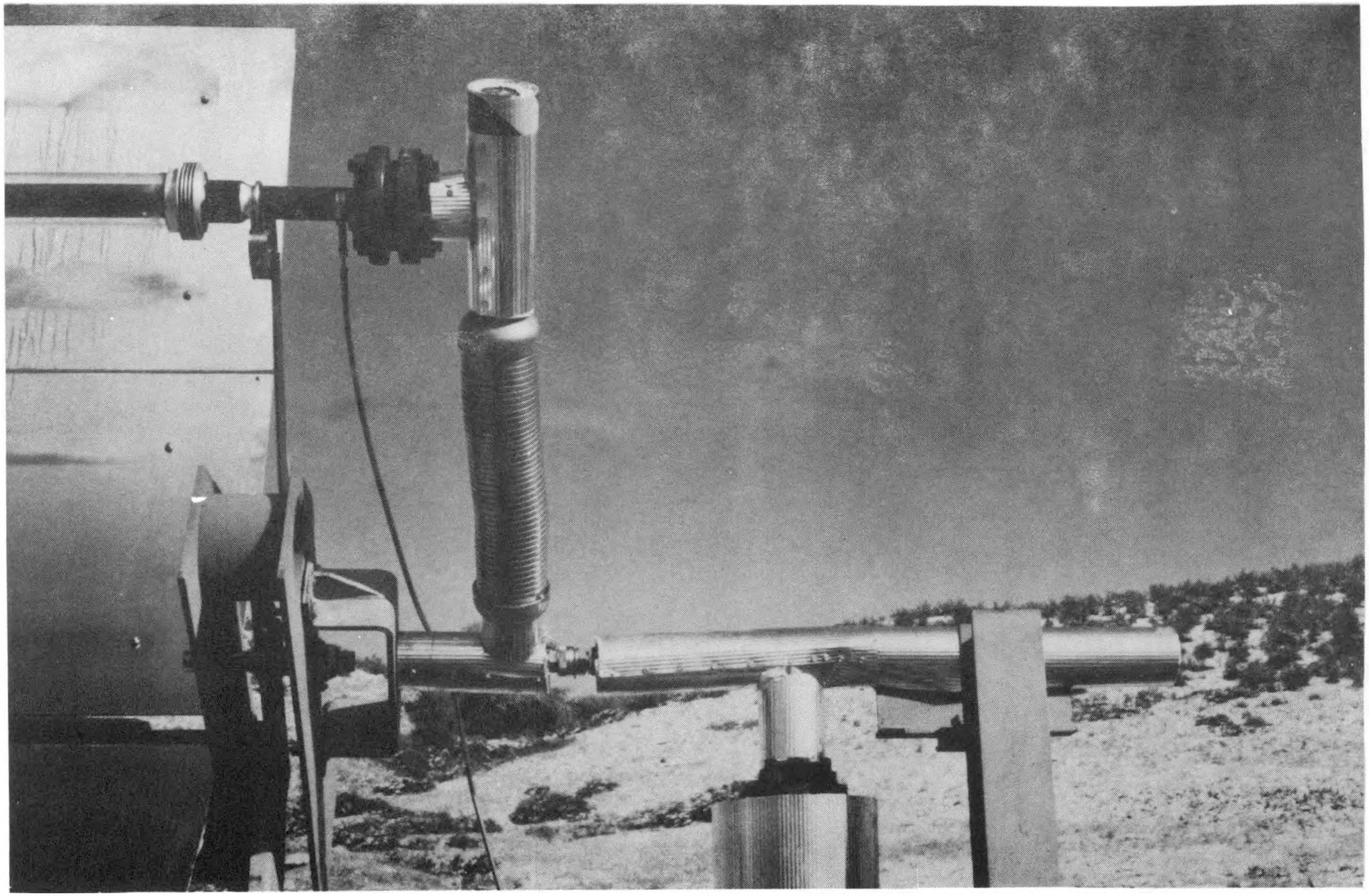
FOSTER WHEELER MISR QUALIFICATION TEST SYSTEM
AT
SOLAR ENERGY RESEARCH INSTITUTE MISR TEST SITE
Figure 1



SUNTEC COLLECTORS IN FOSTER WHEELER MISR OTS
Figure 2



FOSTER WHEELER MISR EQUIPMENT SKID
Figure 3



ROTATING JOINT ASSEMBLY
Figure 4

SOLAR KINETICS, INC.

MODULAR INDUSTRIAL SOLAR RETROFIT (MISR)

SYSTEM DESIGN

INTERFACE DESIGNS

by

Joseph A. Hutchison

and

John Witt

Solar Kinetics, Inc.

INTRODUCTION

Solar Kinetics' personnel, in association with Stone and Webster Engineering, Boston, Massachusetts, completed the MISR design task during 1982. The design was intended to emphasize plant manufactured modular components where possible. Many trade-off studies were made with strong efforts to minimize upper operating temperature. Many decisions were made with the then-current understanding of a fast developing product concept. Some of the ideas have changed since that time and minor changes are anticipated as a result of the experience of the QTS testing program and development in general.

SYSTEM GENERAL DESCRIPTION

The SKI-MISR design utilizes 168 T-800 (Fig. 1) mirror modules arranged in 28 trackable rows of six (6). The target area of 25,000 sq. ft. is exceeded slightly since the proposed return loop design requires even numbers of rows forming a symmetrical pattern and the next lower number of rows, 24, would provide only 22,752 sq. ft. of solar aperture. Current thinking is to use eight T-800 mirrors per row with a module area of 25,400 sq. ft. This layout would place 160 mirrors in 10 delta loops of 2540 sq. ft. each.

The steam generating skid contains all fluid control, pumping and steam generating equipment. The collector field controls and sensors are also part of the skid. This modular factory built skid features a metal enclosure for thermal loss reduction and component life. It is also the point of user interface for both utilities and steam output.

Part of the collector field insulated pipes, supports, connectors and valves are factory built.

COLLECTOR FIELD LAYOUT

Generally speaking, a collector field is most efficient in land use if it approaches squareness. Certain boundaries outside the collector field (i.e. to fences) are required and long rectangular shapes tend to use more land. With trackable rows of 125 feet in length, the length of a delta-T loop also is significant.

The basic trade-off in collector field layout is plumbing length and land use area. If one optimizes for minimum plumbing, the collector field becomes one very long delta T string, but problems with delta-T and fluid transit time occur, not to mention land use. SKI has opted for the square design as shown on Figure 1. This layout uses manifolds at the center and minimizes fluid transit time by use of 2 row delta-T loops.

The return loop design is preferred since it allows vehicle access to all areas of the field and such a return loop would be most easily produced at the factory and sold as part of the collector.

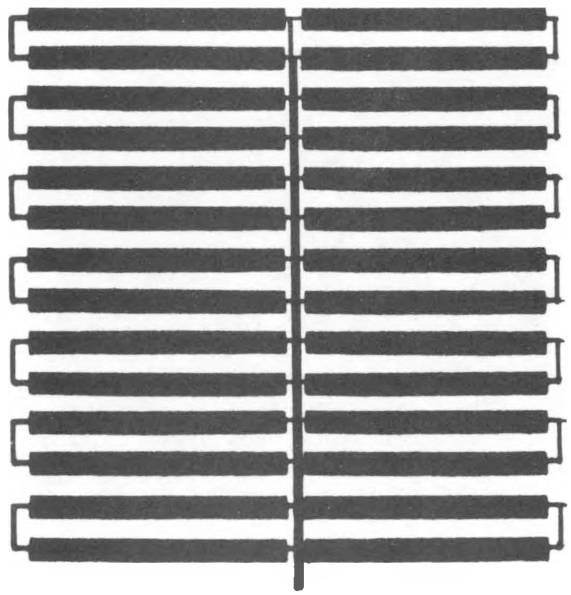


Figure 1.

MISR Array Layout - 2 Row delta-T Loop

Row spacing is proposed at three apertures or 24 feet since the T-800 has a solar aperture of 8 x 20 feet. This spacing minimizes adjacent row shadowing of the collectors.

SITE PREPARATION

Experience has indicated that level ground usually requires some grading to insure proper drainage. This cost is approximately $350 for a MISR module or one day for a small bulldozer.

The site is then surveyed and foundation piers drilled. Factory built rebar/J bolt assemblies will be placed in the holes, attached to fixtures and pier foundations formed. A factory supplied overflow tank will be buried or poured at this time with factory supplied forms.

The perimeter fence is erected to provide security for the site as soon as the foundations are cured.

EQUIPMENT TRANSPORTATION

The steam generator skid will be shipped on specialty hauler flat bed trucks. The design allows for crane handling during loading and unloading. The factory built insulated pipes use special reusable shipping racks which minimize shipping costs. These racks are similar to those developed for shipment of SKI T-700 collectors. The only packaging cost is the return freight cost on the collapsible steel racks. All designs will accomplished to allow shipment on flat bed trucks and flat bed rail cars.

The major equipment components, other than the collector array, are the heat exchanger, HTF circulation pumps, HTF expansion tank, fire extinguisher system, and auxiliary electric generator.

HEAT EXCHANGER (HE1)

Heat Exchanger (HE1) is a basic "kettle" type reboiler. It is a multi-pass tube and shell heat exchanger, consisting of two main sections: the heat exchanger tube bundle and bonnet which carries the heat transfer fluid (HTF), and the steam generator shell (kettle) which serves as the feedwater containment vessel (boiler). Figure 3-1 is a graphic representation of HE1.

The tube bundle is attached at the conical section of the heat exchanger vessel, and is comprised of the bonnet with the HTF inlet and outlet nozzles, and the heat exchanger tubing that is attached to the tube sheet and extends into the shell section of the vessel. The shell itself is a 48" diameter and horizontally mounted. The heat exchanger design is such that during normal operation, water level inside the kettle is maintained within a range (6") that insures

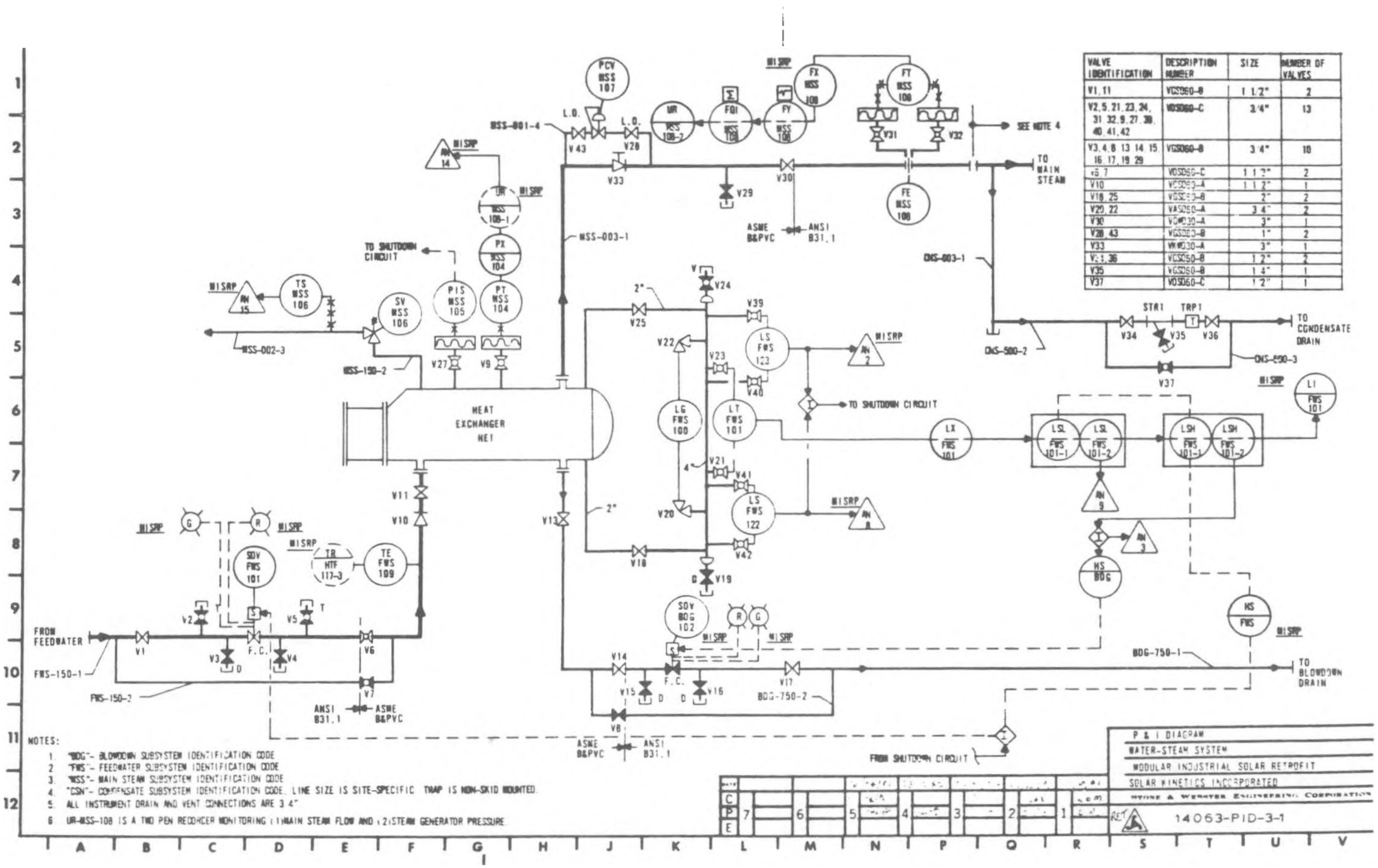


Figure 2.

Piping and Instrumentation Diagram - Steam System.

complete immersion of the tubes (minimum design level) and adequate steam volume space within the upper section of the vessel (maximum design level). Heat of the HTF passing within the exchanger tubes is transferred through the tubing wall to the water around it, raising the water to saturated steam conditions and producing steam at the top of the kettle.

A separate feedwater preheater will be included with the skid for projects which utilize feedwater at condensate return temperatures below 150°F.

HTF CIRCULATION PUMP (HTF-P1)

Circulation pump HTF-P1 provides circulation of the heat transfer fluid within the HTF loop of the MISR system. The pump is located within the SKID enclosure and is controlled from the MISR control panel. A locally mounted push-button test switch is also provided for maintenance.

HTF-P1 is a single-stage centrifugal pump designed to provide a closed loop flow rate of 280 gpm of Therminol at design point conditions (416°F suction temperature). The specified manufactured design rating is 300 gpm at 140 feet head (for water at 60°F).

HTF EXPANSION TANK (TK-1)

Expansion tank HTF-TK-1 is provided as a means to accommodate thermal expansion of the heat transfer fluid. The tank is permanently mounted in place on the SKID and two 4" diameter suction pipes interconnect the tank to the HTF loop piping.

The vessel is 36" in diameter and has a 60 cu. ft. capacity. A 16" man- hole is provided at one end of the tank. The vessel is rated at 50 psig and 600°F. At design point operating conditions, the tank will be pressurized (due to HTF expansion) to approximately 30 psig. At start-up, the tank will be about one-quarter full (15 cubic feet) and at design point operating conditions, about three-quarters full (45 cubic feet).

The expansion tank is physically mounted on the SKID at an elevation approximately 6-8 feet above HTF-P1. This allows for net positive suction head on the pump and for venting of gases at the highest point in the HTF system. The positive suction head ensures flooded pump suction and prevents pump cavitation during start-up and venting of the system.

PROCESS STEAM SYSTEM

To follow the detailed system description below, refer to process and instrumentation diagram PID-3-1 (See Figure 2). The process steam system consists of four separate but integrated subsystems: feedwater (FWS), main steam (MSS), blowdown (BDG), and condensate (CNS). The main function of the system is to receive the feedwater steam from the existing industrial plant and elevate its temperature to saturation steam condition using the heat collected from the line focus heat transfer fluid via the heat exchanger HE1. The steam is then returned to the plant for process use. The blowdown subsystem maintains water impurities in the heat exchanger to levels below limiting concentrations detrimental to system life and operation. A condensate collection subsystem is used to remove water from the main steam piping. Key equipment and process conditions for each subsystem are itemized below.

Feedwater Subsystem

Feedwater is delivered at a nominal 15 gpm at 300 psig to the feedwater line at the utility bulkhead. The system is designed to handle a range of feedwater temperatures from 40°F to 230°F with a design point of 200°F. Flow control valve SOV-FWS-101 is solenoid activated to control admission of feedwater into the heat exchanger in order to maintain water level in the kettle within a 6" level range. Differential pressure taps, drain valves, isolation valves, and a bypass line are all provided for this flow control valve. Check valve V-10 is provided near the heat exchanger to prevent possible backflow of shell side water into the feedwater line.

Main Steam Subsystem

Heat Exchanger HE1 accepts feedwater at 6,425 lb/hr and produces saturated steam at an operating pressure of 250 psig. Steam pressure may be delivered within the range of 100 psig to 250 psig, according to the particular application. HE1 has a gross tube surface area of 848 sq. ft. and is designed to meet the requirements of Section VIII, Division 1 of the Boiler Code. HE1 is provided with a safety valve SV-MSS-100 and a standpipe for level gage LG-FWS-100 attachment. Additional taps are provided for pressure indication and high pressure safety system activation.

Steam exits the exchanger through the main steam line to stop check valve V-33. Back pressure from the industrial process steam system will permit admission of MISR steam only during those periods for which sufficient pressure exists to open this valve. Free blow and stop valves are provided according to the piping requirements of Section I of the Boiler Code. Provisions are included for steam flow monitoring in the main steam line. Pressure regulating valve PCV-MSS-107 is provided as a bypass to V-33 in order to permit a steam blanket for HE1 during extended MISR shutdown conditions. This will prevent air inleakages and concomitant corrosion.

Blowdown Subsystem

The blowdown line from HE1 permits boiler water release via solenoid valve SOV-BD-102 activation or via manual valve release. It is desirable to blow down for conductivity sampling during cold system shutdown conditions in order to preserve solenoid valve life. This valve is provided with appropriate isolation and drain valves.

Condensate Subsystem

A vertical condensate collection leg is provided at the downstream end of the pitched main steam line in order to drain the line during system start-up.

HEAT TRANSFER FLUID

To follow the detailed system description below, refer to process and instrumentation diagrams PID-38-1 for skid-mounted equipment and PID-39-1 for collector field equipment (See Figure 3 and 4).

The function of the heat transfer fluid (HTF) system is to provide a medium for transferring incident solar radiation energy collected by the line focus collector field to the heat exchanger. The heat exchanger fluid utilized is Monsanto Therminol 60. HTF circulation pump P1 is designed to maintain a constant closed-loop flow rate of Therminolo at 280 gpm at design point conditions. Total differential pressure across the pump at design point conditions is estimated to be 51 psi. Total brake horsepower requirement at 68% pump efficiency is 13.2 hp. The pump is designed to meet API 610 specifications for centrifugal pumps.

Thermal induced expansion of the Therminol is accommodated by expansion tank TK1, which is elevated approximately 6-8 feet above the suction side of the pump. This tank also serves as the main venting point of the system. The capacity of the expansion tank is 60 cu. ft. Double drop legs on the tank ensure flooded pump suction and uninterrupted flow during venting and start-up. Bypass valve V-25 on the expansion tank drop leg is opened during normal operation in order to prevent potential thermal siphoning into the tank. Appropriate venting and drain points are provided. A fill line is provided for initial fluid charge of the system, and the tank is provided with a standpipe for level gage LG-HTF-110. Relieve valve RV-HTF-124 is provided in the unlikely event of overpressurization (e.g., a heat exchanger tube rupture).

In the presence of air and at temperatures above 100°F, Therminol 60 oxidized and degrades rather rapidly. Air contact in the closed expansion tank is eliminated and the expanding HTF will pressurize the tank to 30 psig at the design point conditions (416°F Therminol temperature at pump suction). The tank will be one-quarter full during cold shutdown and three-quarters full at design temperature. An additional benefit of pressurization is that it provides more than enough net positive suction head (NPSH) for the HTF circulation pump.

Total dynamic head across the HTF circulation pump is monitored by differential pressure indicator DPIS-HTF-114. In conjunction with a

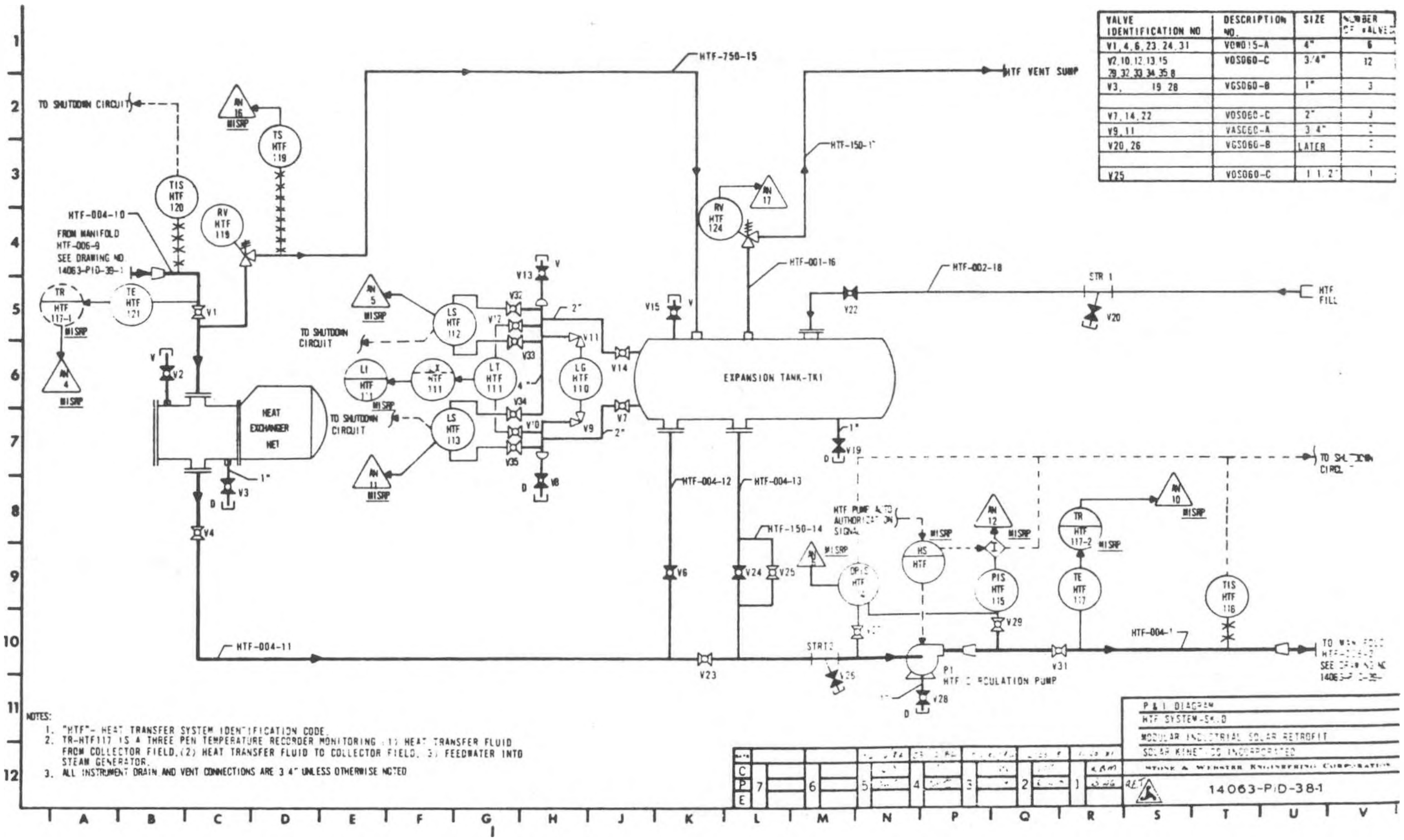


Figure 3.

Piping and Instrumentation Diagram - HTF System.

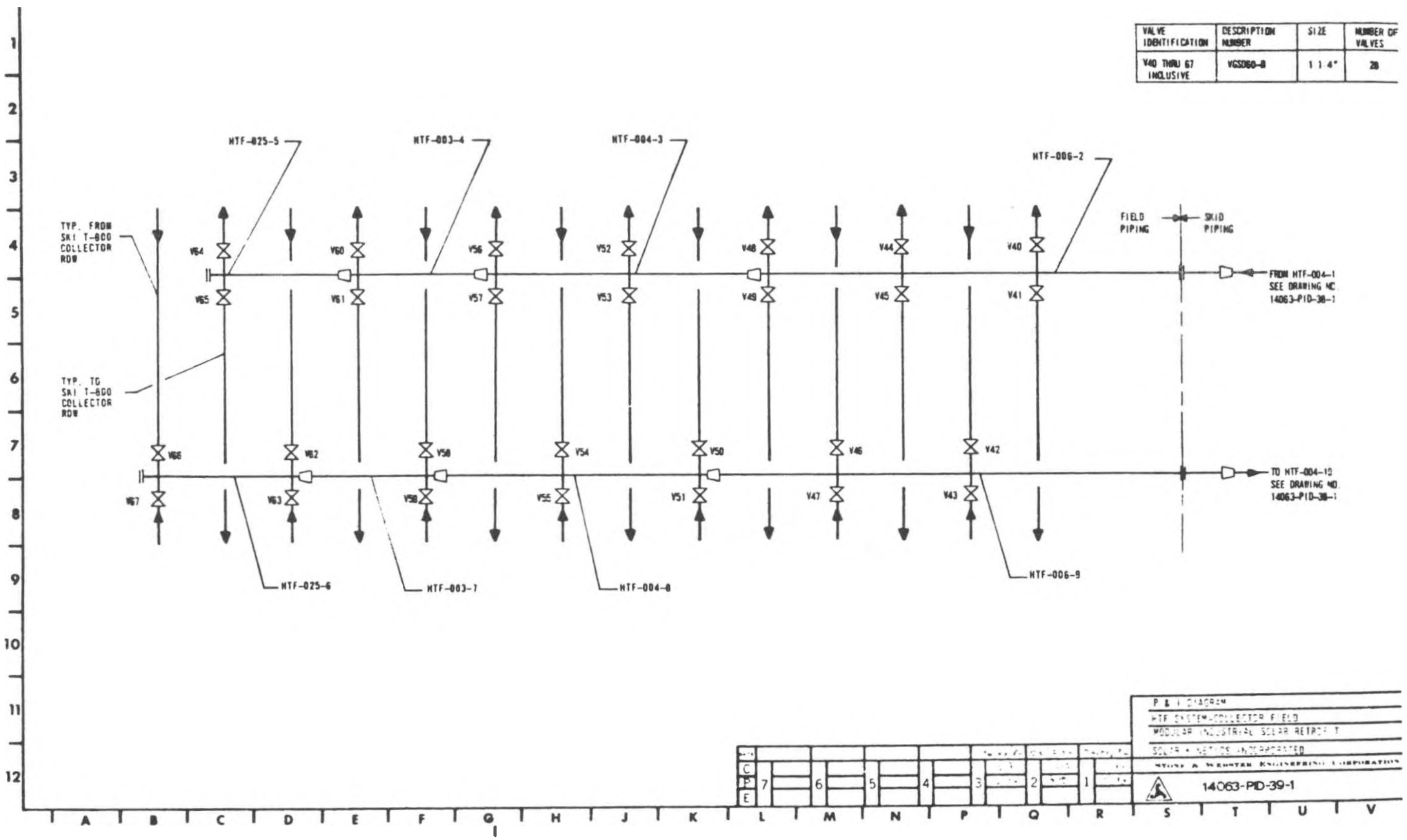


Figure 4.

Piping and Instrumentation Design - HTF System, Collector Field knowledge of the Therminol temperature at the pump, this information allows calculation of flow rate at any time. Static discharge head is monitored by pressure indicator PIS-HTF-115.

Monitoring of the fluid temperature is provided at temperature element TE-HTF-117 and temperature indicator TIS-HTF-118 at the pump discharge. Upon leaving the pump, Therminol is transported via the supply manifold to the solar collector field at 416°F. The field consists of 28 trackable rows of Solar Kinetics T-800 line focus collectors arranged into 14 temperature differential flow loops, each having a 20 gpm design flow rate. Flow from the supply manifold enters each loop under balanced flow conditions. Flow from each loop enters the return manifold at 486°F for transport to the heat exchanger HE1. The temperature of the fluid leaving the collector field is monitored at TE-HTF-121 and TIS-HTF-120 at the exchanger channel entrance.

Heat exchanger HE1 is provided on the tube side with appropriate isolation valves and a vent and a drain. In the remote event of reverse heat transfer during closure of the isolation valves, thermal relief valve RV-HTF-119 is provided as a safety feature. HE1 has a gross tube surface area of 848 sq. ft. using six passes and a log mean temperature difference of 33.7°F at design point conditions.

FIRE PROTECTION

System Design

The function of the fire protection system is to monitor the skid enclosure for high temperature and to extinguish any fire detected using a carbon dioxide (CO) total flooding system. This system has been designed to meet the requirements of NFPA 12-1980, "Standard on Carbon Dioxide Extinguishing Systems", and Factory Mutual Engineering Data Sheet 4-11 1976, "Carbon Dioxide Extinguishing Systems".

Detection of high temperature from heat generated by a fire is provided by two rate-compensated type thermal detectors (FTDR-1&2), installed at the heat exchanger and at the instrument enclosure.

Letdown of CO within the skid enclosure is via opening of a solenoid valve activated by detection of high temperature. Initial discharge is at least 135 lb. with extended discharge provided to maintain a design concentration of CO of not less than 46% for ten (10) minutes. A control panel is provided adjacent to the CO bottles and gel-cell batteries are provided in case of normal power loss.

MISR INTERFACE DESIGNS

In a logical follow on of the designs of the MISR steam system, the Department of Energy solicited interest from appropriate industrial firms in participating in a design study to accommodate a MISR system at a real industrial situation.

Interested firms were interviewed and two of these firms were assigned to each of the participants in the MISR design study.

The El Paso Products Company in Odessa, Texas and the PABCO Insulation Division of Louisiana-Pacific Company, located in Fruita, Colorado, were selected as Solar Kinetics' applications.

Following are summary descriptions of the interface design for each plant.

PABCO INSULATION DIVISION

The PABCO Insulation Division of Louisiana-Pacific Corporation is located on the western edge of Fruita, Colorado. The sole product of this modern, well organized facility is moulded calcium-silicate insulation for piping. The production process requires steam at several pressures. The predominate use is for heating the kilns used for drying the green insulation preforms. There are other peripheral loads including an insulation test loop and wintertime space heating.

The drying kilns are end-loaded with a train of dollies carrying the product. A consequence of this batch-type processing is a large cyclical swing in the steam demand.

Steam is currently produced by a Babcock and Wilcox boiler fired by natural gas. Saturated steam is produced at a nominal operating pressure of 235 psig with a design maximum of 250 psig. Pressure regulators are used on this primary steam to produce lower pressures for peripheral loads.

Feedwater at a pressure of 325 psi is supplied by a pair of Worthington electric pumps. An automatic water treatment system provides boiler quality makeup water to the condensate return system. Piping is carried overhead in racks throughout the plant.

The plant is situated on a flat, level border of the Colorado River. The basic soil type is silty clay with interspersed sand. Adjacent to the plant is an open field available to site the solar collector array.

Solar Process Steam System

Steam generation by the solar collector array is accomplished by pumping a heat transfer oil (Therminol 60) through the collector receiver tubes where the fluid acquires energy, then through the tube bundle of a kettle-type heat exchanger to generate steam.

The heat exchanger, HTF pump, related control and safety equipment, valves and associated plumbing are mounted on a truck-transportable equipment skid. The complete equipment skid is covered by a weatherproof metal enclosure. Maintenance access is provided by doors in the side of the enclosure. Skid controls, the central collector array controls and instrumentation are contained in a small room located at one end of the skid.

Flanged terminations are provided at openings in the enclosure walls to connect the various services to the skid equipment. These are:

* HTF inlet
* HTF outlet
* Steam outlet
* Feedwater inlet
* Blowdown
* Safety valve exhaust
* HTF relief valve exhaust

Electrical service requirements consist of a single 440/480 VAC, 3 phase supply. The connection is made at an enclosed terminal block inside the automatic transfer switch. Voltage reduction and internal power distribution are handled by appropriate equipment in the skid.

Emergency power is generated by an auxiliary power unit supplying the automatic transfer switch. An exerciser is provided to periodically operate the generator system.

Concentrating Solar Collectors

The collector array for the PABCO system is situated next to the plant on the east side. The large, open area available for array placement allowed the use of a standard SKI-MISR module of 26,544 sq. ft. aperture of T-800 solar collectors, oriented with the tracking axis in a north/south direction. Twelve collectors are arranged in a series of two row delta-T loops with a design delta-T of 70°F across the array. Design outlet temperature is a maximum of 486°F.

The design thermal input for the system is 4.756 M BTU/hr. This represents a mass flow of 120,000 lbs/hr of Therminol 60.

Foundation design layout is the standard MISR system with the foundation depth controlled by soil conditions.

Plant-SKID Interface

An insulated 3" steam line is routed from the steam outlet at the skid to the PABCO plant proper. Internal routing of this line parallels the low pressure line from the inner wall of the DE area near the solar collectors to a tee-junction at the 6" central steam main.

The feedwater would also follow this routing, extending past the steam main to the boiler room. A line for condensate return is also routed with the above pipes. A check valve is positioned in the MISR steam line inside the DE bay area. This valve isolates the solar steam system when the system is not in operation. A manual shufoff valve is also provided.

The steam, condensate return and feedwater piping are electrically heat traced for freeze protection. Heat tracing extends from the check valve to the MISR steam skid and is controlled by thermostats which sense the piping temperature.

The insulation system is aluminum jacketed calcium silicate. A thickness of 3" is applied to the steam lines and feedwater lines.

The impact of the additional solar steam production on plant operations was examined. On review of a graph recording of the boiler output, the large cyclical swings caused by the kilns could be observed. The minimum output portion of the cycle occurs at a boiler output of about 15,000 lbs/hr of steam.

Since the maximum output of the boiler is 48 MM BTU/hr producing about 41,000 lbs/hr of steam, the low point corresponds to a turn down of 2.7:1. The maximum output, occurring in June, of the solar array is 4000 lbs/hr. The solar output subtracted from the minimum plant requirement yields a boiler output requirement of 11,000 lbs/hr, still within the 7:1 turn down ratio of the boiler.

In the solar off-peak hours, the match to the boiler is better as the solar contribution is smaller.

EL PASO PRODUCTS COMPANY

The El Paso Products Company's Foster plant is located on the west edge of Odessa, Texas. The plant refines natural gas stock to producer consumer natural gas and various chemical feedstock gases and sulphur.

Steam production supporting the plant processes originates at a single boiler house. Steam is produced by a Wickes and a Cleaver-Brooks boiler fired by natural gas. There are also four boilers which are brought on line to supplement the Wickes and Cleaver-Brooks. Use of the older boilers is confined to times when cold weather increases the heat tracing load. System operating pressure is 190 psig with a 250 psig design point.

The boiler feedwater system is comprised of several steam turbine pumps and reciprocating steam pumps which supply 300 psig pressurized water to the boilers. A water treatment system provides makeup water which is added to the condensate return.

The Foster plant is of the open construction typical of the petrochemical industry. Several buildings, however, are used to house pumping and compressor engines, offices and the boilers. Most of the processing towers and vessels are exposed to the weather. Piping is carried in racks and ranges from ground level to many feet in height.

The plant area is flat and level. The area available for the solar collector array is irregular in shape and would not accomodate the full array in one section. In order to assure adequate access around the array and have no array shadowing, the solar field was split into two sections. The steam main has a termination which is convenient to the proposed skid location and is already furnished with a condensate trap.

Concentrating Solar Collectors

The collector array for the El Paso Products system is situated in two clear areas on the northeast corner of the plant. Because of shadowing and physical interference of existing structures, the array was divided into two sections. The array axis is oriented east-west. In addition, the array piping was rearranged to accommodate the non-standard-MISR layout.

The design thermal input of the system is 4.756 M BTU/hr. This represents a mass flow of 120,000 lbs/hr of Therminol 60 heat transfer fluid. The collectors arranged in two row delta-T loops with a design temperature change of 70°F across the array. Maximum outlet temperature is 486°F.

The collector foundation design is the standard MISR system with the foundation depth controlled by soil conditions.

Plant-SKID Interface

Steam Service: An insulated steam line is mounted on racks and runs from the boiler house to the plant area.

A stub end of this main is available in reasonable proximity to the planned skid location. This stub is already equipped with a shut-off valve and steam trap. A 3" line would be routed from the skid to this location.

The feedwater line would be supported in the racks which carries the steam main and would run from the skid to the boiler room.

The steam and feedwater lines are to be electrically traced for freeze protection. Heat tracing extends from the main line connection to the skid outlet flanges and is thermostatically controlled by sensing the piping temperature.

The insulation system is aluminum jacketed fiberglass. A thickness of 3" is applied to all lines.

The effect of solar steam production on plant loads will be minimal. The existing minimum steam demand is about 45,000 lbs/hr and the maximum array output is about 3800 lbs/hr. The solar output is 8.4% of the minimum existing load which is well within the existing boiler turndown capacity.

Electrical power is available from an existing distribution panel which also serves motor driven fans in a condensor assembly. Rigid conduit carrying the three phase 480 VAC current would route from the distribution panel to the auto-transfer switch on the skid exterior.

SOLAR KINETICS, INC.

MISR - QTS DESCRIPTION AND TEST RESULTS

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ABSTRACT

The Solar Kinetics, Inc. Modular Solar Industrial Retrofit (MISR) system design was evaluated in a single collector loop ΔT and coupled to a full, non-solar, balance-of-plant configuration which was designated as a Qualification Test System (QTS). Installation was completed in December, 1982 and evaluation of the design was begun in January. Initial investigations examined whether the design incorporated contractual requirements relative to operational options and hazardous operation protection. With these requirements satisfied, a two-week unattended operation cycle was inaugurated during which a total of 28 kW-Hr/m^2 was to be experienced. With operational reliability indicated, system performance and life cycle tests will be conducted to obtain data on collector and steam production efficiency, parasitic power requirements, heat losses and service life.

Solar Kinetics, Inc.
Modular Industrial Solar Retrofit Project
Qualification Test System
Description and Test Results

Introduction

Solar Kinetics' MISR QTS has a delta temperature loop consisting of two drive strings of six T-800 collectors in each string. Each collector has an aperture with nominal dimensions of 2.44m(8ft) x 6.10m (20ft) or 14.87m^2(160ft^2). The reflector is an aluminized acrylic film called FEK-244 manufactured by the 3M Company of St. Paul, Minnesota. The T-800 is an all steel monocoque structure which has withstood a torque of 5,400 N-m(4,000 ft-lbs$_f$) before elastic buckling of the back skin occurred. As a result, consideration has been given to extending the drive string to an eight mirror configuration from the presently defined six units.

Collector tracking is by a sun sensor mounted on the edge of the collector immediately adjacent to the drive pylon. A light sensor detector which is part of the main control system initiates movement of the collectors from stow.

The balance of the system is skid mounted and consists of a kettle-type heat exchanger (an unfired boiler) capable of generating 0.56 Kg/sec (4,600 lb/hr) steam between 700 kPa and 1700 kPa (100 and 250 psi), a 1.7 m^3(60ft^3) expansion tank for the heat transfer fluid (T-60), and a pump capable of circulating 1.06 m^3/min (280gpm) of heat transfer fluid.

The system control is exercised from an isolated compartment of the skid which contains the microprocessor, annunciator, recorder, power panel and heat transfer fluid pump. A light sensor, rain detector and wind speed sensor, mounted on an elevated stand, provide environmental inputs to the control system for resolution of system operation.

A separate, propane operated, motor-generator serves as an emergency back up electrical power system in the event utility power is lost.

Figures 1 through 5 show the SKI QTS installation.

Unique Design Features

The SKI QTS skid is totally enclosed which allows the effective use of a carbon-dioxide fire suppression network on the non-solar components of the QTS. The enclosure also serves to reduce the heat loss from the insulated elements within the skid and provides environmental protection for these components.

Freeze protection of the skid mounted components is provided by a temperature sensor mounted directly on the element, under the insulation, which energizes the space heaters when a temperature of about 2 C (35 F) is experienced.

A pressure regulating valve is provided as a bypass to the steam line to provide a steam blanket for the heat exchanger during extended shutdown so that air in-leakage is precluded and thus corrosion suppressed.

The Heat Transfer Fluid (HTF) expansion tank is mounted approximately 7 feet above the HTF pump to provide a Net Positive Suction Head (NPSH) on the pump. This elevation being the highest point of the fluid system also allows the capability to purge any entrapped non-condensibles and water in the HTF. During start-up, the warm fluid in the expansion tank can be introduced into the HTF circulation loop to facilitate attainment of the system operating temperature. When the tank energy is minimal, the flow paths through the tank would be closed. This precludes the heating of surplus fluid and prevents thermal siphoning of the heated HTF into the colder tank. A small by-pass line is provided to accommodate the expansion of the fluid as it becomes heated in the circulation loop.

The electrical power transfer switch, which is an element of the emergency generator system, provides the capability to supply standby power and to exercise the emergency generator automatically at a prescribed interval.

System Operation

The QTS control is configured to require an authorization signal before automatic operation can be initiated. Recision of the authorization automatically suspends operation and stows the collectors.

When the light sensor on the skid detects an insolation level above a minimum (approximately 300W/m^2 or 100 BTU/ft^2-HR) for a duration of 10 minutes, the HTF pump is directed to start. After fluid flow has been established for two minutes, the collectors are rotated out of stow and the sun sensor located on the collector drive string searches for the sun. If the light sensor on the skid maintains the above minimum intensity reading, the sun sensor on the collector will search for and fix on the first source of illumination above this minimum which it detects. Presumably this will be the sun, although a strong reflected light can act as a surrogate. If the sun sensor does not detect a radiation source on the first pass, the system control is programmed to command the collectors to repeat the search several more times. Acquisition failure results in cessation of pump operation and stowing of the collectors.

If operation has been achieved but insolation subsequently diminishes below the minimum, an interval of fifteen minutes is allocated for re-establishing minimum insolation levels before system shut-down is commanded. If the light sensor on the skid detects sufficient solar intensity during this period, the search mode is reinitiated.

The control system also commands the intake or exhausting of water into the heat exchanger as indicated by level sensors in the kettle. Solenoid valves which regulate the admission of feedwater or water discharge through the blowdown circuit are automatically operated as the level indicators dictate. Should either operation not be adequate to rectify the existing condition and it deteriorates to the extent that it activates another set of level detectors, the HTF pump is secured to prevent further deterioration of system operation and the collectors are stowed.

Serial elements are incorporated in the control design which detect conditions which may be hazardous to system operation. Environmental conditions such as high wind or system anomolies such as high temperature, loss of fluid flow or, loss of utility power will either prevent imitation or cause cessation of system operation.

When the steam pressure generated in the heat exchanger exceeds the user facility header pressure, steam is supplied to the user from the solar system. The QTS, comprising 1/14 of the normal MISR collector field will produce a proportionate amount of steam generated by a total MISR field. The MISR output is 0.56Kg/s (4600 lbs/hr) of saturated steam when the insolation is 1,000 W/M^2 (about 317 BTU/FT^2-HR). When insolation falls and thermal input to the heat exchanger decreases, steam production decreases. When steam pressure decreases below the user facility steam header pressure the steam line check valve will automatically close from back pressure and remain in this state until kettle pressure again exceeds the back pressure of the user facility steam header. If a steam pressure of 2 mPa (300 psi) is detected in the heat exchanger, system shutdown will be initiated. The 13/14 balance of a MISR system collector field output is provided by a fossil-fired heater in the QTS to simulate their contribution in the production of steam by the skid mounted heat exchanger.

If the HTF amount in the system is excessive or if expansion of the fluid upon heating exceeds a pre-set level, 0.86M (34 inches) in the expansion tank, system start-up is precluded or a system shutdown will be initiated. Similarly, if the HTF "fill" in the system is inadequate, .05M (2 inches), the low level sensor will prevent system operation.

Pressure Safety for the heat exchanger is provided with a relief valve set at 2 mPa (300 psi) to provide protection against blocked steam flow. Similarly, the HTF expansion tank has a pressure relief valve set at 300 kPa (45 psi) to protect against overfilling or a leak in the heat exchanger tube bundle. If either relief valve opens, a trouble alarm is sounded to alert the operator to rectify the source of the alarm condition. System shutdown is not automatically executed in these cases. A thermal relief valve for the HTF located on the input to the heat exchanger is set to open when a gauge pressure of 500 kPa (75 psi) is reached. This condition can be manifested, with the pump running, if fluid expansion into the tank is blocked or could possibly be experienced if the pump is shutdown and existing heat cannot be dissipated in the heat exchanger.

Should the temperature of the HTF going to the field exceed 249°C (480°F) or the temperature of the fluid leaving the field exceed 288°C (550°F) the system will automatically shut down.

If the outlet pressure of the pump, when operating, exceeds 600 kPa (90 psi) gauge, indicating a low HTF flow condition due to blockage or a closed valve, the system will shut down. A high HTF flow condition, a manifestation of a leak, is detected by a low pressure differential across the pump. The pressure difference is calculated to be less than 340 kPa (50 psi) gauge under such conditions. If a no-flow condition results from an inoperative pump the differential pressure across the pump will be very low. Such a no-flow condition will also cause system shutdown.

The loss of utility power during system operation will automatically start the auxiliary propane fueled motor generator to provide emergency power to stow the collectors. The emergency generator will reach synchronous speed and rated voltage and frequency within 10 seconds of starting. The generator is automatically exercised weekly to insure operational reliability.

The annunciator panel, located in the skid enclosure, indicates the cause of any alarm condition by a flashing light in the appropriate window. Pushing the "acknowledge" button deactivates the flashing and it becomes steady state behind the window. When the alarm condition has been corrected, the system "reset" button is pushed to clear the windows and the system can be restarted.

QTS Site Activity

SKI completed their installation of the QTS in late December and conducted a training session for the site operators. In early January, after the holidays, the SKI system was operated to determine if the contractually required operating functions and measures adequate to provide protection against hazardous conditions had been incorporated. In addition, inspection of the system was made to ascertain if required and recommended procedures had been followed in the mechanical assembly.

These initial acceptance functions led to some modifications to the SKI QTS. A control system programming change was instituted to include a rain-wash cycle when the detector sensed it was raining and to take appropriate action when the sun emerged or hazardous wind conditions arose during the wash cycle. Leaks at the threaded connection for the temperature switch in each collector row were experienced. These sections have been replaced with welded thermal wells which has resolved the problem. The annunciator panel, which reflects system fault conditions, was not responding as expected. Corrections were introduced to produce the proper alarms and to require a definite sequence for clearing the fault indication.

With these preliminaries concluded, the SKI QTS was subjected to the automatic two-week unattended operation cycle to establish an indication of its reliability. The system successfully completed this phase of evaluation.

Thermal loss tests of the collector are to be conducted at several temperatures. Fluid heated to the desired temperature, by the auxiliary heater in the MISR field, will be circulated through the receivers. The collectors will be oriented to shade the receivers from the sun but pointed at the clear sky to emphasize radiative effects. The results will be graphically displayed in a curve which shows the relationship of losses with temperature.

Performance will be evaluated also at various temperatures and over a range of insolation levels. The peak efficiency (at normal incidence) for the test conditions will be shown in a three dimensional plot.

The system efficiency will be evaluated in terms of parasitic power requirements, steam production and overnight thermal loss. The data will be listed in a table which shows these values for various steam pressure levels between 700 kPa and 1700 kPa (100 and 250 psi).

Measurements completed to date are summarized in the attached table.

Summary

The SKI QTS employing T-800 collectors is being tested and evaluated as a potential Modular Industrial Solar Retrofit System. These investigations are to determine if it posses the necessary elements and operating characteristics to qualify it for this use.

Additional tests are being considered with the following QTS modifications:

a. 8 collector module per drive string
b. anti-reflective (AR) coated receiver glass
c. silvered-glass mirror reflectors

Results of tests with the above changes will be reported as they become available.

TABLE 1

PERFORMANCE RESULTS*

Collector Efficiency At Normal Incidence

Average Temperature (°C)	Average Temperature (°F)	Ambient Temperature (°C)	Ambient Temperature (°F)	Direct Normal Insolation (W/m^2)	Direct Normal Insolation ($BTU/hr\text{-}ft^2$)	Efficiency (%)
221	430	10	51	989	314	54
187	369	7	44	966	307	57
166	331	6	43	947	301	58
119	247	5	41	897	285	61

Collector Heat Loss

Average Temperature (°C)	Average Temperature (°F)	Ambient Temperature (°C)	Ambient Temperature (°F)	Wind Speed (m/s)	Wind Speed (mph)	Heat Loss (W/m^2)	Heat Loss ($BTU/hr\text{-}ft^2$)
205	401	14	56	1	2	94	30
150	302	10	49	3	7	63	20
124	255	9	49	4	8	51	16
100	212	7	44	3	6	35	11

*Collector efficiency and heat loss were measured from the inlet to the outlet of the delta-temperature string; thus, heat loss from flexible hoses and interconnecting piping are included in the results.

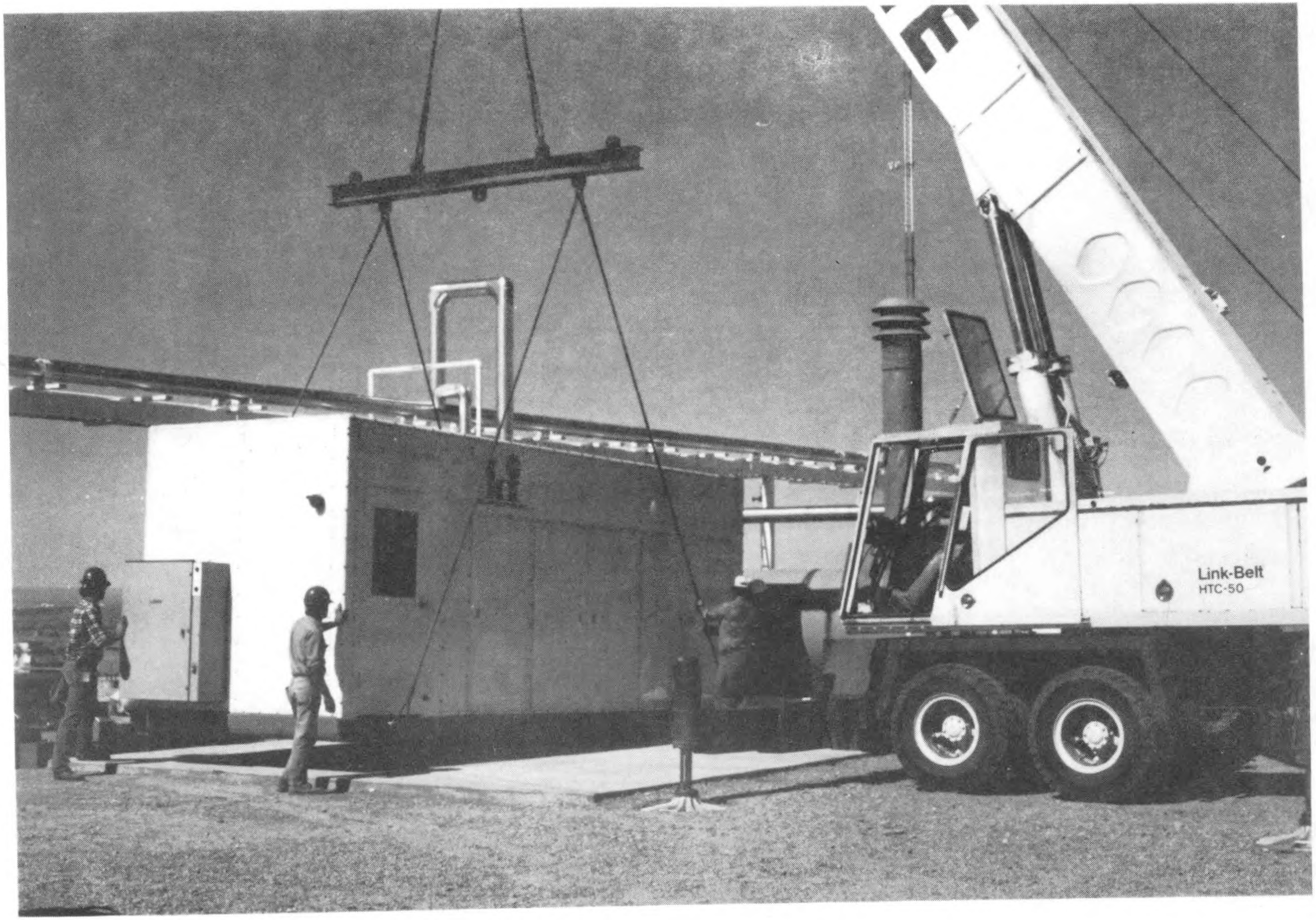

Figure 1 SKI MISR Equipment Skid Being Lowered into Place

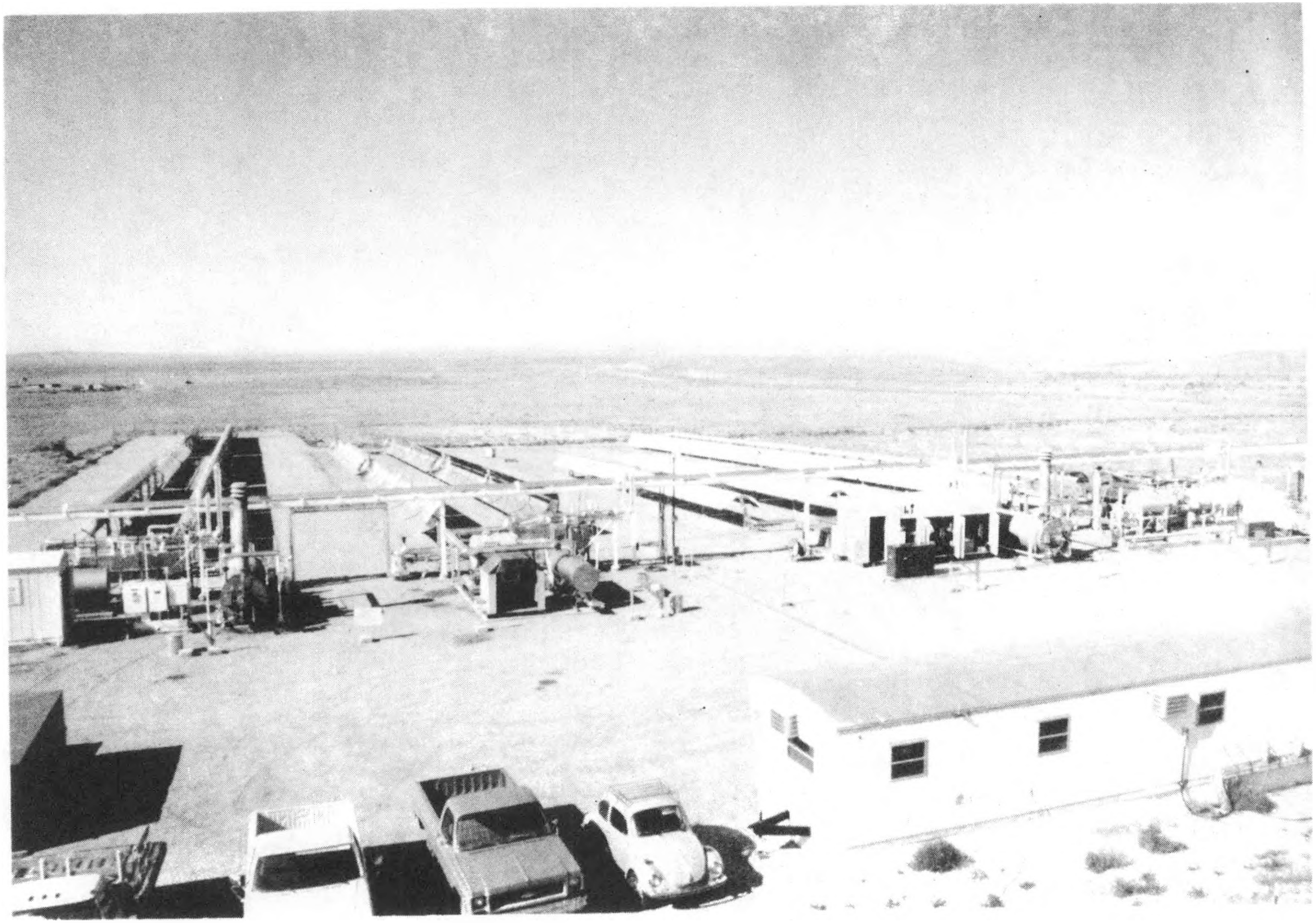

Figure 2 MISR Qualification Test Site at SNLA

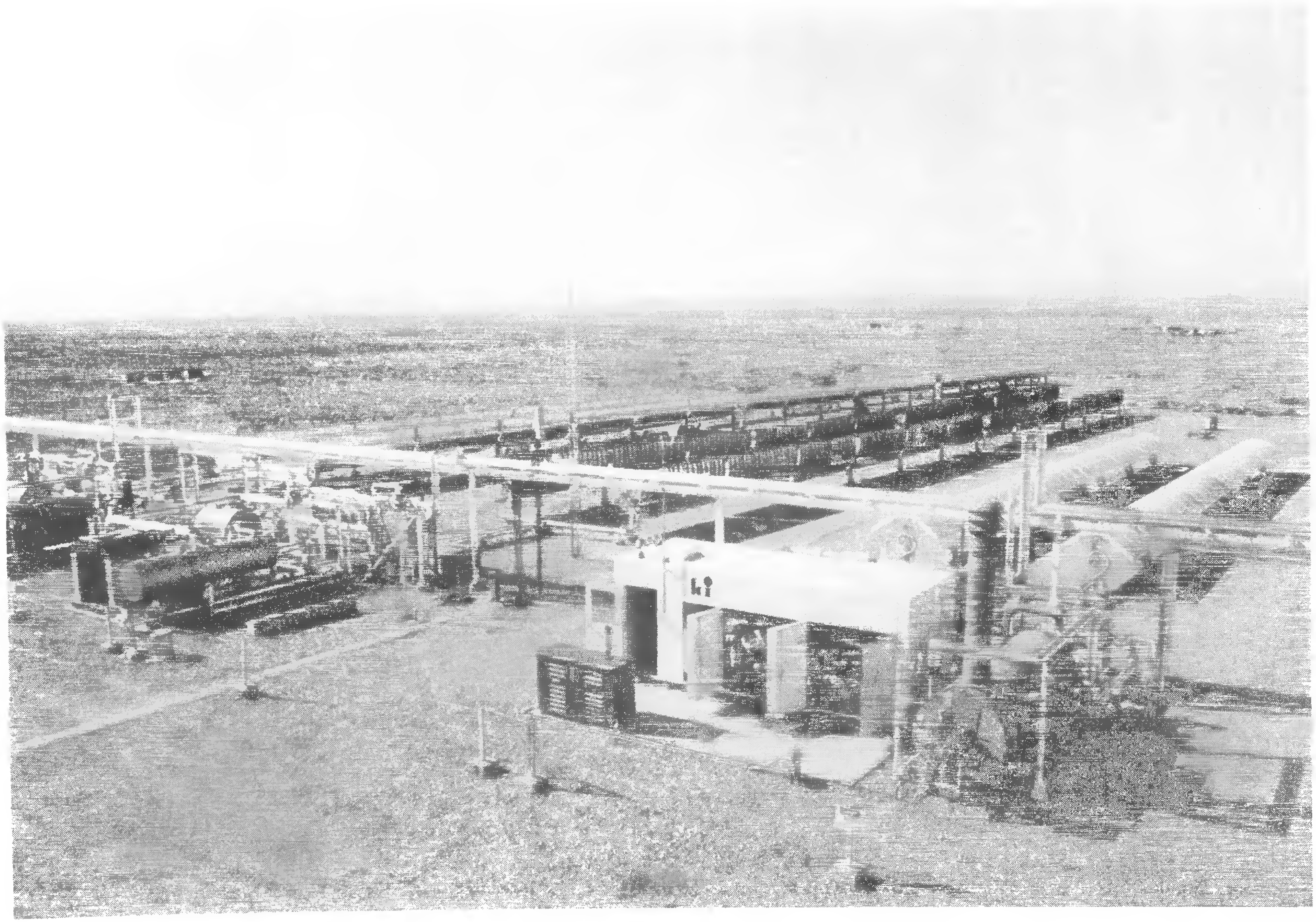

Figure 3 SKI MISR Qualification Test System and Balance of Field Simulator

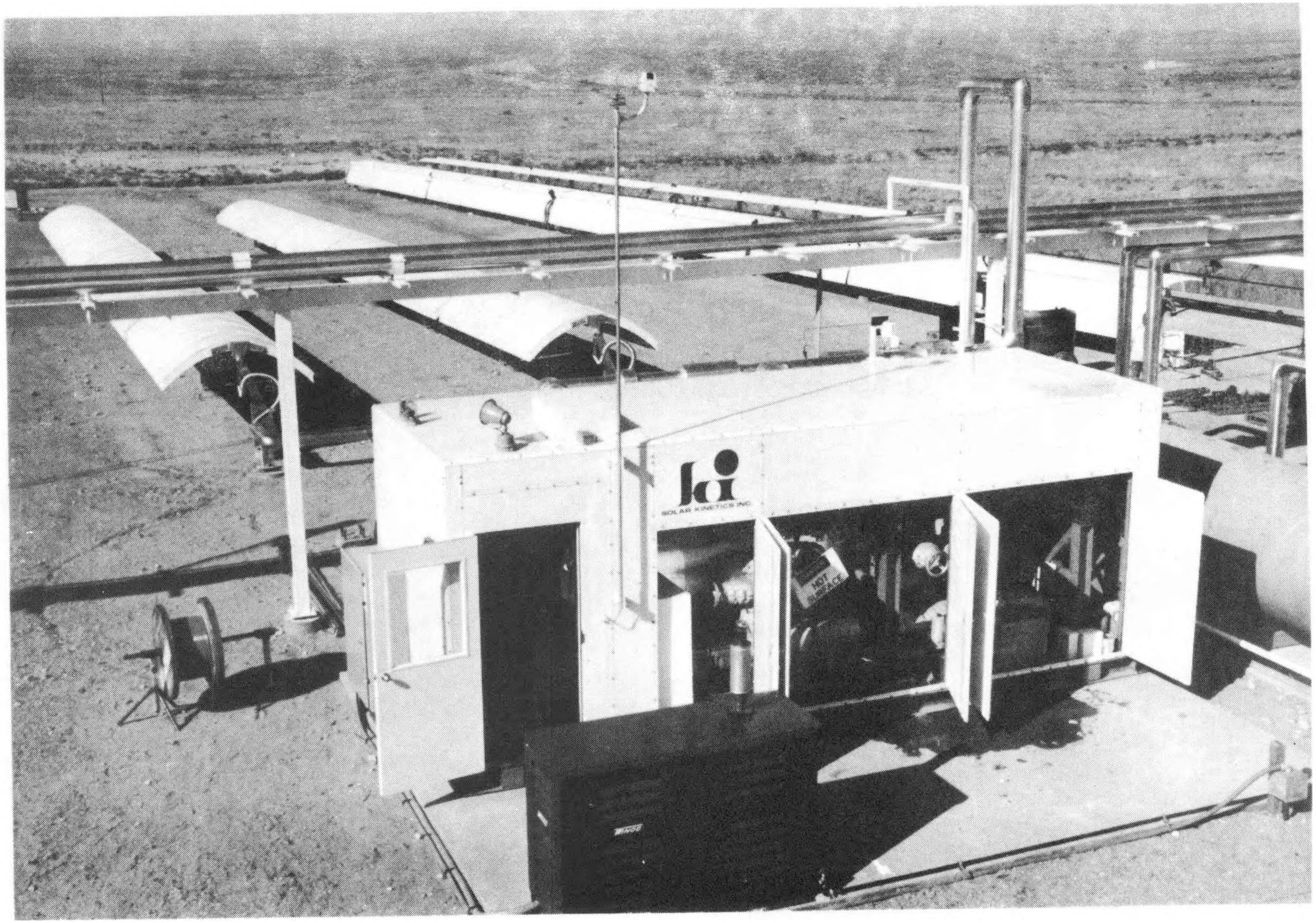

Figure 4 SKI MISR Qualification Test System

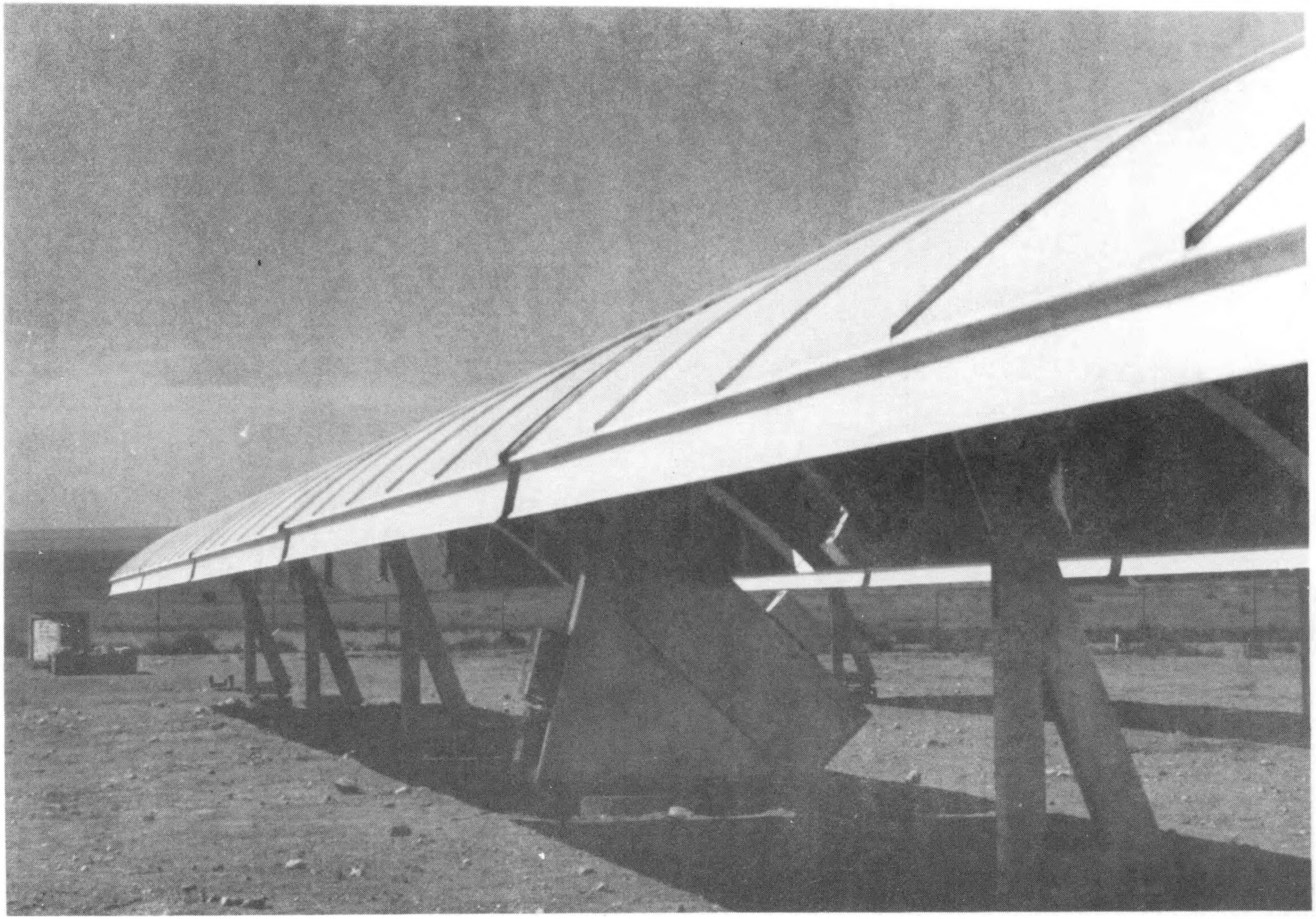

Figure 5 SKI T-800 Parabolic Trough Solar Collector

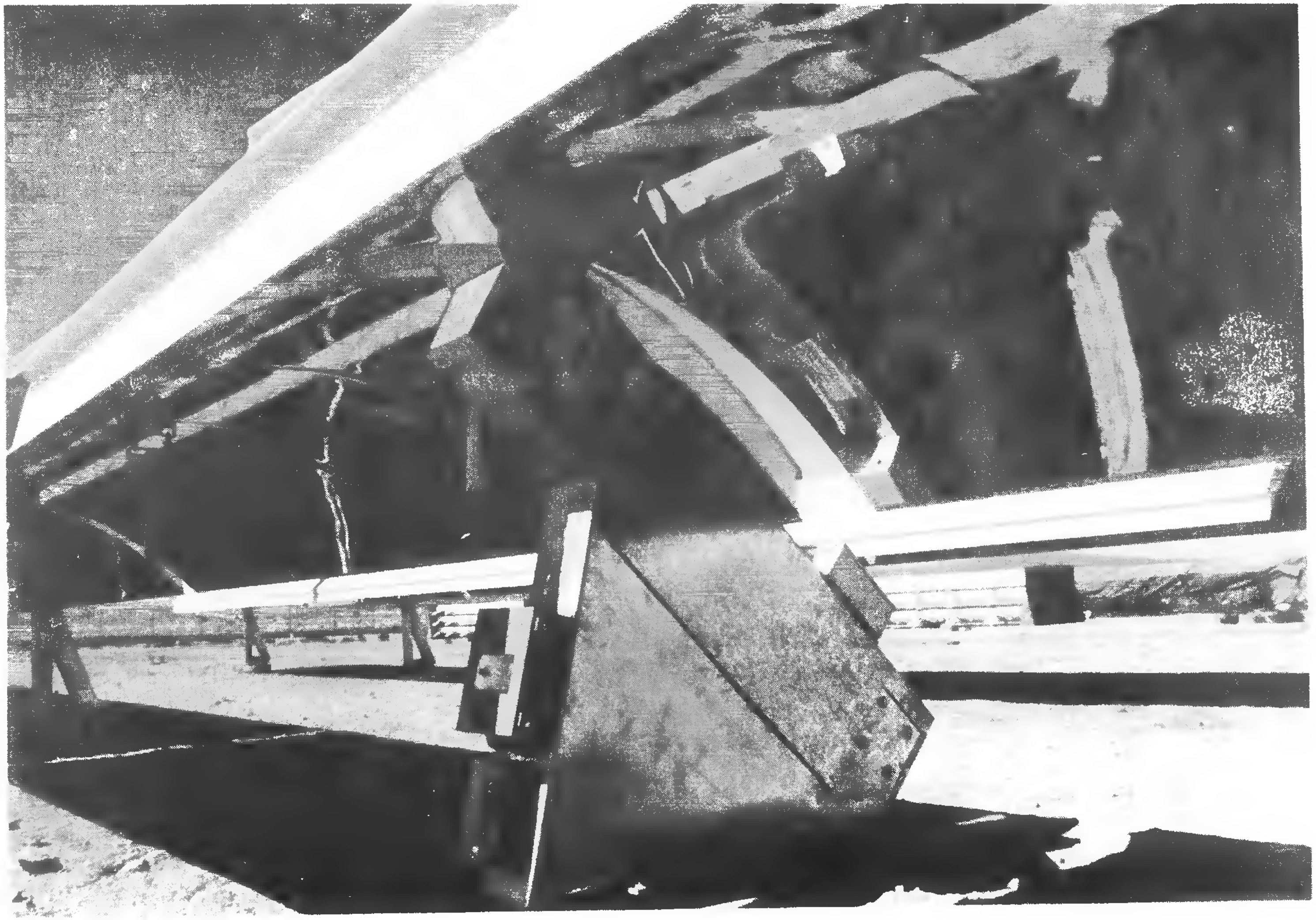

Figure 6 Drive Pylon for SKI T-800 Solar Collector

LESSONS LEARNED FROM OPERATION OF THE MODULAR INDUSTRIAL SOLAR RETROFIT QUALIFICATION TEST SYSTEMS

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ABSTRACT

Four Modular Industrial Solar Retrofit (MISR) Qualification Test Systems (QTS) were installed at Sandia National Laboratories; one was installed at the Solar Energy Research Institute. Side by side operation of these systems during qualification testing provided the opportunity to compare system features and to identify those characteristics which made a system work particularly well or made it especially convenient to operate and maintain. This paper summarizes those features which are generally applicable to all system designs.

LESSONS LEARNED FROM OPERATION OF THE MODULAR INDUSTRIAL SOLAR RETROFIT QUALIFICATION TEST SYSTEMS

INTRODUCTION

This paper describes experiences from the operation of the MISR Qualification Test Systems (QTS). Included are discussions of system features of a generally applicable nature that worked well, were convenient, or that caused problems. This paper is not intended to be a criticism of any particular system or design, but rather it is intended to make available the knowledge gained from the MISR testing. Thus, the beneficial or ineffective features are not identified with any particular systems. System designers may wish to consider the features discussed in relation to their own design. Likewise, present and prospective industrial users may also wish to examine present or proposed system designs relative to the desirability of incorporating some of these features.

EXPANSION TANK CONFIGURATIONS

A variety of expansion tank configurations were included in the four MISR systems which use organic heat transfer fluids. These included tanks which were insulated and tanks which were not insulated, tanks which had nitrogen ullage systems, tanks which were vented, and tanks which were not vented and had no nitrogen ullage. Some systems had large diamter lines to allow HTF flow through the tank for initial system startup, one had small lines for flow through, and one did not use flow through the tank for startup. In addition, some systems had lines which were designed to continuously remove entrained air or vapor during normal or startup operation. Finally, some tanks were built to ASME standards, as required by the MISR contract statement of work, while others were built to the less stringent API standards. In retrospect, we believe that the ASME pressure vessel requirement does not seem warranted, and the API standards are deemed adequate for these systems.

Operation of these systems during the MISR tests has provided some insight into useful design features of expansion tanks. No one system incorporated all of what we believe to be desirable features; however, all systems functioned adequately under normal operating conditions. Most of the system operating difficulties encountered arose from air or water in the system which had to be removed from the circulating HTF during startup or after maintenance. In addition to accommodating expansion of the HTF, the expansion tank provides pump inlet pressure and is the usual vent point for removal of air or water from the HTF.

One of the most useful features incorporated in a system was piping designed to remove air or water from the system through the use of an expanded section near the pump inlet which had a vent line leading to the top of the expansion tank, as shown in Figure 1. The expanded section of piping reduces the fluid velocity and allows the vapors to migrate to the top of the section and out the vent pipe. This technique worked very well for startup and did not require flow through or heating of the expansion tank for air and water removal from the HTF. This process can also be continued during normal operation without the penalty of thermal loss associated with flowing through the expansion tank. Without the need for flow through the tank, relatively small 1.9 cm (0.75 in) vent and 3.8 cm. (1.5 in) liquid thermal expansion lines may be used to minimize thermal loss.

An unknown source of water contaminated the HTF placed in some of the systems and proved somewhat difficult to remove. When the connections to the expansion tank are at the bottom of the tank, entrapped water settles into the bottom of the tank and is drawn into the circulating HTF when the system cools. Thus, it is important that the lines connecting the circulating HTF to the tank have standpipes or enter the side of the tank slightly above the bottom. In addition, there must be a drain at the bottom of the tank so that accumulated water can be drained out periodically. If the expansion tank is subject to freezing temperatures, this drain should be heat traced.

Just as standpipes should be provided for connections to HTF lines, they also are needed for connections to level measuring devices such as pressure gauges or sight glasses to prevent them from accumulating water and freezing. This was a problem during testing of some of the systems.

In expansion tank systems which are designed for flow through HTF, it is possible to heat the entire expansion tank and drive off water, air, and other voltatiles. Unfortunately, pump cavitation would occur when the water recondensed into the oil when the system cooled down, and without standpipes in the expansion tank, would be drawn back into the system. We found that the water could be flushed out by bubbling 100 kPa (15 psi) nitrogen through the hot tank and out a vent line. This required a connection to the bottom of the tank that was separate from the pump suction or else the nitrogen would go directly to the pump and cause cavitation.

In summary, the expansion tank configuration shown in Figure 1 seems to be most efficient and effective. This configuration effectively removes entrained air or vapors; piping to provide flow through the tank is not necessary. Nitrogen ullage is not necessary as long as the minimum HTF level in the tank is about 1 m (3 ft) or more above the pump inlet to provide positive head. Vented tanks are preferable to sealed tanks without ullage since, during thermal cycling, a sealed tank may draw a vacuum and allow air and water to be drawn into the system. Insulating the tank does not appear to be worthwhile; however, we have not yet performed any rigorous analysis or measurements.

FEEDWATER SYSTEM

Two of the five MISR systems have feedwater preheaters; the other three do not. Both of the systems with preheaters modulate feedwater flow to maintain flow through the preheater. This tends to prevent boiling in the preheater that might occur in a nonmodulating or "bang-bang" type system. It is important to recognize, however, that fluctuations in insolation prevent a solar system from continuously producing steam, and, at least daily, the steam generator and preheater are heated up to operating temperature and pressure with no steam or feedwater flow. Thus, steam may form in the preheater and there must be a path for this steam to reach the steam generator or water hammer will occur. The preheater needs to be installed under the steam generator to allow steam to thermodynamically flow up to the generator, as shown in Figure 2, and baffles in the preheater must not prevent the convection flow of steam to the generator.

Of the systems which do not have preheaters, one uses a modulating feedwater control, and the other two use simpler "bang-bang" type controls. Non-modulating controls result in some variation of steam flow as the feedwater flow cycles on and off. It is possible to initially modulate the flow manually to match the maximum steam rate and thus minimize the rate of cycling. Steam flow will still vary, but it will vary in any case everytime insolation falls due to a passing cloud. Thus, modulating feedwater flow just for the purpose of limiting variation in the steam rate does not seem to be a worthwhile undertaking.

Of the three systems which had modulating feedwater valves, two used pneumatically operated valves, and one system used an electrically-powered, hydraulically-driven valve. This hydraulic valve is spring loaded to close on loss of power, and thus overcomes the limitation of many electrically-operated motor-driven valves and has the advantage of not requiring a pressurized air supply system which can be troublesome in either wet or cold environments.

FREEZE PROTECTION

In all of the qualification test systems, freeze protection of the steam system was a requirement, yet without exception, some portion of of the water piping requiring freeze protection was overlooked. All water-containing vessels, lines, traps, drains, valves, and instrumentation needs to be insulated. Lines which do not normally contain water, such as blowdown lines and steam lines, should have automatically actuating drains or traps at ALL low points to permit the removal of accumulated water. Some lines and instrumentation may be kept from freezing via thermosiphoning from the line or vessel to which they are attached. Other lines and instrumentation such as drain lines, steam traps, and feedwater lines are below heated lines and therefore can not be heated by thermosiphoning and should be heat traced or be enclosed in a heated area.

The steam generators on two of the qualification test systems had no freeze protectin other than insulation and thermal mass. In moderate climates this may be adequate; such appeared to be the case in Albuquerque this winter. (At the test site the propane fired heaters occasionally were used to heat the steam generators during long cold cloudy periods just to be sure that no freezing occurred). In colder climates or where extended cloudy weather may occur, some method of keeping the steam generator from freezing, such as an immersion heater, use of plant supplied steam, or a heated enclosure, would be required.

LOCAL COLLECTOR CONTROLS

A variety of local collector control capabilities were provided at the collector drive pylons. All systems have the capability to place the individual drive groups in hold at the drive pylon. They also have the capability to rotate the collectors to and from stow at the pylon, although in two cases the collectors will lock on to the sun and go no further unless the tracking head is covered or disconnected. (At the test site, a disconnect switch was added for this purpose). Some systems use momentary controls which require the operator to remain at the pylon while the collector is moving. These were not very convenient to use, but do provide some safety benefits. In one system, the local control box doors could be swung open into the path of the rotating collector; an external chain was added in the field to restrict the movement of the door. On another system, the designer had conveniently oriented the drive pylons so that the controls were accessible from the access road between delta-temperature strings.

Except for the system which used carrier-frequency technology for transmission of control signals, control signals, which in some cases are 110 Vac, cannot be removed from the local control boxes during maintenance except by shutting down the entire system. However, on some of those systems, removal of one multi-wire plug does disconnect the control signals from the circuit boards, substantially eliminating any hazard to maintenance personnel.

The main difference in controls is the ease with which the collectors can be positioned for cleaning. One system allows the operator to place the entire field of collectors in wash position from the central controller or the operator may selectively place any drive group in wash position in case he should wish the remainder of the field to continue operating. At both the master controller and local controllers of this system, a "wash" switch position caused the collectors to face outward to the access road. None of the other systems have this feature and require either 1) positioning the collectors locally using controls that in some cases are momentary switches; or 2) causing the collectors to move from a central position and stopping to switch half the field to deadband when it is in position before positioning the remainder and/or; 3) covering the tracking sensors on sunny days.

RAINWASH CONTROLS

All of the qualification test systems were required to have the capability for rainwash, in which the collectors could be positioned upward from a central point to allow the collectors to be washed by rain. System safeties were required to be in effect to prevent damage due to wind or due to accidental focussing of the collectors under no-flow conditions. Rainwash was deliberately not automatically actuated since an operator should evaluate the severity of a rainstorm and consider the possibility of hail or sudden high winds. Some of the systems automatically ceased rainwash after a preset time or after the rain ended. A critical feature to an operator, however, is what is required to place the system in rainwash. The most convenient control was a single switch that initiated or terminated rainwash, and that could be remotely located inside the industrial plant. The least convenient controls required the operator to go out into the rain and remain there for a couple of minutes while establishing the rainwash attitude.

COLLECTOR LOOP SAFETY RELIEF VALVES

It is common industrial practice to place a relief valve in any section of piping which can be isolated and where expansion due to heating can take place. However, two of the qualification test systems have no relief valve in the collector loop. Two of the systems, including the pressurized water system, have relief valves which discharge the HTF to the ground. One, however, used a combination relief and block valve which can relieve through the valve to the system manifold. On some other solar systems, a check valve rather than a block valve is installed at the outlet. This allows relief through the valve, but also serves as a block valve for maintenance. A check valve frequently will leak slightly, but the leak is usually not beyond tolerable limits for maintenance. It, therefore, appears that a simple check valve will effectively serve as a block valve while providing a path for pressure relief.

INSULATION

To the extent possible, the use of flanged pipe fittings has been discouraged in the organic HTF systems. Threaded fittings always seem to leak and should not be used. Flanged fittings tend to leak somewhat and most insulation will soak up the oil and become a fire hazard. Non-wicking cellular glass insulation has been used around flanges, but it is difficult to install and tends to crumble in time due to stresses from thermal expansion and contraction of the piping. One of the QTS contractors installed V-shaped sheet metal cup sections around the flanges with a drip-tube through the fiberglass insulation. This both minimized the fire hazard and allowed for an early indication of leaks.

The use of large pipe anchors and slides is also discouraged, especially where their use is questionable because of the supplemental thermal loss from the anchor. One of the techniques used to support the piping was prefabricated calcium silicate insulation, as illustrated in Figure 3.

ODDS AND ENDS

A pressure indicator at the outlet of the HTF pump is useful to determine whether or not the HTF pump is cavitating. When a pump is cavitating, it is common to use a block valve at the pump outlet to assist in reestablishing flow. On some of the qualification test systems, the pressure indicator was placed downstream from the block valve and thus could not indicate the pump outlet pressure when the valve was partially closed. The gauge should be located between the pump and the block valve, as shown in Figure 1.

Four of the five feedwater check valves and at least one of the steam check valves installed with the qualification test systems leaked or jammed. In one case, the steam generator water drained at low pressure back into the feedwater system. In another, the steam generator water flowed back at high pressure and destroyed the seals in the feedwater pump. A third feedwater check valve jammed shut and had to be repaired. The leaky steam check valve caused no serious MISR test site problems, but in actual service would allow the steam generator to remain pressurized by the plant steam main and thermal energy would be wasted. The operation of all check valves needs to be verified to preclude system damage or energy waste.

In many cases, annunciator lights, control system LED's, and computer displays were difficult to read due to interference from strong outdoor light. In addition, control panels behind a plexiglass door can become quite hot in direct sunlight. Even a north-facing panel will receive direct sunlight during the summer months.

In principle, a standard interface for connection to piping at the equipment skids may seem worthwhile; however, in practice it can lead to installation of more piping. See, for example, the steam piping in Figure 4 which begins at the steam generator outlet, drops down to a standard interface at the bottom left of the Figure, and then returns to a point adjacent to the steam generator outlet. Greater expense can be incurred with such standardization than if the physical interface were designed for the particular application. In addition, unless one side of the interface is measured as installed, shop-fabricated interface piping will often not match up and field modifications may be necessary.

SUMMARY

We hope that the discussion in this paper is of value to both solar system designers and industrial users. Most of the system features discussed here are not difficult to implement and are of a generally applicable nature.

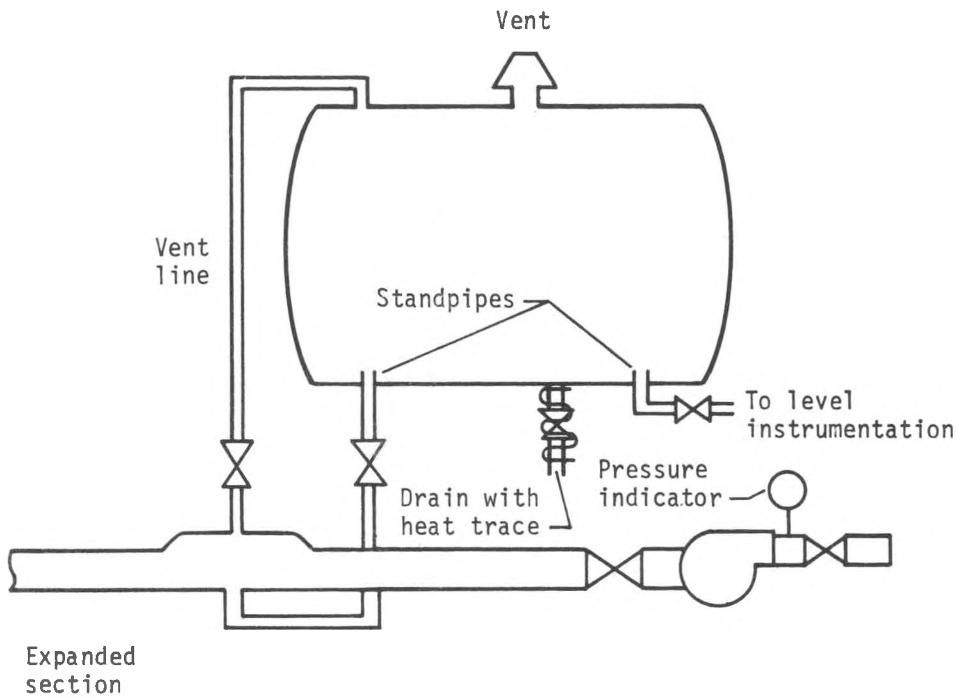
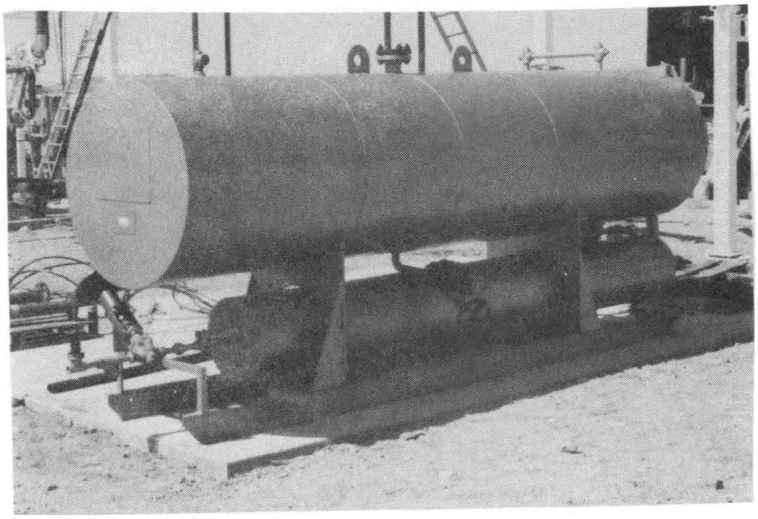
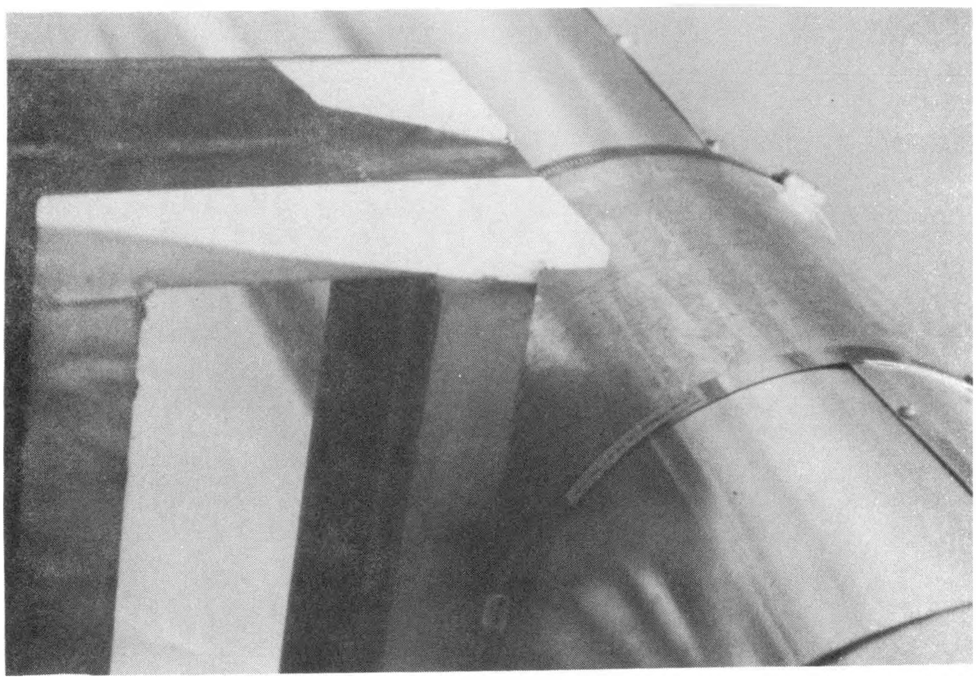


Figure 1. Expansion tank configuration.



FEEDWATER HEATER INSTALLED BELOW STEAM GENERATOR
Figure 2



PREFABRICATED CALCIUM SILICATE INSULATION
AT PIPE SUPPORT
Figure 3

INTERFACE PIPING
Figure 4

SESSION III

SOLAR FIELD PROJECTS

Session Chairman: G. Pappas

SOLAR FIELD PROJECTS

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Energy Technologies Division

In support of the overall solar thermal energy research and development program, numerous field experiments have been sponsored in whole or in part by the DOE. The primary objectives of all of these experiments have been essentially the same, i.e. to establish the technical feasibility of a particular technology, to obtain operating, maintenance, performance and reliability data, to evaluate the systems in an actual user environment, to determine environmental impacts, etc.

A major effort in the field experiment portion of the solar thermal program is the Industrial Process Heat Program, begun in 1976. The IPH program was divided into four cycles and 16 solar energy systems were installed at industrial plants throughout the country. The systems have used a variety of collectors such as flat plates, evacuated tubes and parabolic troughs. In April 1982, seven IPH contracts were transferred from the San Francisco Operations Office to the Albuquerque Operations Office for administration. Construction of all seven is complete and all are in the operational phase.

Relying on Sandia National Laboratories for technical management of this program, data will be collected from all of the systems and information such as performance, reliability, operating and maintenance costs, etc., will be compiled, analyzed and reported.

After an experimental operating period of about one year the systems will be (some have already been) transferred to the industrial hosts. Session IV will include presentations from a variety of projects, including a few outside of the IPH program. Presentations from both the designer/installers and system users/owners will provide insights from the key entities involved in the implementation of these systems.

APPLICATION OF SOLAR ENERGY TO CONTINUOUS BELT DEHYDRATION

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Introduction

A solar collector system utilizing a 553 m^2 (5950 $ft.^2$) array of evacuated tube collectors was designed to augment the heat supplied by natural gas to a Proctor & Schwartz continuous belt dryer used for processing onions and garlic at the Gilroy Foods plant in Gilroy, California. The solar system was started up during the spring, 1979, drying season; and measurements of the system performance were made over a 14-month period beginning in August 1979. During this period, the system delivered 9.81×10^{11} J (930 MBTU) to the dehydration process and the boiler condensate tank. The gross solar system efficiency during the drying season was found to be 31%.

System Design

Large quantities of energy, particularly from natural gas, are consumed in the dehydration of food products. The Gilroy Food plant utilizes eight large continuous belt dryers to dehydrate onions and garlic. Each dryer consumes enough natural gas in a year to provide all of the energy requirements for nearly 500 homes during the same period. A dryer will use heat of different qualities and different forms along the various stages of the process line. Some heated air is immediately discharged after a single pass, some is recirculated, and some must be desiccated before it is used. All of these situations presented different options as to how solar energy could be added to the system. An additional restriction was that the solar system could not interfere with the normal industrial process of the dryer.

Since each dryer draws in large quantities of ambient air and heats this to around 93°C (200°F) with direct firing from natural gas burners, a logical system choice seemed to be to preheat the air with a simple solar air heating system located on the large roof, about 5m above the dryer. However, obstructions such as skylights, piping, and vents and the questionable roof support strength for a large array of collectors prevented the use of collectors which use air. The solar collector system was finally located on a suitable roof of a relatively new warehouse, some 76m (250 ft.) from the dryer.

Evacuated tube collectors were chosen for the system for the following reasons:

a. Because of the long distance over which the heat had to be transferred, a system using a liquid (preferably water) heat transfer medium was required.

b. In the temperature range over which the system is to operate, 60°C to 93°C (140°F to 200°F), the evacuated tube collectors are appreciably more efficient than conventional flat plate collectors.
c. Because the evacuated tube collectors are more efficient, the total collector area required to deliver a given amount of energy is less. This means that structural supports costs, which can be anywhere from 30% to 80% of a total system cost, will be less.

The Gilroy solar energy system is designed to heat water to around 90°C (194°F) in the evacuated tube collectors, and to transport the heated water through an insulated piping system to a heat exchanger mounted in the incoming air stream of the first stage of a large, continuous-belt onion and garlic dehydrator. The solar-heated water preheats the incoming air, thus reducing the requirement for natural gas. Since onion dust and skins tend to clog the heat exchanger fins, a special design for the heat exchanger was required. The dryers and the associated wiring, piping, and peripheral equipment were already in place; and these placed practical limitations on the size of the heat exchanger. The collector field size of 553 m² (5950 ft²) was largely dictated by the requirements of the heat exchanger.

Although a limited amount of drying of specialized products is done during the off-season, the bulk of the drying is accomplished in a 183-day period during the late spring, summer, and early fall. This means an expensive solar system is not being utilized for almost half the year. The Gilroy plant does have a boiler which is used year-round for a source of supplemental heat and for cleaning dryers. To make use of the solar system year-round, as long as the heated water from the solar system is above 60°C (140°F) and not in demand from the dryer heat exchanger, the water is diverted to the condensate tank of the boiler where it helps to preheat water eventually used by the boiler. However, once the system was up and running, it was found that more heat was produced in the winter than could be utilized by the boiler condensate tank; and some of this heat had to be dumped.

The flow diagram in Figure 1 shows the solar system and the piping scheme which delivers energy to the heat exchanger in the dryer and to the boiler condensate tank. The solar field is divided into four arrays, each of which can be isolated from the rest of the system. Provision is made for each array to be vented manually when the collectors are being filled with water, or automatically when air collects in the system and needs to be removed. There is no need for a freeze protection mode for an evacuated tube collector in the Gilroy area; but as a safeguard, the pump will start recirculation of water again if the temperature in the header were to drop below 3°C (38°F). This would draw warmer water into the collector tubes or the piping. The characteristics of the system, including design and operating parameters, are tabulated in Table 1.

Control System

An Acurex Autodata Nine Acquisition and Control System (DACS), block diagrammed in Figure 2, monitored and controlled the entire system. The four basic modes of the system operation are:

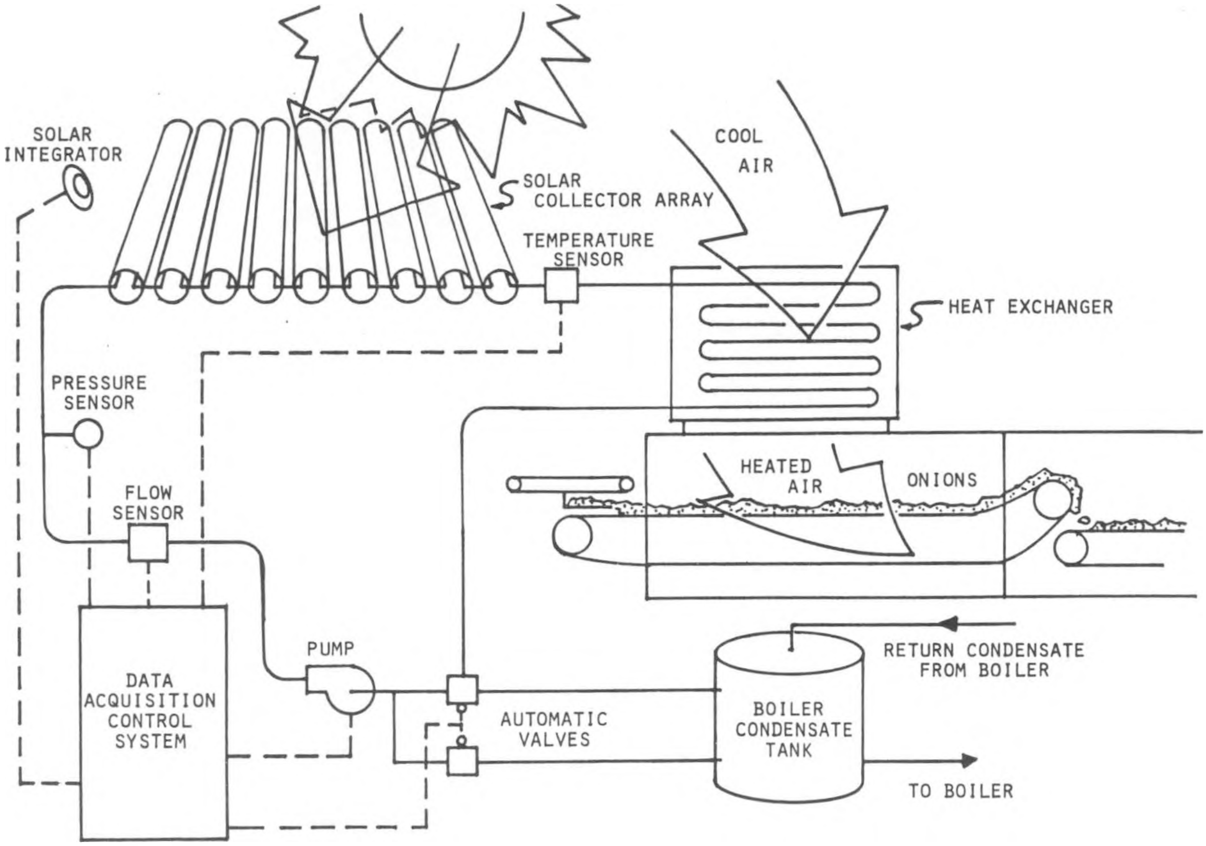

Figure 1. Flow Diagram of Gilroy Solar System and Piping Scheme

- Mode 1: Circulate and Bypass Load -- This mode is used for the system checkout and for freeze protection.
- Mode 2: Circulate and Preheat Air -- This is the normal operating mode. Circulation is initiated when insolation reaches a set level which has been entered into the DACS.
- Mode 3: Circulate, Preheat Air, and Preheat Boiler Feed -- Under some operating conditions, the overall system efficiency can be improved by withdrawing water from the condensate tank, absorbing solar energy in the field, preheating air in the first stage of the dryer, and supplying prehated boiler feedwater.
- Mode 4: Preheat Boiler Feedwater -- This mode is used for preheating boiler feedwater when the dryer is operating with gas heat only, or when the dryer is shut down in the off-season.

Manual push-button control is provided so that any valve or pump can be operated in the opposite position to that called for by the automatic system if desired. The DACS also monitors weather and temperature information. Ten resistance thermometers monitor the temperatures of the ambient air, water in the collector modules, the air entering and leaving the heat exchanger, the water in the headers, and the lines to the condensate tank. Direct and diffuse radiation on the tilted surface is be monitored every 30 seconds and then integrated on an hourly and daily basis. The flow rate of water through the collector

TABLE 1 GILROY FOODS SOLAR ENERGY PROJECT SYSTEM CHARACTERISTICS VICE SYSTEM DESCRIPTION	
SYSTEM PURPOSE	PROCESS HEAT, FOR ONION/GARLIC DEHYDRATION
SOLAR COLLECTOR	GENERAL ELECTRIC TC-100 EVACUATED TUBE SOLAR COLLECTOR DESIGN CHARACTERISTICS NORMAL SIZE: 4'0" x 4'0" NUMBER OF VACUUM TUBES: 8 WEIGHT FILLED: 59 LBS. FRAME: 18 GA. ALUMINIZED STEEL REFLECTOR: POLISHED ALUMINUM FLUID LINES: 1/4" COPPER TUBE MODULE AREA: TOTAL FRAME 1.61M^2 (17.4 $FT.^2$) [ACTIVE*] 1.38M^2 (14.8 $FT.^2$) FLOW RATE: 0.22 GPM PRESSURE DROP-DESIGN: 7.0 PSI @ 82°C (180°F) OPERATING TEMPERATURE: 38°C (100°F) TO 149°C (300°F)
NUMBER OF COLLECTORS	402 MODULES
SLOPE ANGLE OF COLLECTORS	22°
AREA OF COLLECTORS	553M^2 (5950 $FT.^2$) [ACTIVE*]
HEAT TRANSPORT FLUID	DEMINERALIZED WATER
SYSTEM FLOW RATE	88 GALLONS PER MINUTE
SYSTEM OPERATING PRESSURE	65 PSIG PUMP DISCHARGE-30 PSIG COLLECTOR INLET
SYSTEM OPERATING TEMPERATURE	90°C (194°F)
MAXIMUM HEAT PRODUCTION RATE	1.16×10^9 J/HR. (1.1 MBTU/HR.)
TOTAL ANNUAL HEAT PRODUCTION RATE	2.47×10^{12} J/HR. (2340 MILLION BTU/YR.)
PIPING SYSTEM	2-1/2" DIAMETER COPPER PIPE
SYSTEM INSULATION	1-1/2" FIBERGLASS
SYSTEM CONTROL	AUTOMATIC DATA ACQUISITION AND SYSTEMS CONTROL WITH REMOTE COMMAND CAPABILITY
MODULE CLEANING	AUTOMATIC WASHDOWN SYSTEM
* HEAT PRODUCING AREA	

is also monitored. All of the data is collected on a data cassette, and half-hourly information accumulated on this cassette dumped via teletype printer once a day.

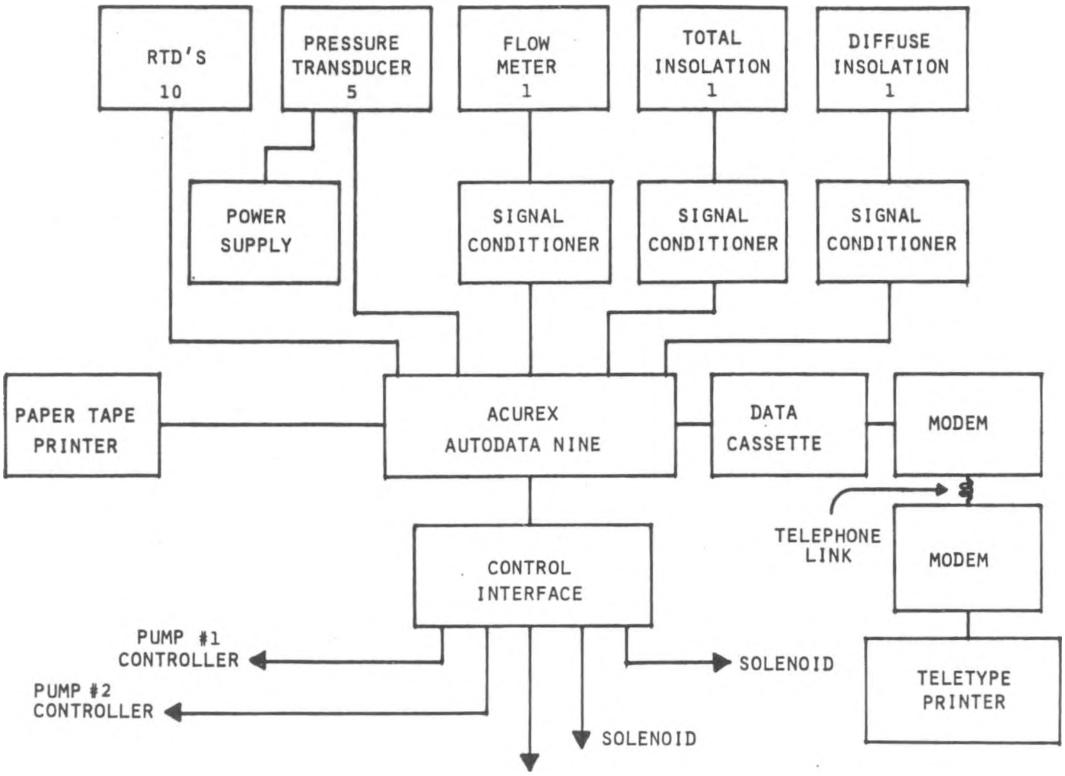

Figure 2. Data Aquisition and Control System

Operational Results

The Gilroy solar system began initial operations for heat production on July 1, 1979. Heat delivery to the process went smoothly with no disruption to the dehydration process. Data from the first month of operation, which was somewhat of an initial test run, yielded the following performance results:

- ° Hours of operation per day..................... 12 hours
- ° Heat delivered by the collectors............... 4.71 MBTU/day
- ° Daily gross efficiency......................... 34.1%
- ° Daily net efficiency........................... 33.3%

The only parasitic loss considered for the system in calculating the net energy production and efficiency is pumping power. Power for instrumentation was considered to be negligible.

During the 14 months over which the testing took place, the solar system was shut down for reasons pertaining directly to the solar system only twice. The first of these was a deliberate shutdown to make stagnation tests, and the second was a shutdown caused by a leak in an expansion bellows. The expansion bellows, although a part of the solar system, was a part of the piping inside the building, some 65m (213 ft) from the site of the collectors.

The plant, during the drying season, processes onions and garlic 24 hours a day, seven days a week. However, periods of shutdown do occur and any plant closure, plant maintenance shutdown, or solar system shutdown affects the solar system and the amount of heat it delivers. Prior to installation of the automatic water washdown system, accumulated dirt and grime cut performance by as much as 8%. The rather large thermal mass of the system accounted for another system efficiency drop on the order of 2.5%.

The overall system performance was found to be 30.3% compared with the predicted performance of 31.5%. During the 14-month period of operation, the solar system delivered 9.80x10 J (930 MBTU) to the dehydration process and to the boiler condensate tank. A graphical display of the cumulative delivered heat is shown in Figure 3. This figure also shows the estimated "potential" heat which would be obtained had there been no plant closures or shutdowns which were not anticipated in the original design.

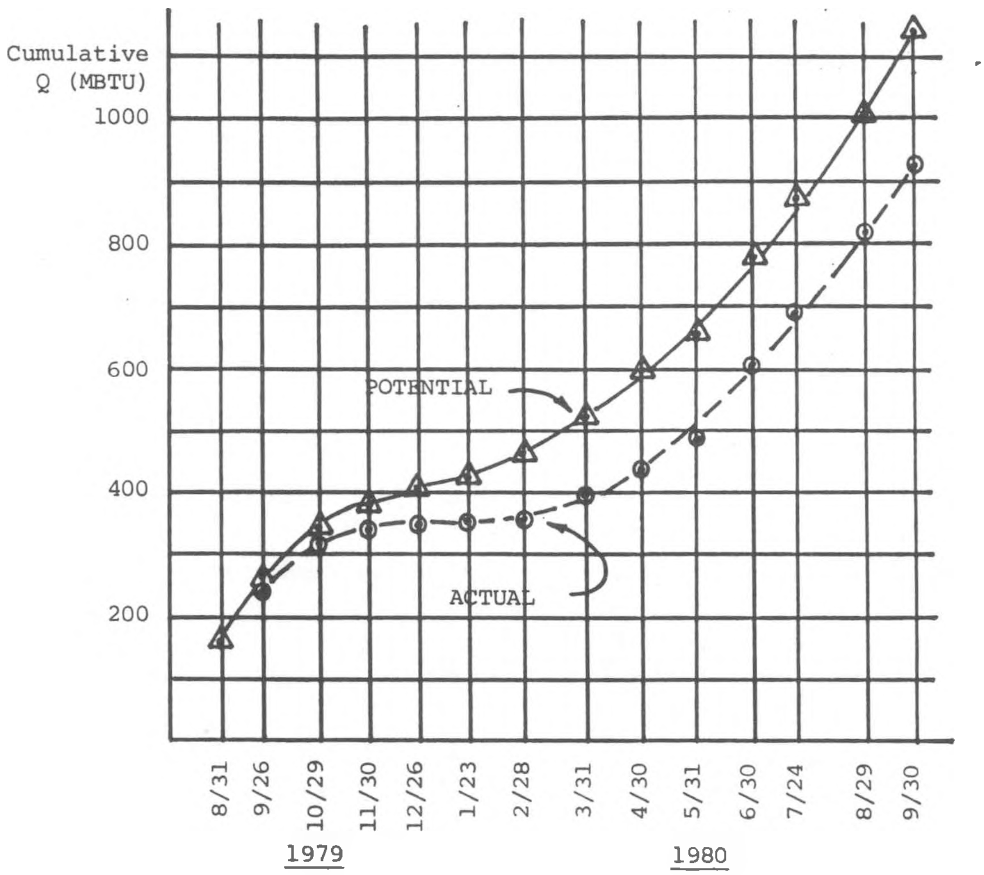

Figure 3. Cumulative Heat Delivered (Net) -- Actual and Potential

IEA/SSPS Project Distributed Collector System

Comparison of one axis and two axis tracking parabolic trough collectors

Prepared by:

Pedro Laguía - Compañía Sevillana de Electricidad
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1. INTRODUCTION

The IEA has constructed in Spain a DCS plant as part of the SSPS Project. This plant was built to test and demonstrate the feasibility of a solar powered electrical generating plant supplying a utility grid or an independent local consumer. The plant has several unusual features:

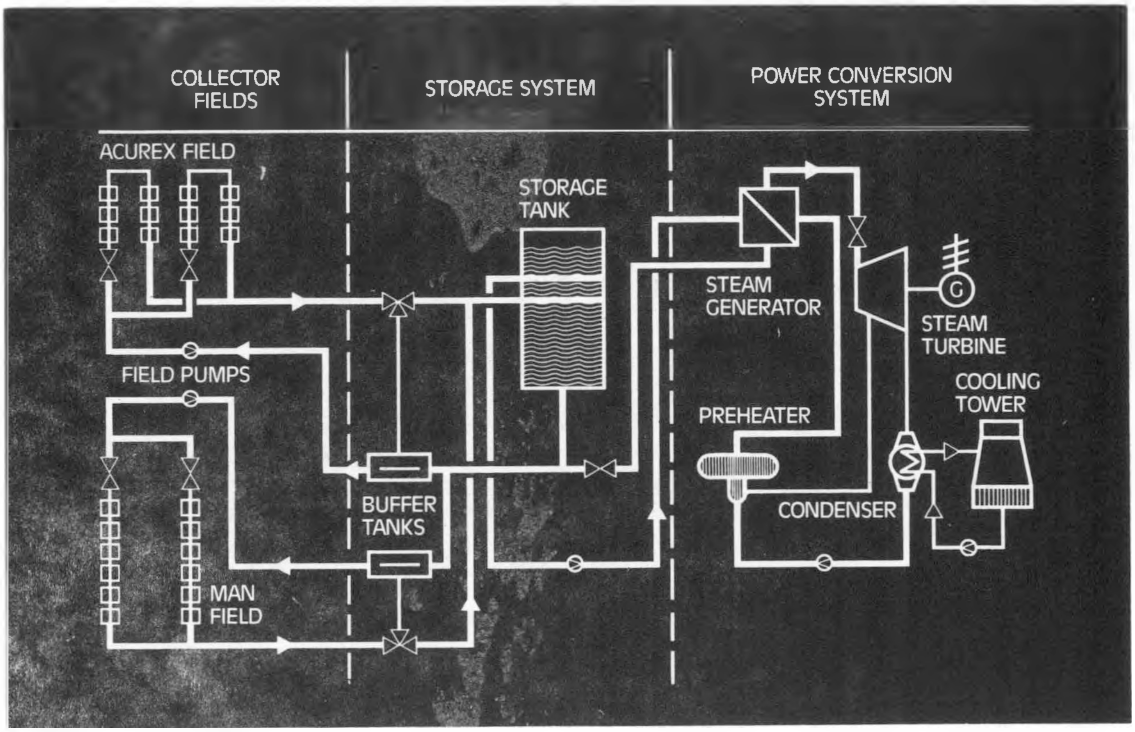
- different types of collectors for comparative evaluation,
- a steam turbine power conversion system,
- a very comprehensive MCS/DAS to facilitate data collection,
- output to grid or substitute resistive load as desired.

The plant was constructed by an international consortium and incorporates equipment from all of the nine countries participating in the project.

2. FACILITY DESCRIPTION

The plant is located in Almería, southeast of Spain, longitude 2º 23' W, latitude 37º 6'N.

The plant consists of two collectors fields, an energy storage and a power conversion system with the following characteristics:



ACUREX COLLECTOR FIELD

Consists of an east-west field of one axis tracking line focusing parabolic trough collectors in 10 parallel loops. Every loop consists of four groups of Acurex 12 - module collector, model 3001. The total reflective aperture area of the field is 2674 m^2 and land use factor is 0,27.

As reflector material is the Glaverbel thin glass on metal substrate. The nominal reflectivity is 93%.

M.A.N. COLLECTOR FIELD

This field consists of two axis tracking line focusing parabolic trough type collectors arranged in 14 parallel loops. Each loop consists of six units of the M.A.N. collector model 3/32 Helioman. The reflective aperture area of the field is 2.688 m^2 and land use factor 0,32. The reflecting surface is a thick glass (5 mm) backed silvered and blacked with an antisplintering protection coating. The nominal reflector area of each module is 32 m^2.

STORAGE SYSTEM

The storage system consists of the thermal storage tank with its manifold and instrumentation, a condensate catch tank, ullage controls, and a fluid make up system to replace fluid loss due to thermal degradation.
The thermal storage tank consists of a conventional oil storage vessel, three diffuser manifolds, one vertical instrumentation tree and a nitrogen blanket ullage system. The aproximate volume is 176 m^3.
The energy storage is based on the thermocline principle. The thermal oil is a syntetic hidrocarbon (Santotherm 55).
Both fields have their own oil pump (variable speed), three way valve for recirculating the oil during start-up or during low insolation periods and buffer tank.
For the steam generator oil circuit, a pump with constant speed is provided. A control valve regulates the amount of oil to the steam generator depending on the steam pressure set point.

POWER CONVERSION SYSTEM

The steam generator consists of a superheater with hot oil inlet temperature (295ºC), a drum, and an evaporator with cold oil outlet (225 ºC). Additional equipment is a blow down tank, a sample cooler and a chemical dosing unit.
The turbine generator set is a multi-stage condensing turbine, a generator condenser ejector deaerator and wet cooling towers.

* Electrical system consists of:
  - Low voltage switchgear
  - Turbine-generator switchgear
  - Uninterruptible power supply

* Auxiliary sytems
  - Emergency diesel generator
  - Water treatment plant
  - Fire figthing system
  - Weather station

* MCS/DAS
  - Master control system has a supervisory function of local and individual controls for subsystems and the system control in total.
  - DAS is a data acquisition system.

A resume of the main design data is shown in the following table:

Design point:	day 80, 12 : 00 (equinox noon) insolation	0,92 kW/m²
Collector fields:	ACUREX collector, model 3001 in 10 loops	2674 m²
	MAN collector, model 3/32, "HELIOMAN" 84 modules in 14 loops	2688 m²
	total aperture area	5362 m²
	concentration ratio	ca. 40
	land-use-factor (ACUREX/MAN)	0,27/0,32
	solar multiple	1,0
	heat transfer medium	thermal-oil (Santotherm)
	collector inlet temperature	225°C
	collector outlet temperature	295°C
Thermal storage:	one-tank-thermocline, storage medium	thermal-oil (Santotherm)
	capacity equivalent to	0,8 MWh_e
	hot/cold temperature	295°C/225°C
Steam generator:	Oil inlet temperature	295°C
	Oil outlet temperature	225°C
	steam outlet temperature	280°C
	steam pressure	25 bar
Power (at design point):	insolation	4933 kW
	thermal	2580 kW
	gross electric	577 kW
	net electric	500 kW
Efficiencies (at design point):	thermal/gross electric	22,4%
	thermal/net electric	19,4%
	insolation/net electric	10,1%

3. INCIDENTS

The plant was handed over to the Operating Agent, the DFVLR of Germany in September 1981. We can consider a period of 9 month for fitting and trimming of all the subsystems.
The main problems that occurred were:

- M.A.N. collectors: Swivel joints defective producing some oil bypass of the modules. Solved in February 1982.
- U.P.S: Uninterruptable power supply for assuring power to the Acurex field, controls and computer, out of service. Due to this, the Acurex field was stowed during all of March. Repaired in April 1982.
- Water leakage in the steam generator. In May and September 1982 two defectives welds caused to leak into the oil circuit. This produced a shut down of all the plant for about 20 days for each leaks. The amount of oil degraded was not relevant.
- Acurex field overheated: Due to missoperation when repairing the UPS and a counter in the low voltage switchgear, the field suffered two overheating periods lasting 5 and 7 minutes respectively.
  No damage or reduction of performance has been detected.
- M.A.N. field oil flow control. After long discussions and modification the field was put on automatic mode at the end of April 82. Additional modifications and adjustments have been carried out by site personnel and ITET (International Test andEvaluation Team) experts.
- Steam generator superheater. The bundle of the superheater was changed in November 81 increasing the interchange surface which then allowed achievement of the nominal design characteristics.
- Condenser level control. Slight modifications in the system in November 1981.

4. OPERATIONAL RESULTS

Due to the above mentioned events, the operation since the beginning has been irregular. After the last steam generator leak in September 82, the plant has operated as designed.
This must be considered when evaluation the data given in the following graphic.

IEA/SSPS PROJECT	YEARLY OPERATION REPORT	APROVED BY: PREPARED BY:	DCS	YEAR	CSE

MONTH	HOURS INSOLAT. $>300 w/m^2$	ACUREX WORKING HOURS	COLLEC. ENERGY	M.A.N. WORKING HOURS	COLLEC. ENERGY	ENERGY TO P.C.S.	P.C.S. WORKING HOURS	SYNCHR. HOURS	GROSS Kwh.(e)	PARASIT. Kwh.(e)	NET Kwh.(e)
JANUARY	91h34	71h30	47361	73h14	18367		28h3	11h6	5121,6		
FEBRUAR.	128h40	57h2	39221	98h12	48042,9	28711	34h8	18h53	7872,7		
MARCH	204h11			167h2	114533	78008	45h35	28h23	12507,2		
APRIL	153h37	103h43	62049	112h44	70852	91169	48h05	33h14	16684		
MAY	197h2	51h4	28348	59h50	28556	21583	12h15	7h22	3688		
JUN.	290h46	196h44	122970	262h16	148762	201304	109h27	78h33	38474		
JULY.	270h25	186h16	107153	238h19	134529	192221	91h41	66h48	34987		
AUG.	269h9	164h26	88016	222h06	115367	154338	110h15	82h8	24079		
SEPT.	200h29	90h39	48698	119h28	58265	58432	32h16	21h53	10682		
OCT.	20h51	131h47	88392	161h3	106314	102968	63h	43h6	20128		
NOVEMB.	137h29	66h52	35110	83h36	34960	49228	29h49	19h40	98837		
DECEMB.	194h	117h54	70394	125h16	54444	93024	57h	34h3	16339		
TOTAL	2341h8	1237h57	738140	1723h6	932900	107100	661h34	445h9	200450		

5. COMPARISON BETWEEN ONE AXIS TRACKING AND TWO AXIS TRACKING

One of the main objectives of the IEA/SSPS project DCS plant was the comparison between two differents concepts of parabolic trough collectors: One axis tracking and two axis tracking. The following study analyzes in three typical days in the year the behaviour of both fields.
It also includes a comparison of both fields from the operational and maintenance point of view.

5.1 Field Performances

Three typical days corresponding to winter solstice, fall equinox and summer solstice have been chosen. The data for each period are the average values corresponding to six different sunnydays as close as possible to the dates 21/12/82, 21/9/82 and21/6/82 respectively.

A) Energy offered to the field

A computer program has been developed to calculate the energy offered to each field. The input data is the day of the year and the direct radiation measured each 5 minutes.

MAN FIELD.- The energy offered is calculated by integrating from sunrise to sunset the solar power offered to the field.

$$E_M = \int_{sunrise}^{sunset} I_b \cdot A_m \cdot SF_m \, dt$$

where:
I_b is the direct radiation
Am is the effective area 2.688 m^2
SF_m is the shadow factor which ranges from 0 to 1, it corresponds to the unshaded mirror surface and it is calculated each 5 minutes taking into account the geometrical characteristics of the field and the sun position (1).

ACUREX FIELD.- The energy offerd is calculated as:

$$E_a = \int_{sunrise}^{sunset} I_b \cdot A_a \cdot SMa \cdot \cos\theta \, dt$$

where:
A_a is the effective mirror area 2,674 m^2
SMa is the shadow factor in addition to the end losses.
$\cos\theta$ is the cosine of the incidence angle.

Table II shows the values for these days, also shown is the thermal energy offered to the fields taking into account the optical efficiency of both fields; (optical efficiency Acurex 0.65, optical efficiency MAN 0.68). (2).

B) Energy Offered while warming up the field

These values are shown in Table II. They correspond to the solar and thermal energies offered to the fields from start up to reach 280 ºC. It is interesting to point out that in the winter time the Acurex field reaches 290 ºC before the MAN field. Observing the curves of energy offered to the fields (fig. 1 a,b,c) both are closer in winter time than in summer time because of the Acurex field EW location at this latitude and considering that the energy supplied to the field during warm up is lower for Acurex field (1330 KWh) than for MAN field (2240 KWh). This explains the small advantage of Acurex over MAN during the winter.
The points shown in the figure I are:

Point 1 - start up of MAN field
Point 2 - start up of ACUREX field
Point 3 - outlet temperature MAN 280 ºC
Point 4 - outlet temperature ACUREX 280 ºC.

C) Thermal energy delivered to storage tank

The same computer program calculates the energy delivered to the storage tank from the fields taking into account the inlet and outlet temperatures and the flowrate measured at 5 minutes intervals. This thermal energy is calculated as:

$$E_{th} = \int_{ti}^{tz} \dot{v} \cdot \rho(Ti) \cdot (h(T_2) - h(T_1))\, dt$$

where:

$\dot{v}$ = oil flowrate
$\rho(T_i)$ = oil density as temperature function
$h(T)$ = oil specific enthalpy at temperature T
T_1 = oil inlet temperature
T_2 = oil outlet temperature

Table II shows the values of the thermal energies delivered from these selected three periods.

5.2 Comparison one axis - two axis from operational and maintenace point of view.

One axis - Acurex Collector:

- Excellent behaviour
- No extra maintenance needed
- Easy and cheap to clean
- Good resistance against hard environmental conditions

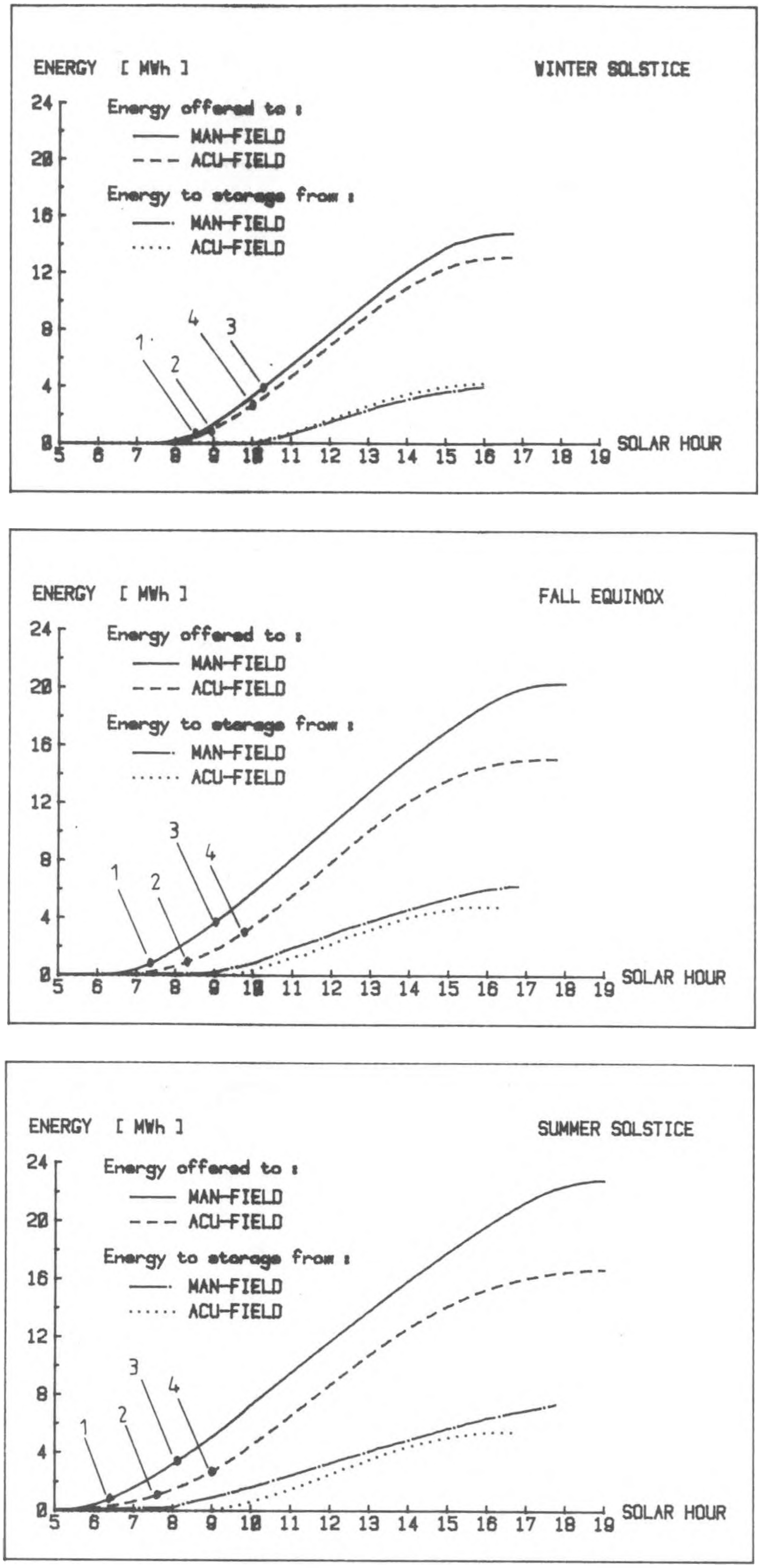
Troubles:

- Small electronic component failures
- Black chrome receiver coating degradation. Nevertheless no losses of performance detected.
- Mirror delamination: Slight delamination observed affecting less than 10% of the total number of mirrors. The problem is being studied by the manufacturer. No losses in performance detected.

Two axis tracking - MAN Collector:

- Good use of the sunshine hours
- Electronic equipment not completely developed
- Difficult to wash
- Difficult and expensive maintenance. Hardware is complicated.
- Sensitive to hard environmental conditions, particularly in high winds areas.
- Requires longs pipes, increasing the thermal losses and makes flow control more difficult.

The electronic and maintenance problems are mainly a reflection of the development level of the collector. The design has been extensively improved in later models.


ENERGY [MWh]
WINTER SOLSTICE
Energy offered to :
MAN-FIELD
ACU-FIELD
Energy to storage from :
MAN-FIELD
ACU-FIELD
SOLAR HOUR
ENERGY [MWh]
FALL EQUINOX
Energy offered to :
MAN-FIELD
ACU-FIELD
Energy to storage from :
MAN-FIELD
ACU-FIELD
SOLAR HOUR
ENERGY [MWh]
SUMMER SOLSTICE
Energy offered to :
MAN-FIELD
ACU-FIELD
Energy to storage from :
MAN-FIELD
ACU-FIELD
SOLAR HOUR

A

B

C

FIGURE I

	WINTER SOLSTICE ACUREX	MAN	FALL EQUINOX ACUREX	MAN	SUMMER SOLSTICE ACUREX	MAN
START UP TIME	8:50	8:15	8:20	7:15	7:25	6:15
TIME TO REACH 280ºC	0:50	10:25	9:45	9:15	8:55	8:05
WARM UP TIME	1:15	2:10	1:25	2:00	1:20	1:05
SOLAR ENERGY OFFERED WHILE WARM UP (KWH)	2050	3300	1950	3100	1700	2850
THERMAL ENERGY OFFERD WHILE WARM UP (KWH)	1330	2240	1260	2100	1105	1930
SOLAR ENERGY OFFERED FROM SUNRISE TO SUNSET (KWH)	13.140	14.780	15.050	20.280	16.670	22.000
THERMAL ENERGY OFFERED FROM SUNRISE TO SUNSET (KWH)	8450	10.050	9780	13.790	10.830	15.000
THERMAL ENERGY DELIV. TO STORAGE TANK (KWH)	4250	4040	4800	6250	5450	7370

TABLE II

REFERENCES

1.- C. Gómez Camacho "Shadow effects in DCS collectors fields" IEA/SSPS Report, Doc. no. R-35/82-CGC, April 22, 1982.

2.- R. Carmona and J.G. Martín "Analysis of optical losses" IEA-SSPS Workshop on Distributed collector systems Almería, December 1982.

3.- C. Gómez Camacho "Stationary piping thermal losses in Acurex and MAN fields" IEA/SSPS Report, Doc. no. R-2/82-CGC, April 13, 1982.

ACKNOWLEDGEMENTS

The authors want to thank L. Castillo and M. Andersson of ITET for their help in developing the software for the computer calculations.

OPERATIONAL EXPERIENCE

FOR THE HAVERHILL SOLAR IPH SYSTEM

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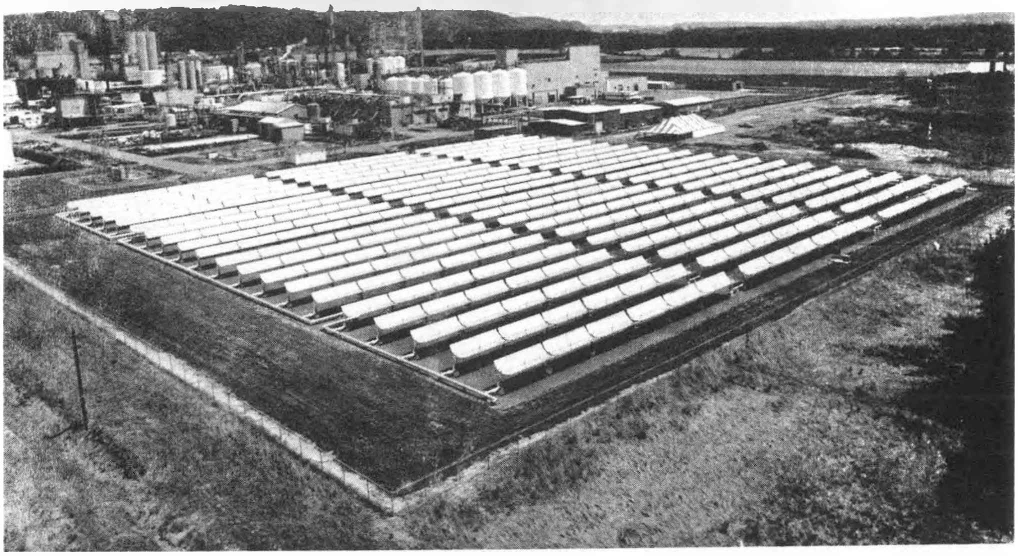
I. INTRODUCTION

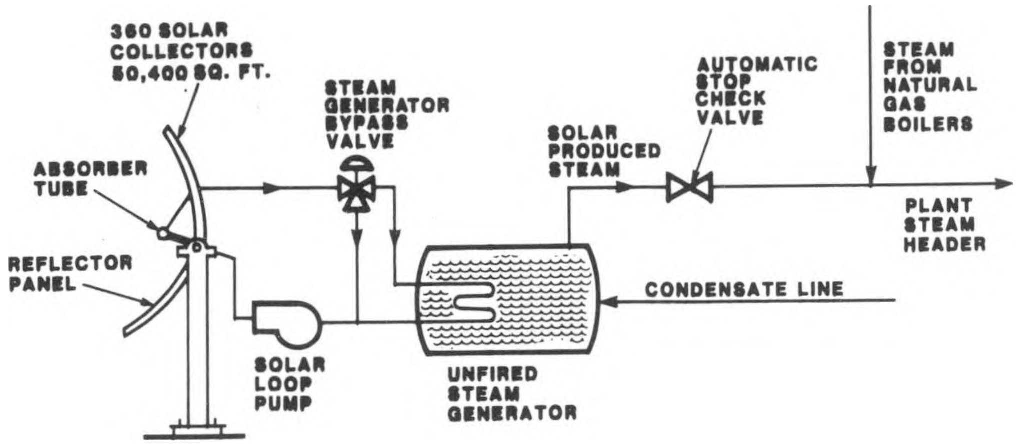


HAVERHILL SOLAR ENERGY SYSTEM

The U. S. Department of Energy, the Columbia Gas System Service Corporation and the USS Chemicals Division of United States Steel Corporation are jointly funding a project to design, construct, operate and evaluate a large-scale solar energy system to provide industrial process steam for the USS Chemicals plant near Haverhill, Ohio.

The Haverhill Solar System design phase was completed in September, 1980 and solar system construction was completed in January, 1982. The U.S. Department of Energy, Columbia Gas and USS Chemicals conducted acceptance testing of the system during the period February through May, 1982.

The Haverhill solar energy system occupies an area of approximately 3 acres. The solar system has 60 separate solar collector rows, arranged in three banks of 20 rows each, as can be seen in the aerial photograph. Each row has six reflector panels, and each of these panels has an aperture area of 140 square feet. The 360 ground mounted, single-axis tracking, concentrating solar collectors have a total aperture area of 50,400 square feet.



HAVERHILL SOLAR SYSTEM SCHEMATIC

As shown in the above schematic, a heat transfer fluid is pumped through the solar collector array to a steam generator at a nominal flow rate of 320 gpm. The design maximum solar collector outlet temperature is 500°F. The solar system is designed to produce steam at pressures up to 150 psig.

Steam produced by the Haverhill solar energy system is currently utilized in the phenol plants at USS Chemicals. The phenol plants require steam at 450, 150 and 50 psig. The solar produced steam is fed into the 50 psig steam system. The phenol plants' process loads exceed the maximum solar system steam output of 10,000 lbs/hour at all times when they are in operation, and no solar energy storage system is required at this solar site.

Steam for the USS Chemicals plant complex is generated with steam generators using primarily natural gas as a fuel, although portions of the plant's total steam requirements can be produced with oil, coal, and now solar energy.

The Haverhill solar energy system has operated unattended since June, 1982. The system will be operated, maintained and evaluated over a 30 month period.

I. SOLAR SYSTEM OPERATION

The Haverhill solar system has operated unattended since June, 1982. The number of operational days and non-operational days for the system have been categorized using the six different status codes identified in the "Monthly Reporting Requirements for Solar Industrial Process Heat Field Tests"[1]. The first nine months of operation for the Haverhill solar system are summarized in Table 1.

TABLE 1

	Status Code						
Month	1	2	3	4	5	6	Total Days
June, 1982	12					18	30
July, 1982	6					25	31
Aug., 1982	28	3					31
Sept, 1982	29	1					30
Oct., 1982	21	1				9	31
Nov., 1982	10	20					30
Dec., 1982	2	29					31
Jan., 1983	31						31
Feb., 1983	28						28

Status Code #1 - Solar system and industrial plant operational
Status Code #2 - Solar energy system not operational
Status Code #6 - Industrial plant down, solar system idle

The availability of the Haverhill solar system over the period has been:

Availability = (167 + 52)/ 273 = 80.2%

The major period of solar system non-availability occurred in November and December, 1982. During that period Solar Kinetics personnel were at the site to replace seals in the receiver tubes.

The utilization of the Haverhill solar system over the period has been:

Utilization = 167 /(167 + 52) = 76.3%

The periods of non-utilization were due to some modifications and upgrading of plant equipment by USS Chemicals during 1982.

[1] Kutscher, C.F. and Davenport, R.L., SERI Document Number SERI/MR-632-714, September, 1980.

II. SOLAR SYSTEM MAINTENANCE

The primary maintenance activity at Haverhill during 1982 was the replacement of seals in the solar collector receiver tubes. A total of 408 technician man-hours were required to complete this activity. This work was done under warrantry by Solar Kinetics.

A second major maintenance activity was the repair of solar collector drive pylons and replacement of tracking controls. A total of 320 Columbia Gas technician man-hours were devoted to this activity.

The solar collectors were washed three times during 1982. The work was done under contract and required 108-man hours. A complete record of all Maintenance Work Orders issued to the maintenance staff at USS Chemicals has been kept. A total of 17 Maintenance Work Orders were issued during 1982, and a total of 58 man-hours were required to complete this maintenance work.

III. SOLAR SYSTEM EVALUATION

A Hewlett-Packard on-site data acquisition and data processing system was installed to monitor the performance of the Haverhill solar system. The data acquisition system includes a desk top computer, a data acquisition/control unit, a magnetic tape drive, and an impact printer.

Data transmission between the data acquisition/control unit and the computer has been a continuing problem with the system. Initially, individual components of the system (including all the interconnecting cables, interfaces and individual P.C. boards in the data acquisition/control unit and the computer) were systematically replaced. Next, the data acquisition/control unit was exchanged for an identical new unit from Hewlett-Packard. Lastly, the desk top computer was changed out. None of these attempts resolved the problem.

Hewlett-Packard engineering has recently published a Service Note for the use of their service offices identifying a design flaw in their 98034 HPIB interface. The Service Note suggests that a data acquisition system bus lockup may occur in approximately 6 hours of normal operation. The lockup is caused whenever there is a timing conflict between clock and the clear signal.

From September, 1982 through January, 1983 the longest uninterrupted period of data acquisition system operation was seventeen hours. Throughout the period manual intervention was required at least once and usually two or three times per day to unlock the bus. Hewlett-Packard has replaced the 98034 P.C. board assemblies, and we have installed the new revision HPIB in the field. The data collected at Haverhill over the last five month period appears to be reasonable for the periods when the data acquisition system was operating. However, the data has numerous gaps and gives an indefinite picture of the actual monthly performance of the solar system.

IV. SOLAR SYSTEM UPGRADES

Eight specific upgrades were undertaken on the Haverhill solar energy system during 1982. The following is a brief description of each of the upgrades.

1. Columbia Gas mounted 360 spacers (collars on the collector support arms. The spacers, furnished by Solar Kinetics, mechanically prevent the rotating solar collector panels from striking the solar collector support pylon.

2. Special aluminum jacketing and insulation was designed and installed over flexible metal hose at the inlet to and outlet from each solar collector string.

3. Columbia Gas installed individual solar collector manual controls at each solar collector drive pylon. This upgrade was undertaken to improve the safety of the system.

4. USS Chemicals fabricated and installed a water cooled feedwater sample station in order to allow daily testing of feedwater quality.

5. A removable insulation blanket was added to cover the steam generator heat exchanger mounting flange and distribution head.

6. Columbia Gas installed braces to support the flex hose on both ends of each solar collector string.

7. An uninterruptible power supply with battery pack was purchased and installed to power the on-site data acquisition and data processing system. This prevents interruption of data acquisition when there is a plant or grid power outage.

8. USS Chemicals installed an air bleed system for the steam generator.

OPERATION OF THE SOLAR HOT WATER SYSTEM AT THE CAMPBELL SOUP PLANT IN SACRAMENTO, CALIFORNIA

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System Description

The solar hot water system at the Campbell Soup Plant was designed and installed in 1977 and upgraded in 1982. The upgraded system consists of a collector field for heating potable well water, a tank for storing excess hot water, a supply line for delivering hot water, a control system, and a data acquisition system. The system schematic is shown in figure 1. Cold water is taken from the plant water main and heated in the solar collector field located on the roof. This collector field, shown in figure 2, consists of 3,810 ft^2 net of flat plate collectors and 2,880 ft^2 of parabolic trough concentrating collectors. The heated water is piped to a 17,150-gal storage tank. When water is demanded, it is piped to the inlet of the can sterilizer heat exchanger. The control console for the system is mounted on the control cabinet with the annunciator panel and the datalogger.

Before the upgrade, hot water demand was limited to only two canning lines and the control console was early minicomputer-based rather than the present relay-logic-based.

Operation Experience

Routine daily operation of the system began in April 1978 and, except for approximately 6 months downtime to accommodate the upgrade and an earlier period of control system and data acquisition problems, this routine operation has continued to date. As an example, during the period from February through August 1980, system availability was over 90 percent, with 100 percent availability in the period April through August. Utilization of the available energy was less than 100 percent, except in August during tomato canning season.

The primary problem encountered prior to the upgrade was utilization of the hot water generated by the solar system. The solar system was tied directly to either of two can washers. If these can washers did not operate continuously (as had been the case), the solar storage tank filled and the collector field shut down in the day. Consequently, the plant could use only a fraction of the energy the solar system was capable of generating.

Another problem was the minicomputer-based control system. Campbell Soup personnel were unfamiliar with this type of equipment and were hesitant to use it for system checks and to maintain it.

The other problems encountered were:

- Jamming of remotely operated flow control valves by inert matter in the well water. An in-line separator was installed in 1979 which eliminated this problem.
- Magnetic tape deck of the data acquisition system was unreliable, and when replaced a format incompatibility arose. The datalogger interface board was modified for the new format.
- Minor leaks at the flat plate glazing seals caused localized corrosion of the absorber surface

The energy utilization, control system, and flat plate collector problems were addressed in the upgrade. The tank charged by the solar system was connected directly to the plant hot water heat exchanger. In this manner, the system output could be fully utilized independent of the source of the hot water demand and at very low plant demand.

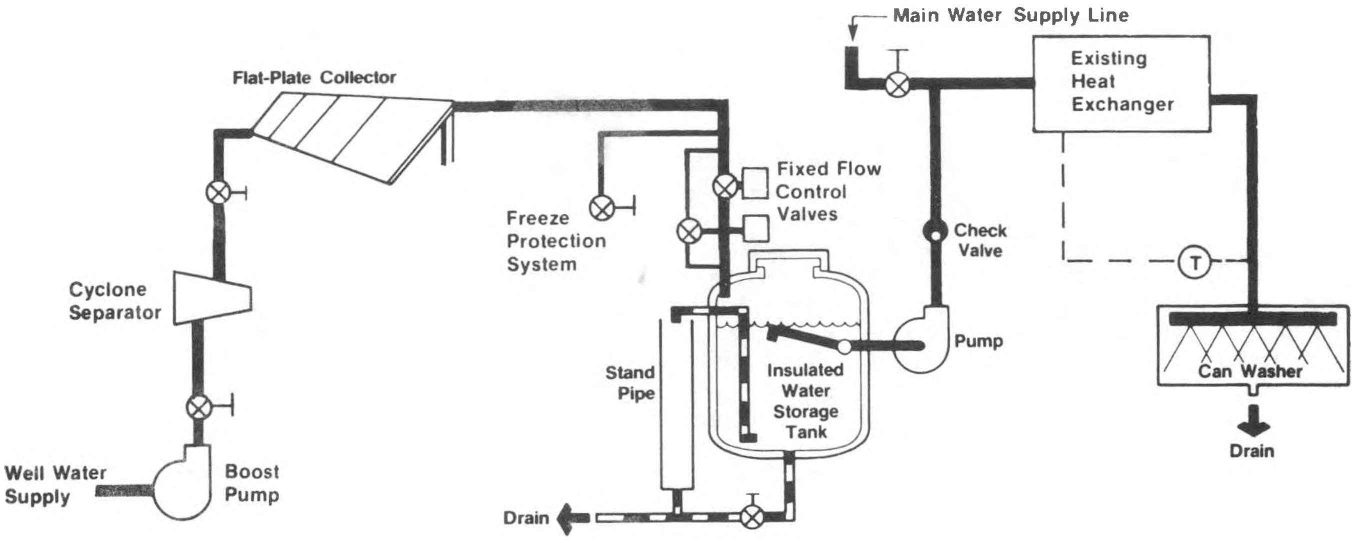

Figure 1. Solar Hot Water System Schematic

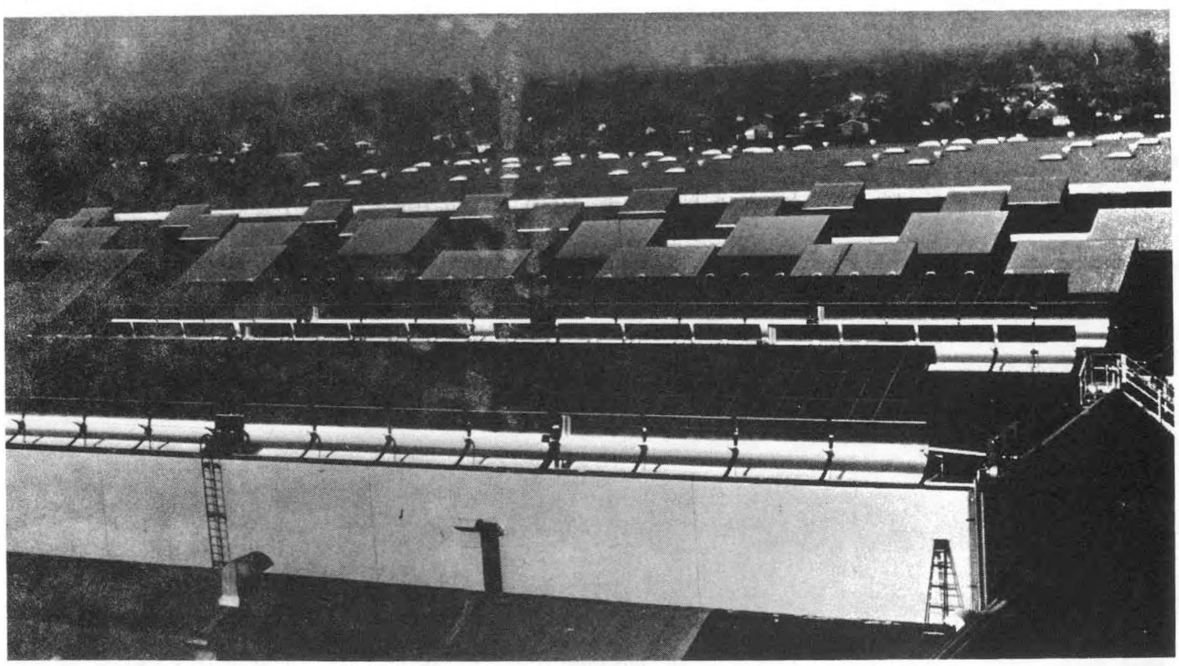

Figure 2. Campbell Soup Plant and Upgraded Solar System

The control system was replaced by one with relay logic and components familiar to Campbell Soup personnel. They are now fully trained and comfortable with the control and data acquisition system.

The flat plate leak and corrosion problem was solved by total replacement of all flat plate collectors with new flat plate collectors.

Final debugging of the upgrade system was completed on December 11, 1982. The operating period since that time has been brief; availability and utilization have been 100 percent since that date. Problems with one tracker and the data acquisition system have occurred but they have not impacted system operation.

SOLAR TOTAL ENERGY PROJECT (STEP)

SHENANDOAH, GEORGIA

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Introduction

The Solar Total Energy Project (STEP) is a cooperative effort between the U. S. Department of Energy (DOE) and the Georgia Power Company to further America's search for new sources of energy.

A part of the National Solar Thermal Energy Program, funded primarily by DOE, the project is the world's largest industrial application of the solar total energy concept. It is an outgrowth of research started in 1972 by Sandia National Laboratories in New Mexico for the U. S. Energy Research and Development Administration. The objective of the Shenandoah project is to evaluate a solar total energy system that provides electrical power, process steam, and air conditioning for a knitwear factory operated by Bleyle of America, Inc. Solar energy will displace a large part of the electricity and fossil fuel normally used to run the factory and produce the clothing.

The construction of the system was completed near the beginning of 1982. During most of that year, startup operations were conducted by a joint operational team of Sandia and Georgia Power Company. A relatively large number of unexpected electrical and mechanical problems offered major design knowledge for subsequent system design applications. These have been recently resolved, and the program has moved into the experimental operations test phase. The highlights of these anomalies and subsequent high quality system performance results are the content of this report. The report is presented chronologically by each month of 1982 and concludes with the performance results that were primarily achieved during the first quarter of 1983. This report is intended to complement the Solar Total Energy Project, Shenandoah, Georgia Site, Annual Report No. ALO/3994-82/1, provided as part of the Distributed Solar Collector Summary Conference -- Technology and Applications, March 15-17, 1983, Albuquerque, New Mexico.

January Activities

The STEP Steam System Integrity Tests were conducted throughout the early part of January, and culminated on January 21, 1982 with the first synchronization and generation of electricity to the 100 kW level. Manual control of the Balance of Plant (BOP) was also achieved during the month. Support to planning and checkout of the water treatment system was provided, with Georgia Power Company (GPC) General Office and Plant Yates personnel providing review and recommendations relative to water chemistry.

Sandia, DOE, Georgia Power Company, and STEP personnel participated with Heery & Heery in the preparation of an overall Safety Plan required by the Cooperative Agreement Modifications for Operations.

February Activities

Extracted steam was supplied from the turbine to Bleyle for dryout of thermal insulation that had been dampened during construction activities. This operation was carried out under manual control of the BOP. The electrical wiring for the STEP/Bleyle interface was completed. The turbine air seal pump failed, and the first attempt to repair was unsuccessful. Temporarily, air was supplied by the main air compressor. The air pump was subsequently repaired.

March Activities

The month's major event was a two day inspection of STES by a formal Readiness Review Committee. The group was composed of the U. S. Department of Energy, Sandia National Laboratories, Rockwell International Energy Technology and Engineering Center, and Georgia Power Company. The review report identified no major problems but provided some recommendations.

The condensate storage tank was sandblasted and painted to prevent rusting. This action resulted from analysis of water samples from tank which yielded a high content of rust.

The original motors (3) and potentiometers (2) for each collector (114) were found to be not suitable for their outdoor operation in an area with considerable rainfall. To reduce an intolerable failure rate, each was removed, water proofed, and reinstalled.

By the end of March, all construction was essentially completed.

April Activities

The month's major event was an operational status review by DOE, Sandia and Georgia Power Company. The group gave provisional acceptance of STEP subject to resolution of certain specific anomalies. The major anomaly was operation of the Control and Instrumentation Subsystem (CAIS), with the Collector Field Subsystem (CFS) and the Balance of Plant (BOP). However, this anomaly persisted until late in the year when a major design change was identified.

The Boiler Feed Pump (BFP) discharge Pressure Safety Valve (PSV-8036) required extensive repair. A nineteen (19) day period, due primarily to vendor coordination, was required to complete the repair.

Near the end of April, the Heat Transfer Fluid (HTF) valves were inadvertently opened on a computer command and approximately 700 gallons of Syltherm 800 TM was spilled in the mechanical equipment area through the piping system that was opened for mechanical repairs. Operational and maintenance procedures, along with mechanical protection, were instituted to prevent a reoccurrence.

Major fiber optic replacement was required due to improper placement of fiber optic cables in the insulation of the receiver units.

May Activities

A major milestone was achieved when the Site dedication was held on May 10, 1982. More than 500 people attended the formal ceremonies at the Shenandoah Solar Center. Participating were Georgia Power Chief Executive Officer Bob Scherer; DOE's Dr. Robert San Martin; Congressman Newt Gingrich; Sandia's Don Schueler; and Atlanta Mayor Andrew Young.

On May 12th at 2:40 pm, the generator was synchronized to a load of 200 kW and solar generated electricity was produced for the first time.

Pressure relief valves (PSV-6440 and PSV-6448) on the condensate storage tank (T-103) and its' condenser (T-113) were found to be completely blocked by condensed (solidified) HTF. Both were removed, cleaned, and insulation was provided on both valves to maintain a temperature that would prevent condensation. Other HTF relief valves were inspected and found clear. After many problems over a five-month period with the condensate pump (P-8740), Gould Pump Company inspected it on-site and found it to be running backward because of a directional flow arrow on the casing that had not been clarified by the manufacturer. It was then made fully operational.

June Activities

After the integrity of the chilled water system to Bleyle was verified, the absorption chiller was started. There were several days of successful operation of this air conditioning system leading to a major milestone on June 15th: cogeneration with approximately 250 kW (electric) and 50 tons of air conditioning (thermal).

A leaky accumulator was removed from the boiler feedwater pump discharge and shipped to St. Louis for repair. It was determined from inspection that the problem was more than a leak. The Viton bladder would not accommodate a working temperature of 330°F. An accumulator of a piston design with Viton o-rings was purchased. This problem curtailed turbine-generator operation in the last week of the month. The resolution of this problem caused the system to be down for seventeen (17) days.

Control of the Fossil Fired Heater (FFH) has been difficult and numerous instrumentation, control, and mechanical problems have been discovered and resolved.

Following continued water control problems from the solar collector field, repairs were made to the concrete drainage system to the north of the field. A french drain and a barrier wall were installed on the north and east of the property to intercept ground water that accumulated in the rockfill of the collector field.

July Activities

Mode C (Thermal Energy Mode) was started under Control and Instrumentation Subsystem (CAIS) control.

FEK-244 film of fifteen (15) solar collectors was damaged because stray concentrated light from adjacent collectors had been focused to back of the damaged collectors during a construction activity. All of the collectors with melted film on reflector surface were repaired.

The boiler feedwater pump discharge pressure relief valve (PSV-8036) failed for second time on July 26th, effectively shutting down steam operations last five (5) days of month. (In February, 1983, a third failure occurred. However, a spare unit had been procured, and the STEP was back in operation in less than one hour.)

August Activities

During month, process steam was provided Bleyle for pressing needs for first time. On August 26th, the Solar Total Energy System provided 600 ton-hours of air conditioning and 5,600 pounds of process steam by semi-manual operation of the solar collectors. During August, thermal energy was provided Bleyle for thirteen (13) days.

The steam generator was thermally shocked causing leaks which contaminated the heat transfer fluid (8/20/82). This major anomaly was not completely identified and resolved until December. The leaks at the tube-tubesheet interface were repaired by Tungsten Inert Gas (TIG) welding, and subsequent operation proves the repair to be successful.

The refractory rings in the Fossil Fired Heater (FFH) failed due to thermal transients and were replaced.

September Activities

The STEP Staff replaced seals on steam generator pump (P-7110). This pump has been disassembled seven (7) times since its installation. A new type seal (AAA Seals) replaced the tungsten carbide seals. This seal has proven to correct the problem.

During this month, it was determined that the CPU memory of the DEC PDP 11-34 (128K word) computer would be inadequate to handle multiple sub-systems by the CAIS. A change from this computer to a DEC PDP 11-44 (256K word) enabled the operation of all sub-systems safely and efficiently. On September 23rd, 112 of the 114 solar collectors were manually auto-tracked. For 7½ hours that day, solar energy was produced and used for chilled water production for air conditioning and process steam for pressing clothes. With a nominally bright sun, 10 x 10^6 BTUH of solar steam was produced through computer control of the collector field by the CAIS.

October Activities

The Balance of the Plant (BOP) was operated for significant time in Mode C (Thermal Energy Mode). On October 15th, a typically good autumn day in Georgia, the solar collectors auto-tracked for 9 hours, 23 minutes, providing over 38 x 10^6 BTUH of energy.

The formal classroom training of the STEP Staff was initiated using Trane, Mogul, Georgia Power Company Energy Research, and Georgia Power Company Safety.

November Activities

The DEC PDP 11-44 computer, delivered to the site on November 8th, was powered up and was functional. DEC personnel performed a System Generation (initialization and definition of operating units) on the PDP 11-44. The STEP Staff, with assistance from General Electric and Auburn University, continued with changeover, debugging efforts, checkout of the operation programs, and creation of data analysis programs.

It was confirmed that water was contaminating HTF. Repair of the steam generator was started in mid-November.

December Activities

The steam generator repair was completed in mid-December. The water contamination problem, detailed above, was resolved. CAIS was readied for final task building checks and system operation.

A redesign of the nitrogen supply system and new method of purchasing nitrogen using a 315 gallon bulk liquid tank resulted in an operating cost savings of $10,000 per year.

Pump seal (P-7001) failed late on last working day of 1982 in conjunction with a low oil level shutdown of the air compressor. The failure allowed approximately 100 gallons of HTF to flow onto patio floor.

Since the air compressor proved to be a continuing problem and was considered to be inadequate, a new air compressor, with different operational characteristics, was ordered. The old unit will be used as a spare system.

STEP was unable to operate for eleven (11) days because of a pressure regulating valve (PCV-8230) failure on the sixth day of January. PCV-8230 reduces the steam pressure from 700 psig to 100 psig in the extraction line of turbine bypass. Vendor supply problems inhibited the repair.

Computer control of the BOP by the PDP 11-44 was achieved in late December, and the collector field control was performed in early January.

The aggravating electro-mechanical problems presented above have provided valuable experience to the design and operation data base necessary for subsequent designs. Each individual sub-system has performed at its design level, and the total performance of the total system is now being carried out. This performance is given in the following paragraphs.

Recent Performance Activities

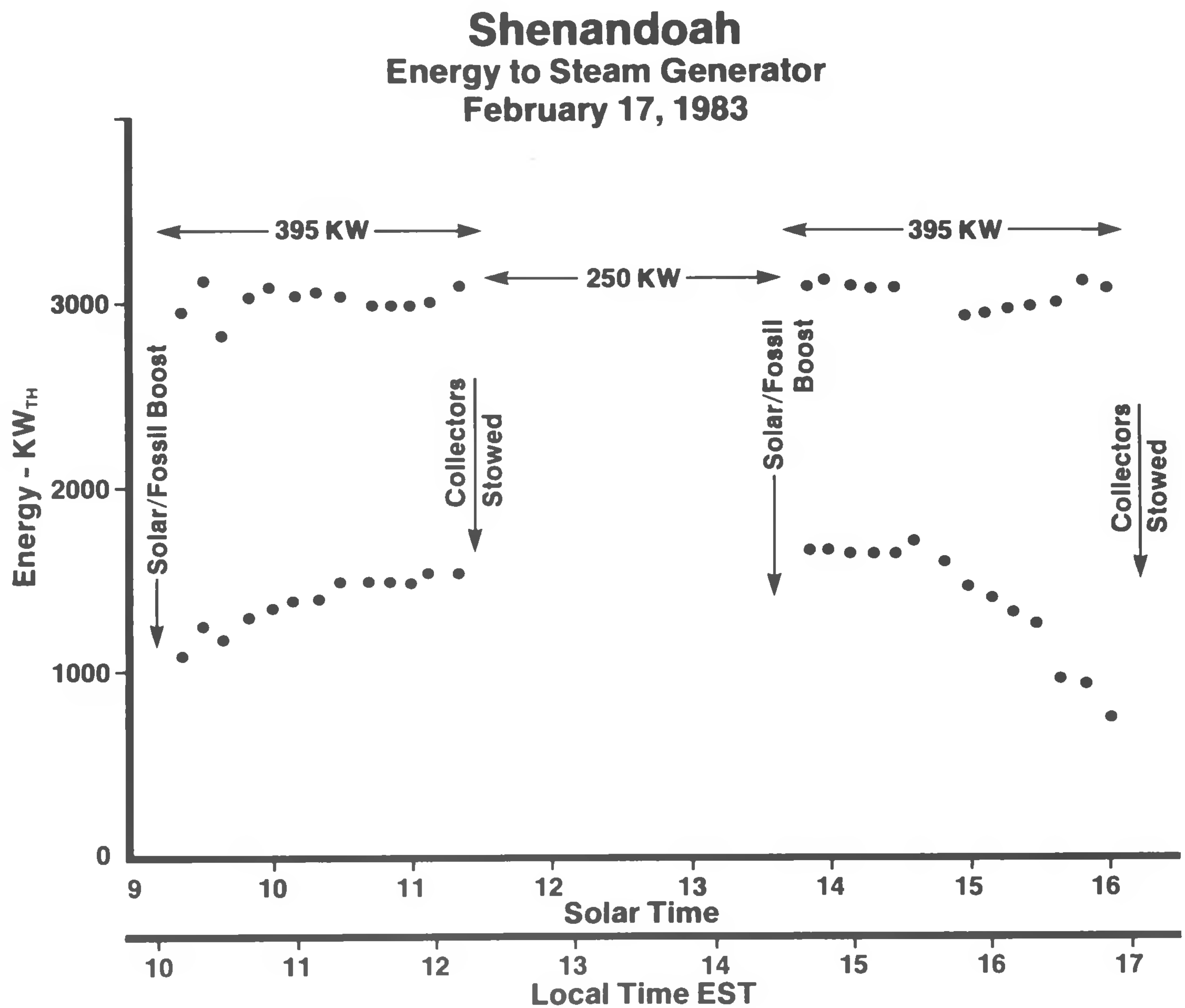
The fossil fired heater is capable of generating enough thermal energy to allow the turbine-generator to be operated at generation level of 290 kW. With a solar assist in the solar/fossil boost mode, the turbine-generator can be operated at 400 kW. During January, repeated attempts to operate at levels above 330 kW would cause a trip to be generated. Once protective relaying that was causing the trip was removed, the turbine-generator was able to operate at 400 kW level for hours without a trip. The boiler feed pump also had been indicating a problem of not being able to keep up at 400 kW generation levels, and the drive pulley was exchanged for a larger diameter pulley, increasing the flow approximately 20%. During the week of February 14th through 18th, the STEP was in operation all five (5) days of the week. On February 15th, 17th and 18th, there was adequate sunshine to operate the solar collector field (SCF). On each of these days, 114 solar collectors were brought into focus by the Control and Instrumentation Subsystem. The Absorption Air Conditioner was not in operation at this time because of the economizer cycle of the Bleyle air conditioners.

On February 15th, the SCF and BOP were started up late due to the cleaning of a pipe strainer on the suction side of the fossil fired heater pump (P-7001). The SCF started supplying energy to the BOP at 10:00 solar time. Generation levels were increased from 280 kW to 400 kW. The SCF supplied 50% of the energy to the steam generator until alto-cirrus clouds moved in at 11:20 solar time dropping the insolation to between 400 and 600 w/m^2. During the time when the alto-cirrus were present, the SCF supplied 20 to 30% of the thermal energy required by the steam generator. Shortly after 13:00 solar time, heavier clouds moved in and the SCF was stowed. The turbine-generator generated 1713 kWH in 5¼ hours and 3775 pounds of steam were provided to Bleyle in 6¼ hours. One solar collector failed at mid-day due to fiber-optic problems and was repaired by the end of the day.

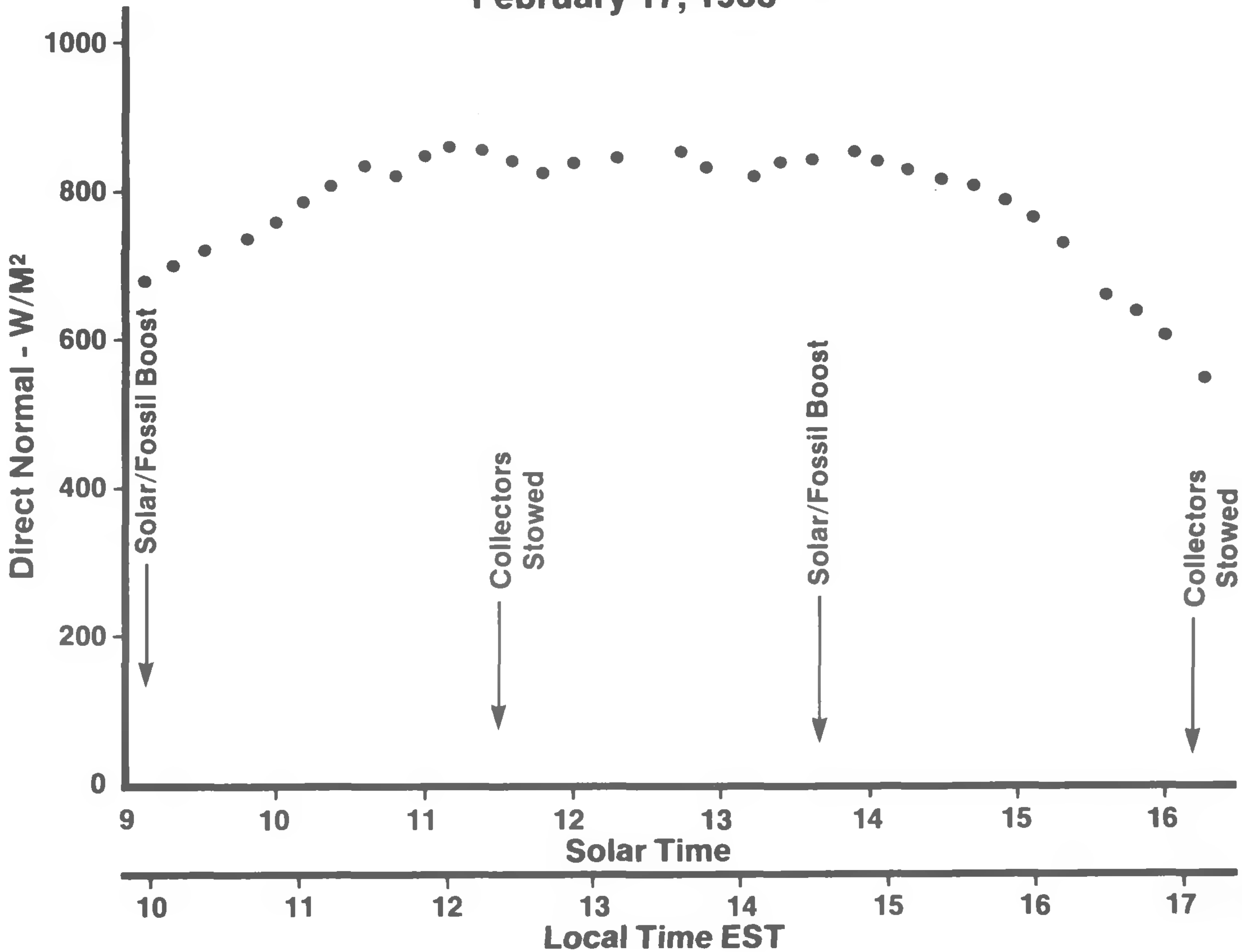
On February 17th, the field was in focus by 8:00 solar time and started to provide energy in a solar/fossil boost mode by 9:00 solar time. The turbine-generator was increased from 280 kW to 395 kW a short time later. At 11:20 solar time, the PDP 11-03 computer lost communication with all but one of the solar collectors, and the solar collectors were defocused. The turbine-generator was reduced to 250 kW until the SCF could again reach temperature. Difficulties in re-starting the computer were overcome, and the SCF was brought into focus at 13:15 solar time, and the SCF started supplying energy to the BOP in 15 minutes. The STEP was shut down at 16:10 solar time (17:00 EST). The turbine-generator supplied 2797 kWH in 9 hours (an all time STEP record for one day). 5100 pounds of process steam were supplied to Bleyle in 10¼ hours. A declination drive motor failed on one solar collector during the second focusing of the SCF and was replaced within an hour.

On February 18th, some alto-cirrus clouds moved in by 10:00 solar time and had thickened just before noon. The SCF was providing 20 to 35% of the energy to the steam generator at solar insolation levels of 400 to 700 w/m^2. When the solar insolation level dropped to less than 200 w/m^2, the SCF was able to provide sufficient energy to only break even (temperature out=temperature in). The clouds were clearing when communication to the SCF was lost again. The turbine-generator supplied 1806 kWH in 7 hours and 4700 pounds of process steam were supplied to Bleyle in 8½ hours.

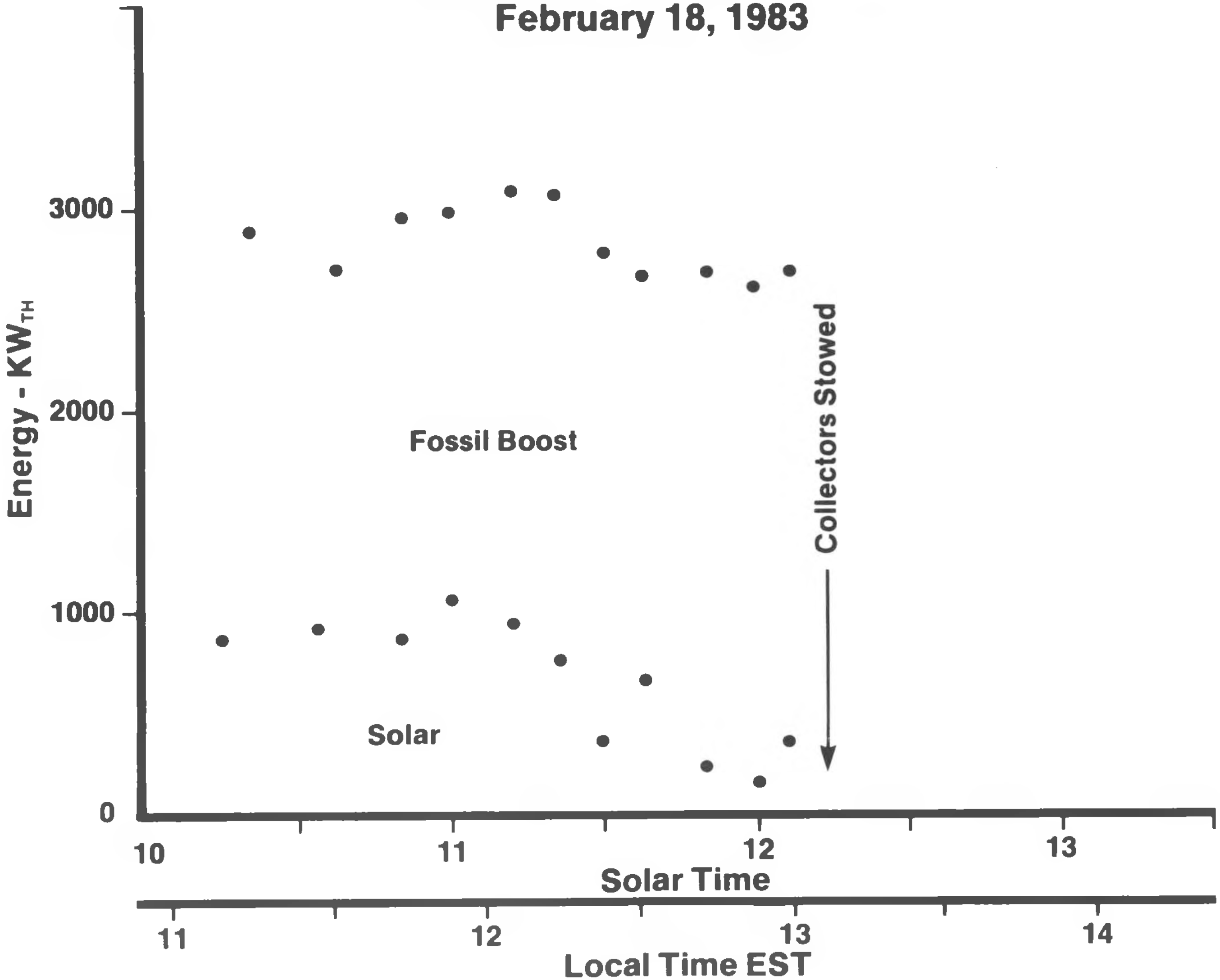
The loss of communication to the solar collector field problem has been tracked to the possibility of receiving a noise burst as a byte in the receive buffers in the PDP 11-03. This would step the next legitimate receive transmission over one step in the array and would be flagged as a non-communication. A change has been made to the PDP 11-03 program to empty the receive buffers just before receiving the transmissions from the SCF. This program will be checked out by operating the SCF during sunny days.


Shenandoah
Energy to Steam Generator
February 17, 1983
395 KW
250 KW
395 KW
Solar/Fossil Boost
Collectors Stowed
Solar/Fossil Boost
Collectors Stowed
Energy - KW_TH
3000
2000
1000
0
9
10
11
12
13
14
15
16
Solar Time
10
11
12
13
14
15
16
17
Local Time EST

Shenandoah
Direct Normal Insolation
February 17, 1983



Shenandoah
Energy to Steam Generator
February 18, 1983



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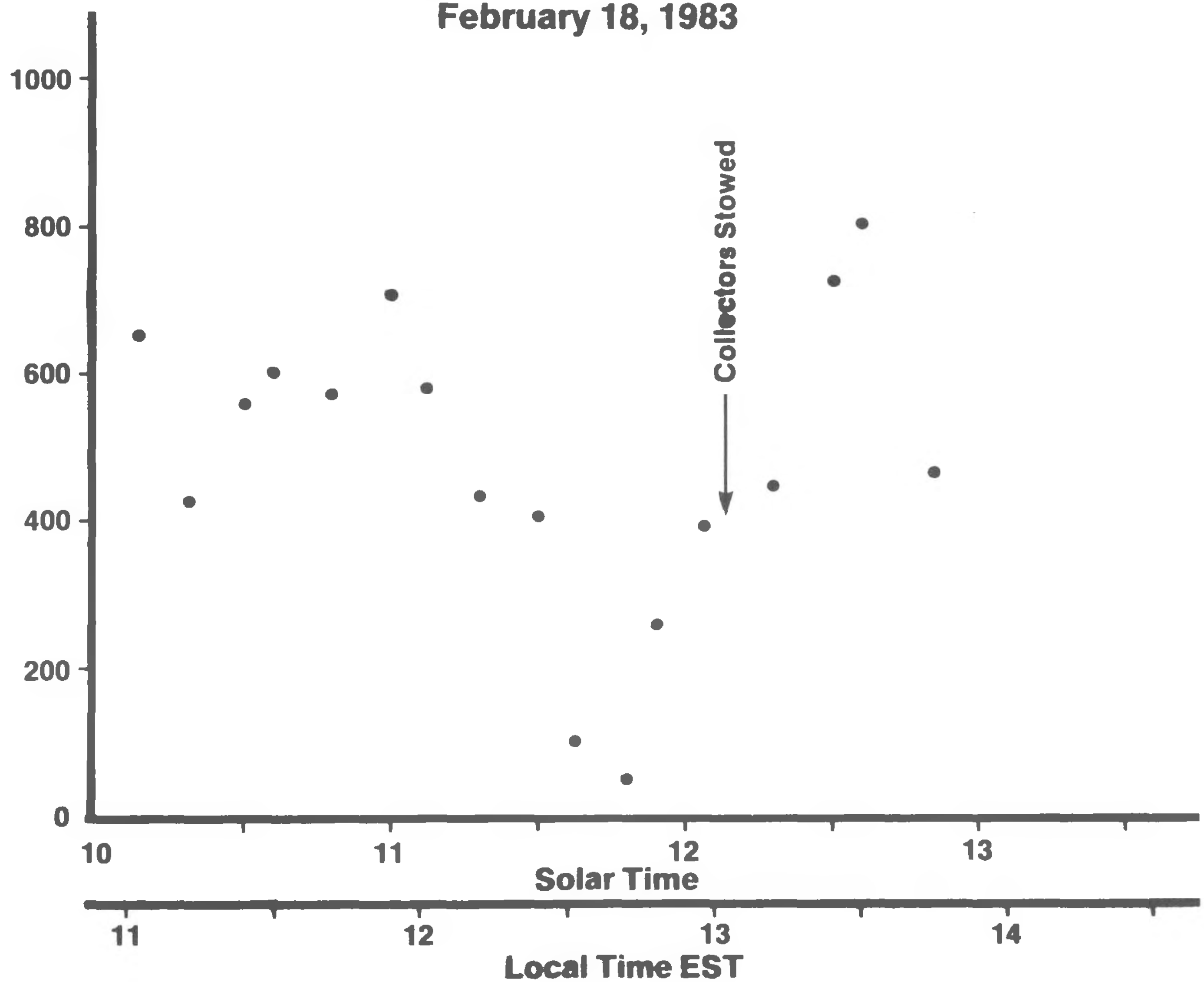

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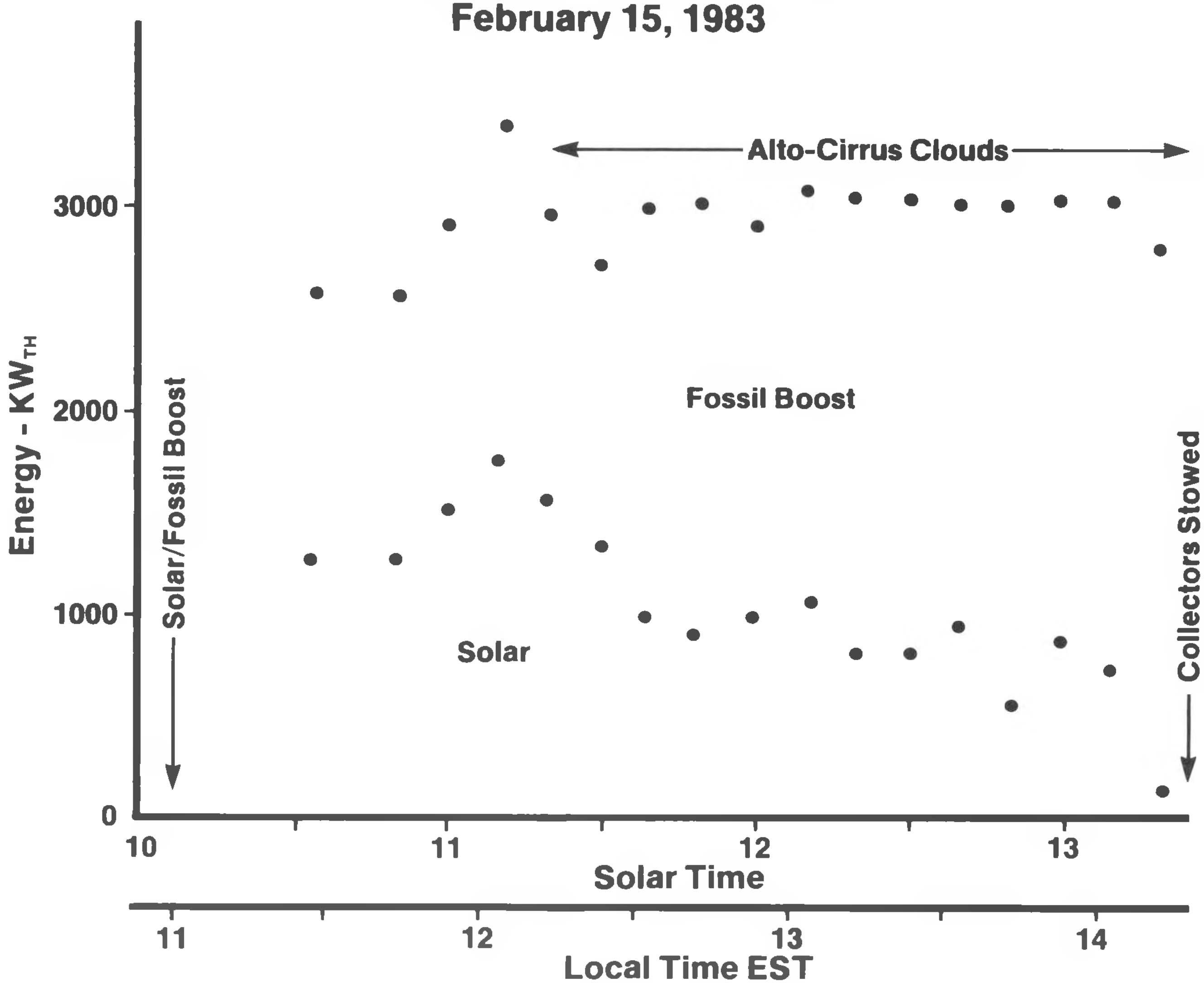
February 15, 1983



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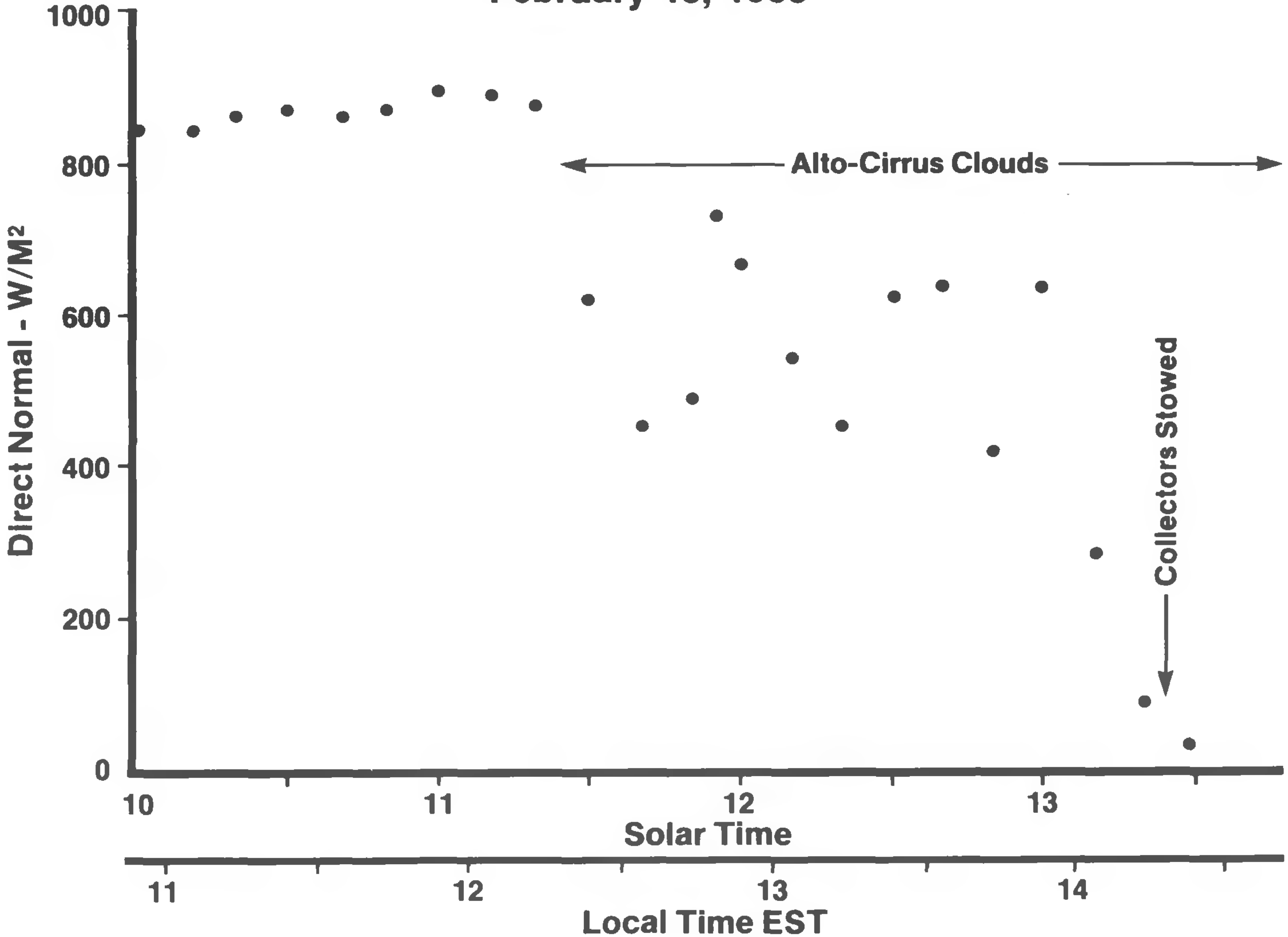

COOLIDGE SOLAR POWERED IRRIGATION PROJECT

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Introduction

The Coolidge facility was constructed to evaluate the feasibility of using a solar thermal-electric power plant to drive deep well irrigation pumps. The plant began operation in October 1979 and was operated by the University of Arizona until November 1982. In October 1982, the plant was deeded to the owner of the farm on which it is sited, Dalton Cole, Jr.

Facility Description

The solar plant consists of solar collector, energy storage and power conversion subsystems, Figure 1. The collector field includes 2140 m^2 of line-focusing parabolic trough collectors made by Acruex Corp. The collectors are oriented north-south and arranged in eight flow loops. The flow loops contain six collector groups, each made up of eight collector troughs. Each group has its own tracker and drive mechanism which causes its collectors to rotate as a group to follow the sun.

The collector troughs are about 1.8 m across by 3 m long and originally had aluminum reflective surfaces. These surfaces were laminated with aluminized acrylic film (FEK-244) in Spring 1981. Caloria^{TM} is pumped through the receiver tube at a rate controlled to obtain the desired collector loop outlet temperature. The receiver tubes are coated with a selective black chrome surface and surrounded by a glass tube to increase energy collection. The sun's energy is concentrated about 36 times to heat the oil to the desired operating temperature, normally 288°C.

Heated Caloria is stored temporarily or sent directly to a vaporizer heat exchanger. A 114 m^3 insulated tank of Caloria provides energy storage capacity sufficient for over 5 hours of power conversion subsystem operation. A thermocline separates heated Caloria which is input near the top of the tank from cooler oil in the lower part.

Thermal energy is converted to electrical energy by means of an organic Rankine cycle engine and generator. The power conversion subsystem (PCS) includes a heat exchanger to vaporize the working fluid toluene, single stage impulse turbine, gear reduction unit, synchronous generator and evaporative cooling tower to recondense the toluene. A regenerator stage is included to improve energy conversion efficiency.

The electrical generator is interconnected with the local electrical utility company grid. The utility receives energy generated by the plant and supplies energy required to meet solar plant and irrigation pump needs. Energy above plant requirements is purchased by the utility.

Energy Performance

The solar power plant was operated daily to maximize operating hours and energy production except when special tests or equipment modification activities interfered.

The collector subsystem operated 90-95 percent of the possible operating hours during each month with three exceptions. In February and March of 1980, the collectors were inoperative for three weeks while awaiting pump repair. Piping modifications prevented collector operation for 8 days in December 1980; thermal energy storage tests reduced collector subsystem operation in July 1981.

During the 1981-82 operating year, the collector subsystem operated 97 percent of the hours having sufficient insolation. Two equipment problems caused the bulk of the downtime. The high wind speed/ambient temperature lockout relay required manual resetting and the pump motor/motor controller required repair, on two occasions each.

Collector subsystem modularity was responsible for the operating record. One or more of the eight collector loops or 48 tracking systems can be removed from service independently. Thus, collector tracking sensors and motors and reflective surfaces were replaced while the collector subsystem was operating. Of course, energy collection was reduced in relation to the amount of inoperative equipment.

Available solar energy and collected thermal energy were recorded every day. Additionally, collector subsystem performance tests were conducted on clear days near each winter solstice, spring equinox, summer solstice and autumnal equinox. In 1980, peak collector subsystem efficiency was about 42 percent in summer, 34 percent in fall and spring and 14 percent in winter performance tests.

The efficiencies obtained in these tests were lower than predicted, partly because collector reflectivity did not meet expectations. Reflectivity of clean polished aluminum reflectors, originally about 70 percent, was measured to be less than 60 percent in Winter 1981. Consequently, in April and May of 1981, aluminized acrylic film (FEK-244) was laminated to the reflective panels of all collector modules.

Subsequently, peak collector subsystem efficiency was found to range up to 47 percent in summer and 39 percent in spring performance tests. Reflectivity of clean FEK-244 surfaces was measured to be up to 83 percent. In 1981-82, average sunny day collector subsystem efficiency ranged from about 35 percent for June to 28 percent in March and September and about 10 percent during December.

The power conversion module (PCM) was operated each day that sufficient thermal energy was available for sustained operation of an hour or more at near the 200 kW design electrical energy production level. The PCM operated reliably; PCM equipment problems seldom prevented operation for more than two successive days.

In 1981-82, the PCM was inoperative for 9 days because of 3 separate problems. These were a toluene pump seal failure in November, jammed generator relay in May and vaporizer toluene gasket failure in July.

Electrical energy production during the 1981-82 year was 178,030 kWh. June production was the highest, 27,350 kWh. Electrical energy production typically was greater than 1000 kWh on a sunny, summer day; the peak daily output was over 1,300 kWh. In January, 5020 kWh of electricity was produced, the September production total was about 17,000 kWh.

Thermal to electrical energy conversion efficiency was 19.7 percent at the 200 kW design point in January 1980 tests, nearly equal to the 20 percent expected value. Power conversion subsystem pumps and other auxiliary equipment required 24 kW, about half for cooling tower operation. Substracting this usage yields a net cycle efficiency of 17.3 percent for the PCM.

Maintenance of a thin, stable thermocline layer separating hot Caloria (285°C), located in the upper part of the energy storage tank, from warm Caloria

(200°C), in the lower part of the tank, is required to maximize the energy available for PCM operation. Static storage tests in 1979 and analysis of dynamic operation in 1981 found a thin thermocline separation layer to be maintained in the Coolidge storage tank.

Energy storage efficiency also was determind in a 1981 evaluation of thermal energy recoverable from storage. Less than 70 percent of the thermal energy input to the storage tank was recovered for use by the PCM.

Therefore, to minimize storage energy loss, normal operating procedures consisted of putting collected energy into storage only during the initial part of the day. PCM startup was initiated when there was sufficient stored energy to sustain PCM operation until plant shutdown, with PCM and collector operations terminating at nearly the same times. The PCM drew energy directly from the collector field supplemented by energy from storage as required to support operation at its rated production level. This mode of operation appeared to maximize electrical energy production.

The energy flow diagram in Figure 2 depicts overall solar plant performance on a hypothetical sunny June day. The plant produced about 1080 kWh of electrical energy, but utilized 220 kWh to power plant equipment and cool the control building. Solar energy collection and thermal energy conversion efficiencies were about 35 and 19 percent, respectively. About 4.3 percent of the received solar energy was made available as electrical energy for pumping.

At the times of vernal and autumnal equinoxes, all day solar energy collection efficiency was reduced to 29 percent, but parasitic energy requirements also were less. Gross electrical energy production on a hypothetical sunny September day was about 810 kWh with about 180 kWh of that amount being used by plant equipment. Thus, about 3.5 percent of the received solar energy was made available as electrical energy.

Equipment Changes

Some equipment modifications were made during the first two years of plant operation to reduce operator requirements, make equipment operation more reliable, increase plant energy production and test new plant operating methods.

The original collector tracking systems required considerable attention to assure proper operation. Moisture collected in sensor windows and cable connectors, through condensation and during rainfall, causing incorrect focusing and searching. Photodiode arrays in many sensors developed cracks due to thermal stressing and control circuitry failures resulted in additional tracking problems. About half of the collector drive motors failed or began operating erratically during first year's operation. Collector tracking units were replaced with the newer model in 1981. Drive motors were factory inspected and repaired and returned to service.

The original collector subsystem flow loop included a buffer tank for use during field warmup, a butterfly type valve to cause collector outlet flow to be recirculated or directed to storage and valves to balance flow among collector loops. The buffer tank was a source of heat loss and was found to be unnecessary. Flow control valve metering elements were removed for repair during plant startup and never reinstalled. Oil flow rates to the eight collector groups were nearly equal as judged by outlet temperature measurements. The butterfly valve leaked oil to the closed path. Thus, in December 1980, the buffer tank and loop flow control valves were removed and the butterfly valve was replaced with a globe type valve.

The original sensor measuring toluene level in the vaporizer frequently gave erroneous values, particularly during PCM startup, and thus required operator monitoring and control. It was replaced with a different type level sensor which automatically controlled the toluene level.

The power conversion subsystem usually required some manual control during startup and sometimes required operator actions during operation. A number of adjustments and equipment changes in 1981 resulted in routine automatic operation of the PCM during the past year. The modifications included a change in the Caloria™ flow controller to better regulate energy input rate, installation of generator phase voltage balancing equipment, location and stoppage of vacuum leakage and reprogramming of startup function controls.

Incidents

A few operational incidents were particularly significant. Some occurrences, such as toluene and Caloria leakage, had safety implications while other events, such a power outages and FEK delamination, affected performance.

In Spring 1981, collector Coilzak reflective panels were removed, FEK-244 aluminized acrylic film was applied to them and the laminated panels were reinserted into collector modules. Tunnel separations of FEK from aluminum backing sheets or within FEK film layers subsequently occurred with over 10 percent of the panels. The initial tunnel separations appeared after collectors were exposed to a July 1981 rainstorm accompanied by heavy winds. The tunnel separations were initiated at collector edges where the FEK film had been trimmed. A few new tunnel separations initiated during the following year and some older tunnels continued to grow until meeting another FEK edge. A second major delamination incident occurred after deliberate washing by gentle rainfall in July 1982. Tunnel delamination appearing similar to that of previous occurrences was discovered next morning.

Application of edge sealant, edge taping and creation of new FEK edges by razor cutting FEK film from edge to edge were utilized to prevent or limit delamination. These techniques were found to be effective in reducing the rate of tunnel formation.

The local utility company provided electricity used at the solar facility. A backup energy system was not installed initially. Although electrical outages occurred frequently (sometimes two or three occurred in one month), outages only occurred while collectors were tracking and Caloria was hot in a couple of instances. In those cases, the operator first desteered the hottest one or two groups in each loop. No evident overheating resulted from outages.

A backup gasoline powered generator was added after one year's operation. It was started weekly to assure reliable operation, but still failed to start automatically on two occasions. Some control system modifications were made to obtain reliable restarting of plant operation after outages.

Caloria pump seals were noticed to be leaking when pumping high temperature (280°C) oil soon after the plant began operation. The rate of leakage gradually increased. Late in the day in February 1980, a fire occurred in the area of the shroud of the collector field pump. Hot oil apparently autoignited near the leakage site. The fire was limited to oil in the shroud area and was extinguished by the operator with a portable fire extinguisher. Carbon dioxide gas systems, using refillable cylinders and flow control valves, were installed to purge pump seals. Pump seals also were replaced. These changes reduced, but did not eliminate Caloria leakage.

Smoke was sighted in the collector field at about noon on a day in August 1981. The source was hot oil dripping from a severed flexhose. One flow loop had been shutdown for replacement of a seal in the remote flow control valve. Manual flow valves had been closed during the repair period and had not been reopened before activation of flow loop operational control. The collectors in the loop began tracking although supposedly prevented from operating by a no-flow control signal. The resulting temperature and pressure increase apparently caused the flexhose failure.

Except for a broken glass receiver tube cover, there was no other evident damage. However, other flexhoses in this flow loop also began leaking during succeeding months. All leaks were detected from smoke emanating from hot, oil saturated flexhose insulation. Each leak was limited to seepage of oil from a small single break in the flexhose. Leaking flexhoses were replaced.

Three flexhoses located in other flow loops also developed leaks, all of the oozing or slow leakage type. Two were detected after noticing a small amount of smoke. The third leak resulted in a fire. The fire was confined to the Caloria soaked insulation surrounding the leaking flexhose and was extinguished with a fire extinguisher. The fire may have initiated in Caloria soaked insulation or from contact of the insulation cover with the exposed flexhose.

Toluene vapor overpressure caused pressure relief disks to rupture in both vaporizer and condenser heat exchange loops in March 1980. The vaporizer toluene level controller was not functioning properly so toluene level was being modulated manually. Improper modulation caused overheating, and thus overpressurizing, of toluene in the vaporizer. An inoperative condenser coolant flow sensor apparently permitted the condenser toluene overpressure incident. Automatic vaporizer toluene level control was obtained by replaceing the original controller in Fall 1980. The condenser flow sensor was repaired. No additional overpressure incidents were experienced at the plant.

Toluene vapors also have escaped because of seal failures and during repair efforts. The vapors caused personnel to feel lightheaded or resulted in headaches with extended exposure (10-20 minutes or more) even though all PCM equipment is located outdoors and thus well ventilated. Toluene odor is strong and distinct; operators must carefully limit exposure.

Caloria was inadvertently added to the toluene supply during routine replenishment, making the toluene supply about 10% oil, in 1980. Reduced performance of the power conversion subsystem, particularly reduced vaporizer performance, was the observed problem symptom. Contamination by Caloria then was suspected and later was confirmed by laboratory tests. The Caloria gradually was removed from the vaporizer, which acted as a distillation unit. The process involved PCM operation, which resulted in separation of Caloria from toluene, Caloria removal from the vaporizer, and toluene replenishment.

Additional Equipment Experiences

A number of additional equipment experiences have provided information for designers and manufacturers. Some experiences may have resulted from the Coolidge environment or plant configuration. Other information is more generally applicable.

Collector receiver tube black chrome coatings deteriorated visibly during the first year. In most collector loops, deterioration is substantial in the two highest temperature groups, moderate in the two medium-temperature groups, and slight in the two groups experiencing the lowest temperatures.

Inadequate end sealing of collector receiver tube glass covers permitted dust intrusion, greatest with tubes at the ends of collector groups. There, sunlight reflection is apparent. A modified insulation cover that abuts the glass receiver cover reduced dust intrusion in limited tests at Coolidge.

Receiver tubes at collector group ends rotate within stationary foam glass insulation covers. The relative motion increased the foam glass insulation interior diameters, causing the covers to sag. Another insulation material is recommended where relative motion is substantial.

The bending motion required of flexible hoses is variable. Some hoses are bent into an "S" shape, and, in many groups, nonplanar bending occurs. Compound bending probably hastened Coolidge failures. The new-style Acurex flexhose used at Almeria, Spain was tested with good results.

Nearly all flexhose covers located at the north end of collector groups deteriorated due to sunlight reflection and subsequently tore in flexure, permitting flexhose insulation to slip down thus exposing the flexhose. Many covers on flexhoses located at south ends of groups also were affected. Sun shields were installed on the north end of collector groups to limit reflection of sunlight onto flexhose covers.

Caloria leakage occurred from storage tank flanged covers, flanged pipe connections and valve stems. Flange joints required periodic retightening to minimize leakage. Valves were repacked to reduce leakage and oriented to minimize insulation contamination and personnel risk from leaks.

In addition to tracking motor problems, electric motors which drive the collector field pump, PCM toluene pump, pyrheliometer tracking unit and air compressor also failed, requiring repair or replacement.

Air compressors are outside; overnight freezing of water in the dryer delayed morning plant startup a few times each winter. Air leakage from valves and connectors caused excessive compressor operation and system maintenance.

Flow meter signal conditioning equipment, located outdoors adjacent to the meters, malfunctioned many times after being wetted by condensation or rainfall. The equipment was rehoused and relocated, solving the problem.

High gain transmitters of insolation measurements and temperature, pressure and flow sensors all malfunctioned at various times. Plant operation was prevented while awaiting parts procurement or component repair.

Operational Requirements

The Coolidge Solar Irrigation Facility operated every day during the hours of solar availability. Plant personnel performed operational, repair, and maintenance tasks, recorded data and incidents of interest, explained plant operation to visitors, and made plant equipment improvements. Initially, one or more of the three operators was in attendance during all plant operation. Monitoring and/or control actions were required during collector startup and shutdown and PCM startup and operation.

Installation of automated supply and isolation valves and restart relays and improvement and reprogramming of PCM controls made possible fully automatic operation of the entire plant. The plant operating staff was reduced to one full time technician for the third year of operation. During that year, the plant operated automatically on routine, incident-free days. However, operator attendance was mandated during PCM startup for safety reasons.

Summary

The Coolidge solar irrigation project was a significant step in the development of reliable components and systems of equipment to more efficiently collect solar energy and convert the collected energy to electricity. Plant operation also provided needed data on the operational and maintenance requirements of a medium sized solar thermal-electric power plant.

References

Duffy, D., M. Matteo and D. Rafinejad. 1980. Design, Construction and Operation of a 150 kW Solar-Powered Irrigation Facility. ALO/4159-1, NTIS, U.S. Dept. of Commerce, 5285 Port Royal Rd., Springfield, VA.

Torkelson, L and D.L. Larson. 1981. 1980 Annual Report of the Coolidge Solar Irrigation Project. SAND80-2378, NTIS, U.S. Dept. of Commerce, 5285 Port Royal Rd., Springfield, VA.

Torkelson, L. and D.L. Larson. 1982. 1981 Annual Report on the Coolidge Solar Irrigation Project. SAND82-0521, NTIS, U.S. Dept. of Commerce, 5285 Port Royal Rd., Springfield, VA.

Acknowledgement

Plant construction and operation was funded by the U.S. Department of Energy. The information in this paper was obtained through cooperative efforts with Leroy Torkelson of Sandia Laboratories, since deceased.

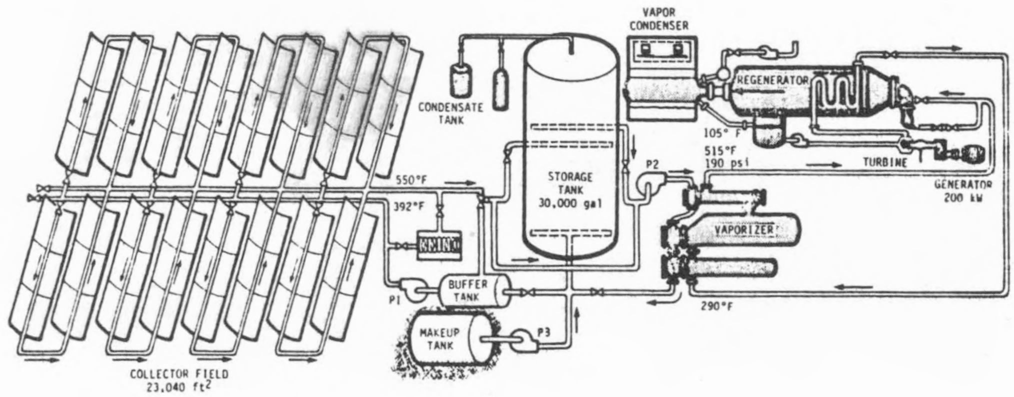

Figure 1. Schematic diagram of the solar thermoelectric power plant at Coolidge, Arizona

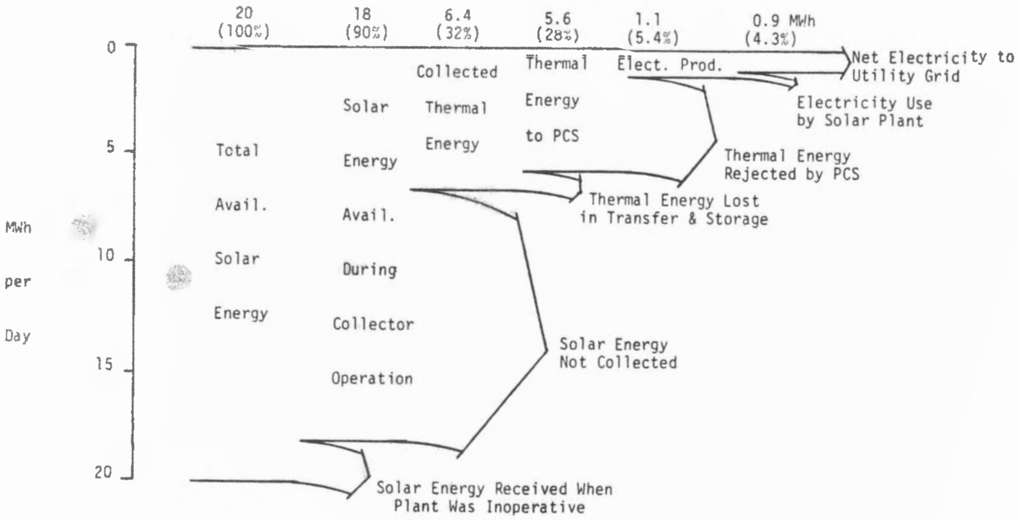

Figure 2. Solar energy collection and electrical energy production on a sunny June day.

CAPITOL CONCRETE SOLAR INDUSTRIAL PROCESS HEAT EXPERIMENT

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1. Overview

The Capitol Concrete Industrial Process Heat Experiment was conceived and initiated in 1980 by the Jet Propulsion Laboratory as a system feasibility field test. Its managerial objective was to develop a high level of confidence in the operability and performance of a point focussing solar thermal process heat plant in an industrial environment. Its technical objectives were to develop a functional understanding of the capabilities and limitations of the technology, through performance testing, operational testing, and plant failure analysis. From December 1980 through May 1982, the experiment was conducted by Applied Concepts Corporation and its subcontractual team members, Power Kinetics, Inc. (PKI), Capitol Concrete Products Company, Inc., and the University of Kansas Center for Research, Inc., under JPL program management. From June through November 1982, research was concluded under the management of the Department of Energy's Albuquerque Operations Office (DOE/ALOO).

Under the program, which was designed to encourage innovative, small business participation, the nation's first point focussing solar industrial process heat plant was designed, installed, and operated for evaluation at Capitol Concrete Products. The solar collector, which was designed and fabricated by PKI, was incorporated into a plant to provide steam for curing concrete blocks in an autoclave at pressures of 15 to 60 psig. The plant was operated for a four month period of technical evaluation (July 26 - November 24, 1982), subsequent to final check out testing. Plant ownership has been accepted by the user, who continues its operation as of the date of this report. A similar plant, modified to reflect lessons learned at Capitol Concrete, has been installed at Hill AFB, Utah, and is now providing steam to the Worldwide Landing Gear Maintenance Facility there.

2. Experiment Results

A. System Failure Analysis. During the course of verification testing of a plant prototype at Sandia National Laboratories, Albuquerque (SNLA) and of check out testing at Capitol Concrete Products, a total of seventeen plant failures were observed. An additional three failures occurred during the period of operational testing at Capitol Concrete. In each case, the plant was restored to service after appropriate design modifications or procedural changes were implemented.

Most of the problems which were uncovered by failure analysis were solved by sub-component-level design improvements which were incorporated into subsequent plant designs. As a consequence of this field testing, the PKI system has been substantially improved.

Failure analysis led to the preliminary explication of a phenomemon of azimuth variation in focus as a function of sun elevation angle which is geometrically inherent to the present PKI design. The consequence of this effort is an hour-glass-shaped variation in focal pattern at the receiver as sun elevation angle changes from that angle at which the system was initially focussed. In addition to decreases in conversion efficiency due to focal dispersion, safety system interactions have been observed. Solar flux incident on the flux trap can cause the system to stow when flux trap-mounted thermocouples signal to the control system a temperature rise which is falsely interpreted as a "walk-off".

This problem was sufficiently alleviated at Capitol Concrete, through a modification of focussing procedures, to permit routine operation, although, at some cost in system efficiency. Further improvements were made at the Hill AFB plant, by modifying the safety system, raising the flux trap temperature threshhold to minimize specious stows.

The variation in focal dispersion with sun elevation is not well-understood at this time. A combination of system modelling and engineering test (rigorous, controlled performance measurement) should be undertaken to increase our knowledge of Fresnel mirror systems. This is prerequisite to utilizing the PKI design in higher temperature applications or in more southerly latitudes, and is advisable for increasing system efficiency.

b. System Operability Testing. The PKI design concept was found to be compatible with industrial application in all regards, although system mechanical **reliability must be** improved before general industrial application is undertaken. The system has been successfully operated by the Capitol Concrete production manager. The brightness of the focal image has not proved to be a problem, being accepted as part of the background by the production crew. No negative environmental impacts have been reported. As of this date, Capitol Concrete has accepted plant ownership, and continues to run the plant at its own expense. We believe that system availability (75% over the period) will improve with experience, as "bugs" are ironed out, and appropriate spare parts stockages developed.

C. Performance Testing. The solar plant was operated for a known total of 231 hours over a 122 day test period. During hours of good direct insolation ($\geq$ 700 watts/m^2), typical conversion efficiencies of 40-50% were achieved (from sunlight incident on the collector to energy delivered as steam to the Capitol Concrete distribution system). Average plant output of 75,000 BTU/hr and conversion efficiencies of 37% were recorded over 107 hours when direct normal insolation was $\geq$ 600 watts/m^2. Actual performance was probably higher. The discrepancy is due to data acquisition system problems, which are believed to have understated system flow rate and thus system output.

During the test period, the solar energy system displaced approximately 2% of total Capitol Concrete fuel consumption, 3.4% during the month of September. System availability was 75% during the period. The longest delays were due to the awaiting of parts and to awaiting good weather for system check out subsequent to repair.

Due to a truncated, four month period of evaluation, a system performance envelope could not be determined. Poor weather and system down time in November, for example, led to only nine hours operation in that month. Thus, overall system performance was much higher than average during August through October, and the most meaningful results were anticipated for May-July 1983. Changing national priorities, however, led to a decision not to extend the evaluation.

3. Conclusions

1) The experiment has substantially advanced the state of the art of Fresnel mirror concentrating solar technologies through the experience and lessons learned in industrial operation at Capitol Concrete. Plants at Hill AFB, Utah and Yanbu, Saudia Arabia are directly attributable to this experiment. The PKI system design and manufacture have been further developed and improved as its result.

2) The experiment has revealed the importance of the phenomenon, inherent to the PKI concept, of focal dispersion in azimuth as a function of sun elevation angle. Deleterious consequences of the phenomenon were minimized at Capitol Concrete through field engineering and revision of focussing procedures. The precise characteristics of this effect will not be known until system modelling and rigorous, controlled performance measurements have been accomplished. Performance testing at Capitol Concrete, though insufficient to characterize the phenomenon, indicate that acceptable performance is attainable without design modification for mid temperature applications in temperate latitudes. Further research should be undertaken before high temperature or tropical latitude applications are undertaken.

3) Scientific research and knowledge of Fresnel mirror solar energy systems would be substantially furthered if the substantial investment in the Capitol Concrete Plant were exploited through support of a full year's testing cycle.

DOW SOLAR STEAM PLANT: OPERATING RESULTS AND EXPERIENCES

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Abstract

A solar steam facility has been designed and constructed for The Dow Chemical Company's latex manufacturing plant at Dalton, Georgia. The solar plant is designed to produce 1.03 MPa gage (150 lb/in^2g) saturated steam and provide approximately 5 percent of the process steam required for the steam stripping operation at the latex plant.

Introduction

In September 1978 Foster Wheeler Development Corporation, working with The Dow Chemical Company, began work on a three-phase project to design, construct, and operate a solar process steam plant for Dow's latex manufacturing plant in Dalton, Georgia. This work was funded by the U. S. Department of Energy (DOE). The primary objective of Phase 1 was to design a cost-effective solar steam generating system, and this work was completed in September 1979.[1] Phase 2--Fabrication and Installation began in October 1979 and was completed in November 1981; Phase 3--Operation and Performance Evaluation began in November 1981.

The system is designed to supply 1.03 MPa gage (150 lb/in^2g) process steam to Dow's plant, where styrene butadiene latex* is manufactured for carpet backing. Within an 80-mile radius of Dalton, over 70 percent of the world's carpets are produced. In the latex manufacturing process, steam is used for heating the reaction

*Latex is a generic term for the family of polymers and copolymers manufactured by emulsion polymerization.

kettle and for steam distillation of the unreacted monomer from the raw latex. Steam distillation is a standard unit operation that is used to produce many chemicals and products. The plant consumes about 45 Gg (100 x 10^6 lb) steam annually--50 percent of which is used by the steam stripping operation. The steam is provided by two package boilers [2.53 kg/s (20,000 lb/h) each]. The solar steam system interfaces with these package boilers and supplements the plant steam requirements.

A schematic of the solar steam system is shown in Figure 1. The system consists of 15 rows of parabolic trough solar collectors manufactured by Suntec Systems, Incorporated. The total collector aperture area is 929 m^2 (10,000 ft^2), and the collector rows are oriented in a north-south direction with a 10-degree tilt to the south. The reflector panels are made from 3M's FEK 244, a plastic reflective material, attached to an aluminum, honeycomb, parabolic support. The solar concentration is 40 to 1. Collector receiver tubes are coated with a black chrome surface and are enclosed by an insulated housing on one half and glass on the other.

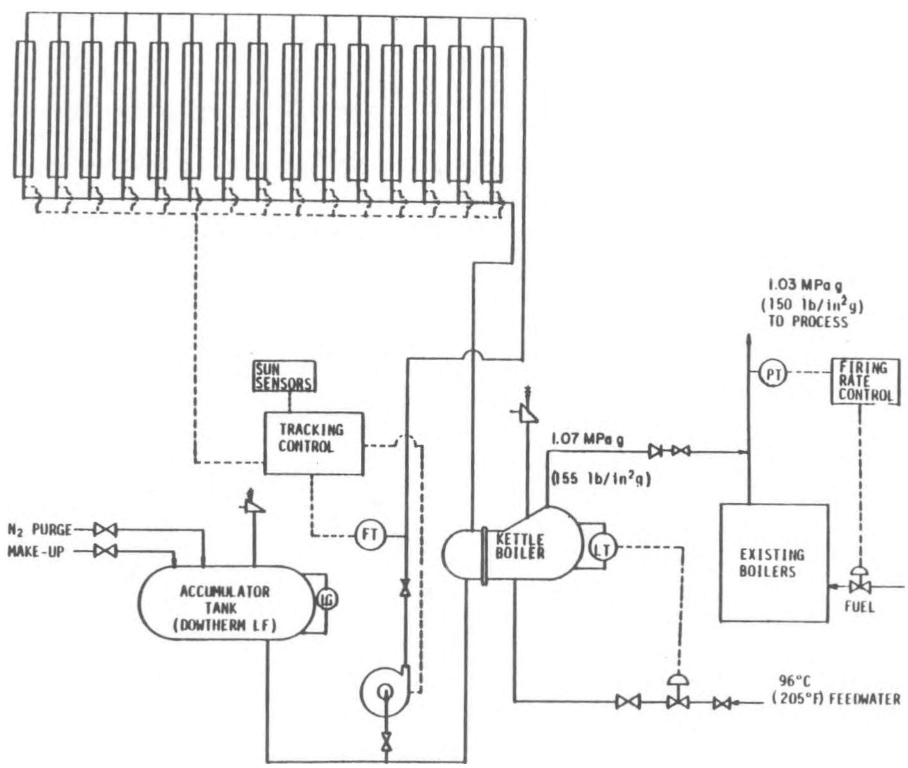

Figure 1 Schematic of Selected Solar Steam System

Dowtherm LF, the intermediate heat-transfer fluid, is circulated in parallel in the receiver tubes to an unfired steam generator and then returned to the solar collectors. The system is completely automated with many features that ensure safe operation. The collectors are rotated to the stowed or protected position if:

- There is inadequate insolation
- No steam is demanded
- Wind speed is excessive
- The pump fails
- The temperature in any of the collector rows exceeds a preset limit
- Power to the system is lost

System pressure is controlled simply, by a check valve at the interface between the solar and the conventional steam systems. Steam from the process plant is delivered only if the solar steam pressure is higher than the process steam pressure. This simple control scheme allows maximum utilization of the solar-produced thermal energy. An accumulator tank serves as a dump tank, if needed; it also accommodates thermal expansion of the Dowtherm LF. The system is usually not drained at night.

A data acquisition, reduction, and performance evaluation system is also provided. It enables on-line performance evaluation and data storage on a backup magnetic tape. The performance projected at the end of the design phase indicated that the system would produce 0.19 kg/s (1500 lb/h) steam at peak insolation and 1.1 Gg (2.5×10^6 lb) steam annually.

During Phase 2, the solar steam plant was fabricated and installed according to the approved design and performance specifications developed during Phase 1. During Phase 3, the system is being operated, maintained, and monitored by Dow. Progress reports indicate performance data and operating experience.

This paper discusses some of the problems we have experienced during system operation and presents operating and performance data generated during November 1982.

Problems Encountered and Solutions

Because the collectors are installed on a hillside with a 10-degree slope, their downhill thrust caused several problems during installation and early operation. The sloped field caused interference by the bolts in the torque tube flanges with the stanchion roller-bearing support assemblies on the two stanchions south of the center drive stanchion. Figures 2 and 3 schematically show the solar collector assembly and define the terms used in this section of the paper. This problem was corrected by adjusting the nuts on the anchor bolts on the drive stanchion so that a counteracting force was transmitted through the stanchion to the torque tube, thereby reestablishing adequate clearances at each stanchion. For added strength, a support plate was welded to the bottom of each drive stanchion.

The U-bolt riser support bracket at the center drive stanchion of each collector row is tightened to enable the receiver to thermally expand toward both ends from the fixed center. At the other four riser locations, the receiver is designed to slide in its assembly. Because the reciever bows slightly and clearances are minimal at each riser location, the receiver does not expand freely. When it expands, it bends the riser weldment assemblies. We are currently reviewing this problem.

The receiver is enclosed by an insulated aluminum housing. Curved glass panels, which fit into the channels on each side of the housing, cover the receiver aperture. These glass panels are secured to the housing with spring clips. Local crimping of the aluminum housing at each stanchion support location, oversized glass covers, or both of these caused the glass to fit incorrectly in the aluminum housing and to crack during system operation. A special tool was designed to expand the housing, permitting the glass to fit properly.

Several of the mechanical limit switches failed, causing the collector to bottom out against the stanchions and bend the pipe risers at each end of the failed row. Because these switches were unreliable, they were replaced with highly reliable mercury switches. The new switches have a built-in backup set at 6 degrees forward and reverse of the extreme limits.

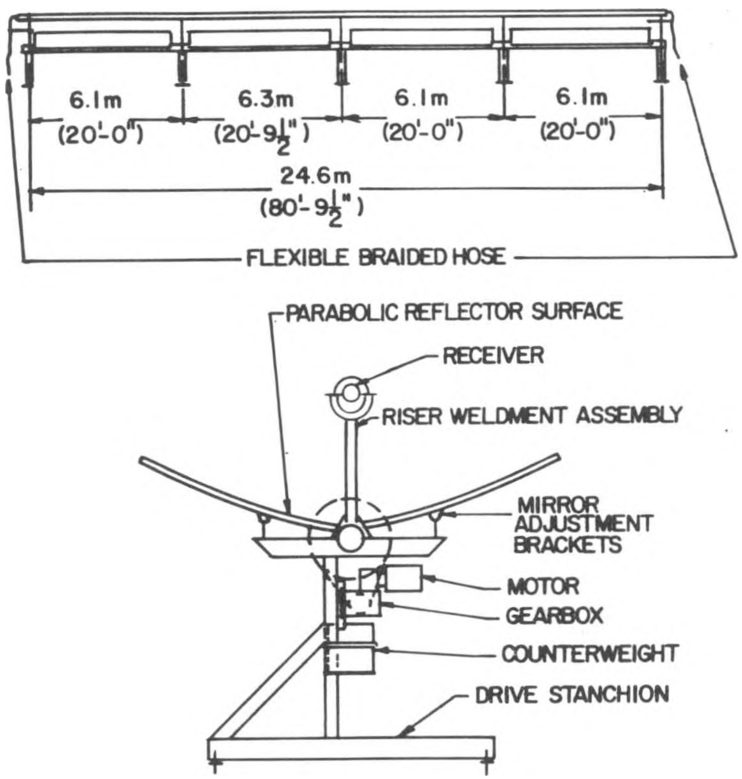

Figure 2 General Arrangement of Solar Collector Assembly

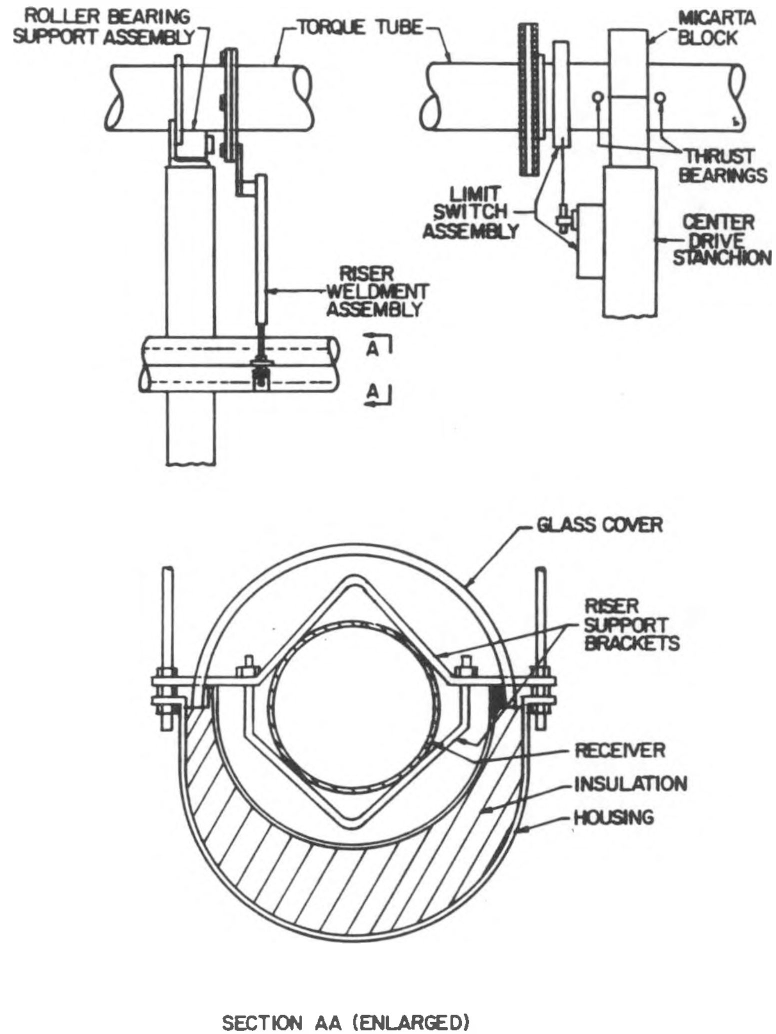

Figure 3 Detail of Receiver Support Assembly

The sun-tracking assembly on several collector rows was unreliable after several months of operation. A close examination of the tracker heads revealed that the leads from the photodiodes, which were originally sleeved, were badly rusted and in some cases "open." The badly rusted photodiodes were replaced, and tracking reliability has improved significantly. The new photodiodes have been sprayed with a sealant to reduce rusting.

When the pressure in the solar boiler exceeds the plant process steam pressure, the check valve opens and steam is provided. An automatically actuated ball valve was installed adjacent to the check valve to prevent reverse steam flow from Dow's main steam line into the solar boiler. This valve closes when the collectors stow, thereby providing an additional stop against any leaks through the check valve.

Several of the flexible hoses on both the north and south sides of the collector field have failed. Based on a review of the problem and the work conducted by Sandia National Laboratories, all the flexhoses have been replaced. The original flexhose design consisted of a 142.2 cm (56-in.)-long metal flexible hose welded to each end of the collector. The hose assembly is welded to the receiver downcomer at one end and to the pipe header riser at the other. The primary hose which takes the service temperature and pressure is a stainless steel, Type 316L, 19 mm (3/4-in.) nominal I.D. flexhose. It is covered with a stainless steel cross braid and then wrapped with 25 mm (1 in.) of fiberglass insulation. It is slipped inside a metal flexible hose (bellows) with a 60 mm (2-3/8 in.) nominal I.D. The outer hose protects the insulation from weather. As the result of a field installation error, two different lengths of receiver downcomer were used. The lengths on the north side of the field were 737 mm (29 in.); on the south side, they were 584 mm (23 in.). A simplified stress analysis of the flexhose was performed, and we found that the relative position of the flexhose with respect to the center of rotation is an important parameter with respect to flexhose fatigue life.[2] Several of the flexhoses on the north side (longer downcomer) failed after approximately 100 cycles; several on the south side failed after about 600 cycles. Based on work performed by Sandia National Laboratories, we chose a new flexhose assembly that consisted of the original type of inner hose, but with an outer metal cover made of a strip-wound flexhose. The strip-wound outer cover limits the bend radius to a specified value. The replacement hoses are working satisfactorily.

System Performance

A clear-day performance graph for November 6, 1982, is presented in Figure 4. It shows the measured and calculated performance values for the solar plant on a day when all collector rows were operating and the measured solar insolation values were at their highest for the month. The shaded area represents the steam actually provided to Dow's process. Figures 5 and 6 show the collector field inlet and outlet temperatures and the collector field efficiency as a function of time. Daily performance is summarized in Table 1, which is a duplicate of the printout provided by

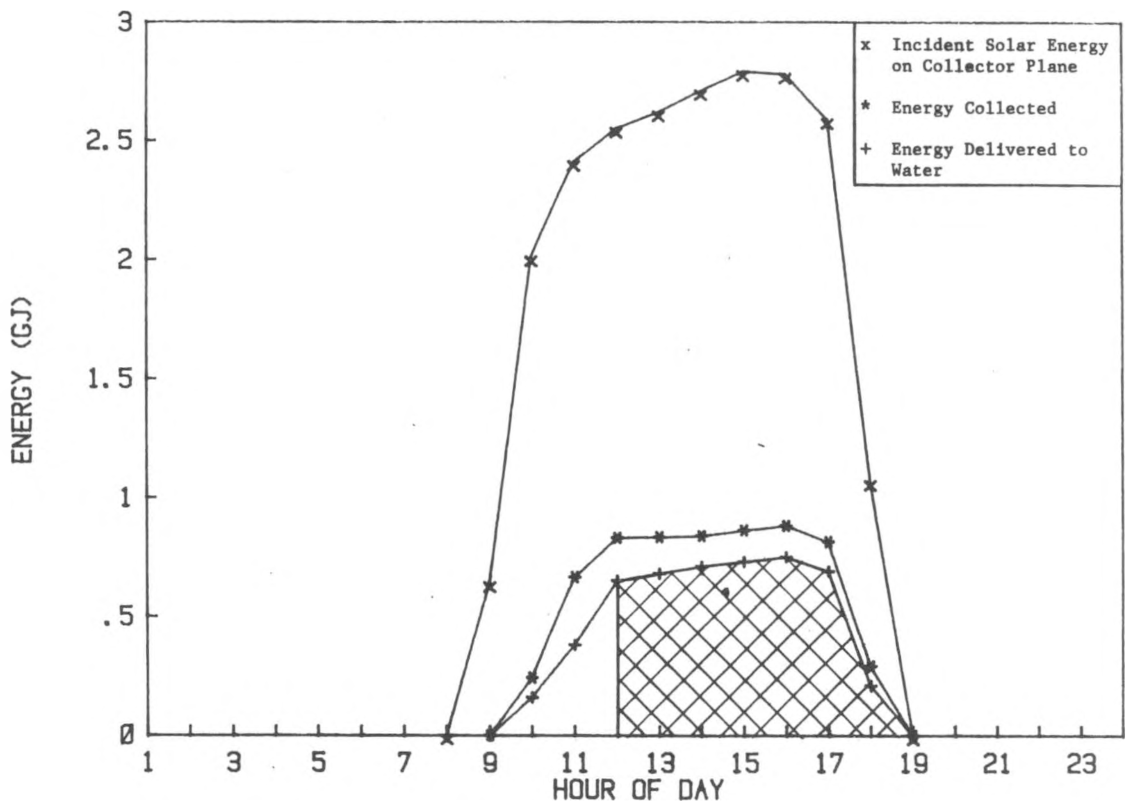

Figure 4 Clear-Day Performance Summary--November 6, 1982

the on-site data acquisition system. As seen from these data, the calculated solar collector efficiency (defined as energy collected divided by the incident solar energy in the collector plane) for November 6 is 28.22 percent, compared with a predicted value of 34 percent from a computer simulation generated by Suntec, during Phase 1 of the program. The energy of the delivered steam was approximately 80 percent of the energy collected. This difference is the result of system thermal losses.

Table 1 Clear-Day Performance--November 6, 1982

Solar Collector Efficiency (%)	= 28.22
Parasitic Energy (kWh)	= 23.04
Piping Loss (Btu x 10^6)	= 1.2246
Thermal Loss (Btu x 10^5)	= 1.8346
Total Energy Collected at Collector (Btu x 10^6)	= 5.9305
Total Solar Energy on Collector Plane (Wh/m^2)	= 6672
Total Energy Delivered to Boiler (Btu x 10^6)	= 4.8756
Total Energy Delivered to Water (Btu x 10^6)	= 4.7059
Solar Steam Production (lb)	= 4421

During November the system was available for 10 days, 7 of which had adequate insolation for system operation. Figure 7 summarizes performance for the month. On November 11 the system was shut down for maintenance and repair.

Summary

Although a limited amount of data have been obtained to date, the solar plant has operated for at least 100 days and has provided steam for Dow's process. Problems have plagued the system--both those associated with the solar collectors and those associated with instrumentation and the "balance of plant." However, we believe that the experience gained during the project has resulted in significant improvement in the design and operation of the plant, and we look forward to its continued operation.

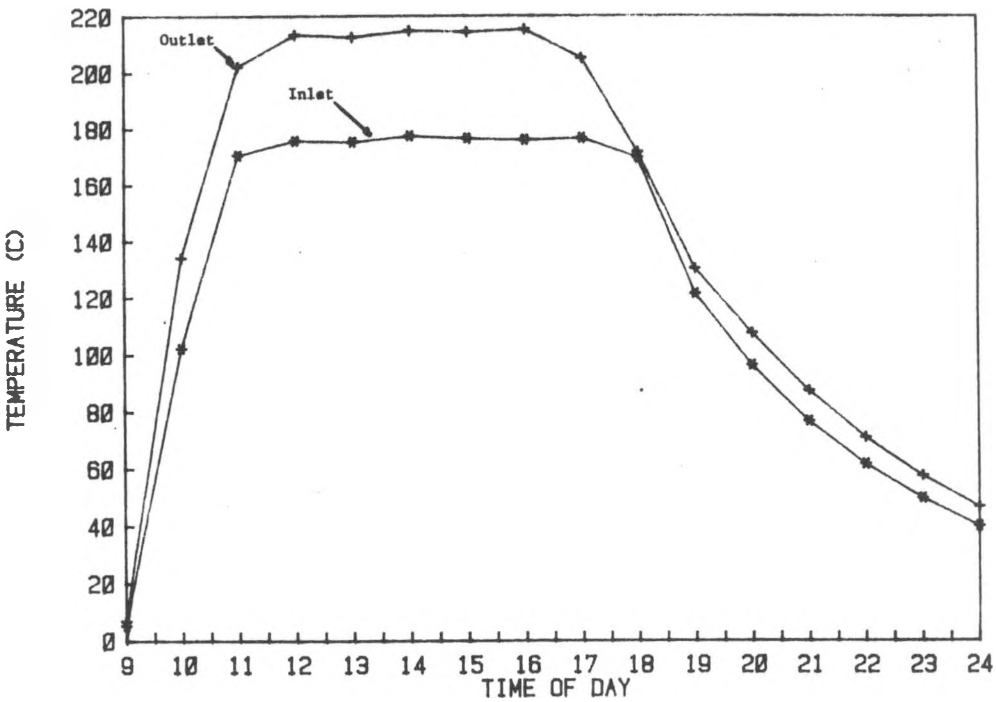

Figure 5 Collector Field Inlet and Outlet Temperatures--November 6, 1982

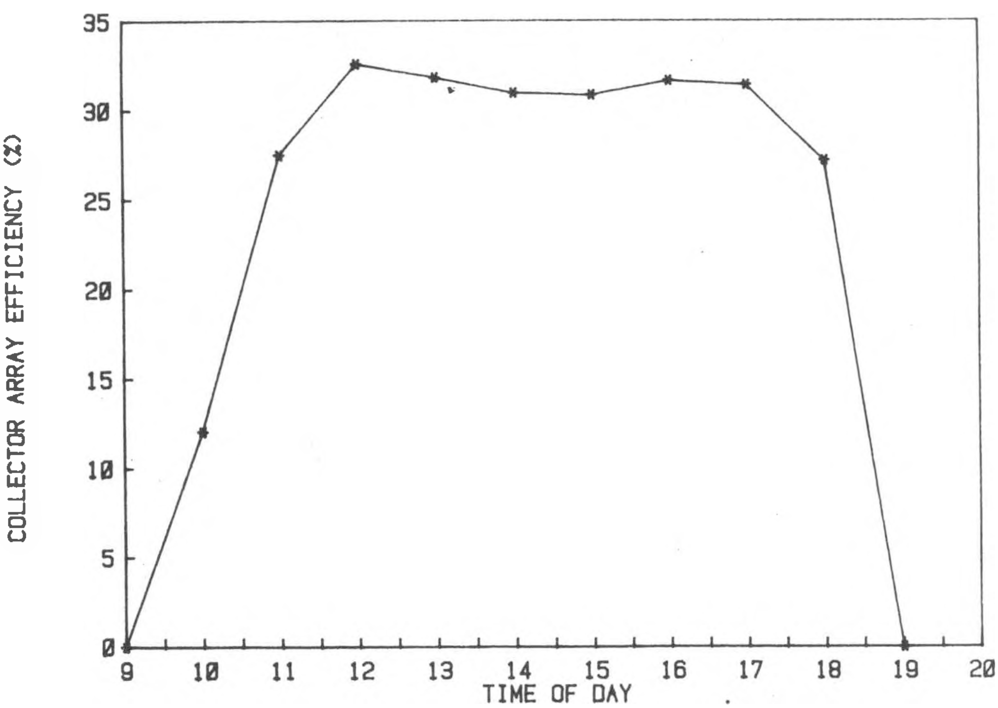

Figure 6 Collector Field Efficiency--November 6, 1982

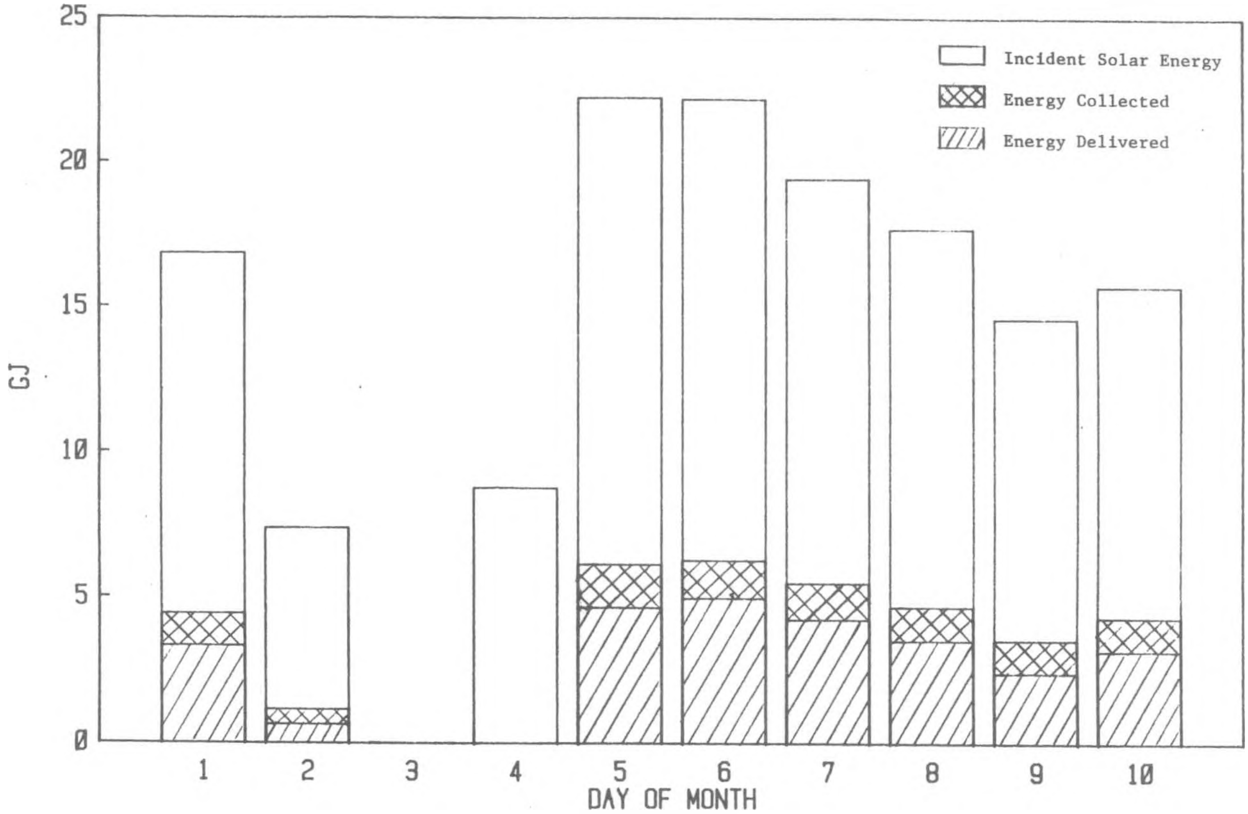

Figure 7 Monthly Performance Summary

Acknowledgments

The authors thank DOE, Sandia National Laboratories, and the Energy Technology Engineering Center for their support and guidance during the project. We also thank the many people at Foster Wheeler and Dow whose contributions have proved invaluable.

References

1. Foster Wheeler Development Corporation, "Final Report for Solar Production of Industrial Process Steam Ranging in Temperature From 300°F to 550°F (Phase 1)," prepared for the U. S. Department of Energy under Contract No. ET-78-C-03-2199, June 30, 1979.

2. M. S. Rao, "Design of Flexhoses in Parabolic Trough Solar Collectors," Foster Wheeler Report FWC-FWDC-EST-81-07, September 1981.

SOLAR IPH SYSTEM FOR CATERPILLAR TRACTOR COMPANY AT SAN LEANDRO, CALIFORNIA

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INTRODUCTION

A solar industrial process heat (SIPH) system has been designed and installed at the San Leandro plant of the Caterpillar Tractor Company (CTCo.). An aerial view of the collector field is shown in Figure 1. This system is one of the cycle 4 projects in DOE's SIPH Demonstration Program. This work has been performed for the Department of Energy under contract DE-FC03-79CS30309 with 25% of the design and construction cost being shared by CTCo.

Fig. 1. Aerial View

SYSTEM DESCRIPTION

Descriptions of the solar system, plant process heat system and the data acquisition system (DAS) are given here. The normal operation scenarios are also described.

Solar System

The solar process heating system is a simple open loop hot water preheat system. A schematic of this system is shown in Figure 2. Water is pumped from the hot water process return line (HHWR) at a rate of 450 gpm and is split between the system north field at 120 gpm and the south field at 330 gpm. The pumping system consists of two parallel pumps that laternately operate to provide full flow from a single pump. This water then passes through each collector delta-T string via a reverse return piping system. Each delta-T string consists of two 125 ft long collector drive rows piped in series. The flow rate through each delta-T string is 15 gpm. After exiting the delta-T string the solar heated water is then returned to the HHWR.

A circuit setter is located at the inlet of each delta-T string so that the flow can be set and measured for flow balancing purposes. A thermometer well is provided at the outlet of each string so that the outlet temperature can be measured.

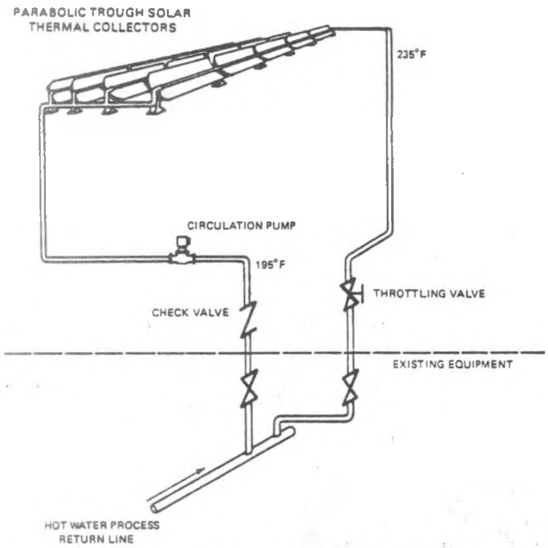

Fig. 2. System Schematic

To minimize thermal shock on the plant system a temperature regulating valve (TRV) with a by-pass line set at 10% of design flow is located at the exit of each bank of collectors. When the system starts up water is passed from the collector field at 10% flow until the cold fluid initially in the collector piping has been replaced by water from the HHWR which has been heated by the collectors. The TRV then opens completely and full design flow is allowed.

When the central controller's direct normal light switch indicates adequate direct normal radiation levels for a minimum period of five minutes, and if the plant process hot water system is operating, the central controller issues a "track ready" command which starts the system flow pumps. After a 2-minute delay to establish steady fluid flow the collectors are directed out of the stow position. As each collector row approaches the sun and falls within 20° of focus, the individual row controllers will switch the respective rows to automatic track. This signal is maintained as long as the minimum light level is present and the receiver tube temperature is below the critical value. If the collector outlet temperature falls below the HHWR line temperature, the TRV closes and the flow drops to the 10% level. In the event that this continues for a predetermined period (adjustable up to 45 minutes), the collector central controller will stow the collectors and shut off the pump. The collectors will remain in this position until the original automatic startup sequence can be reinitiated. If the HHWR temperature becomes too high, the collectors are defocused until the HHWR returns to its normal temperature level. This condition occurs when the solar system overdrives the plant process system during low load conditions and high radiation levels.

The only exception to the above operating scenario occurs when a temperature switch senses a freezing condition. This sequence is overridden and the system pump is activated to pump the 10% by-pass flow through the collectors. The pumps will cycle on and off based on a predetermined timing cycle to prevent freeze damage to the system.

Plant Process Hot Water System

In the CTCo. manufacturing operation a major portion of the energy consumed is for industrial parts washing. These washers are required to clean parts after critical machining operations so that inspection can be performed for quality control

Basically, hot water is generated in hot water heaters and is then pumped through a hot water supply header that encircles the building. The building circulation pump system consists of four hot water pumps piped in parallel; likewise, the heater feed pump system also consists of four pumps piped in parallel. The required flow rate through the process equipment is nominally 836 gpm for a 40°F temperature difference. The process hot water generating system is comprised of two natural gas fired hot water heaters rated at 500 boiler horsepower (~16.7 x 10^6 Btu/hr). A list of the process heating loads is shown in Table I. The maximum total load is 32.5 x 10^6 Btu/hr with a 10% reserve. Most of the process equipment operation is intermittent and past experience indicates a 14 x 10^6 Btu/hr mean load condition for the manufacturing process is normal.

It should be noted that the present process heating load is much less than the 14 x 10^6 Btu/hr nominal condition. This is partly due to an active energy conservation effort recently undertaken by CTCo. In addition, CTCo. has unfortunately been forced to drastically reduce its production, so that, at times, the solar system overdrives the plant process system.

This results in the defocusing situation described above. While this decreases solar system performance, the portion of the load carried by solar energy approaches 100%.

Table I. Process Heating Hot Water Load

Description	Connected Load Quantity	Flow Duration	System Type	Heating (MBH)	Water Flow (gpm)
Process washer	1 each	Intermittent	Closed	10,508	525
Process washer	6 each	Intermittent	Closed	8,407	420
Office heating		Intermittent	Closed	7,800	390
Tumbling area	2 each	Intermittent	Closed	1,201	60
Tacco H.T. unit	4 each	Intermittent	Closed	1,201	60
Wash and test - Met Lab	1 lot	Intermittent	Closed	300	15
Insulation line loss	1 lot	Continuous	N.A.	111	0
Reserve	10%			3,000	150
Total				32,528	1,620
Caterpillar Tractor Co. design criteria (including diversity) manufacturing process				14,000	

Data Acquisition System

A computer based data acquisition system (DAS) was designed and installed to monitor the performance of the solar system. This DAS collects data from various sensors that measure temperature, flow, etc., and processes these data to produce complete summaries of system thermal performance. The objectives to be fulfilled with the aid of the DAS, then, are as follows:

- Determine the energy delivered to the process by solar collector system on a monthly and an annual basis.
- Determine parasitic energy used by the solar collector tracking and pumping system on a monthly and an annual basis.
- Determine the fraction of the total plant thermal load taken by solar on a monthly and annual basis.
- Determine significant losses (piping runs, etc.).
- Determine changes in collector system operational characteristics with weather exposure.
- Determine long-term reliability in terms of materials, components, and system performance.

A major portion of the DAS components are shown in the photograph of Figure 3. Shown are the PDP 11/23 computer, LA-36 lineprinter, system console, the two disk drives for software and data storage, and modem for off-site monitoring. Not shown, of course, are the system sensors which are placed throughout the plant.

Each of the sensors is connected to the A/D converters in a 4-20 ma current loop across a precision resistor. In this way, the lead resistance due to the long wiring paths necessary in this large plant is not a factor in the sensor calibration. The PDP 11/23 is configured to read the A/D inputs at a predetermined time interval and to process the data before storing the data for later retrieval and analysis. This real time processing includes (1) conversion to engineering units, (2) computation of "instantaneous" energy transfers, (3) integration over several time periods for on-site data review, and (4) storage of short-term (5-minute) averaged data for off-site analysis and review.

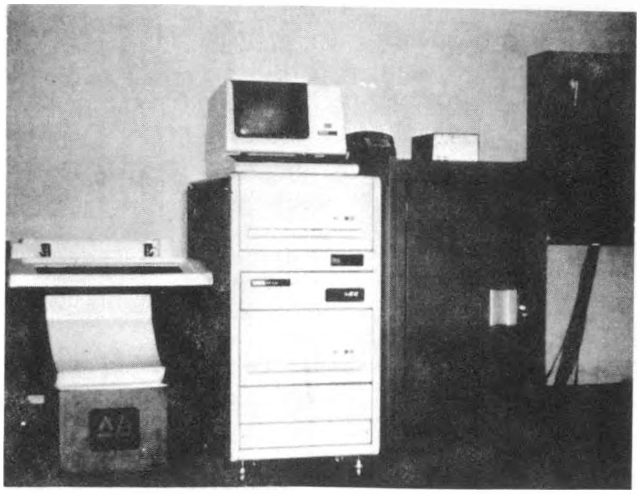

Fig. 3. Data Acquisition System

The on-site data processing software allows the user to view data for windows of time ranging from 5-minutes to 24-hours. Since the DAS is configured around the PDP 11/23, it can supply the computing power necessary for most conceivable data analysis requirements. However, this is usually done off-site so the computer is not deterred from its data acquisition responsibilities.

SYSTEM CONSTRUCTION AND INITIAL OPERATION

The construction of the solar IPH system began in June 1981 and was completed in September 1982. Due to various problems encountered during initial operation and, later, inclement weather conditions the acceptance test was postponed until February 1, 1983.

A brief description of the major construction problems will be given here while a more complete description of the construction is given by Deffenbaugh [1].

First of all, there were several major revisions to the structural design after construction was initiated. This design consists primarily of modifications to the existing building structure to accommodate the roof-mounted collectors. The local code authority questioned several points of the design and requested substantial changes to increase the load capacity of the roof support structure. There were also numerous damaged structural members which could not be identified until the collector supports were being placed. While these damaged members did not affect the integrity of the existing structure, they had a large impact on the collector support structural integrity. These field changes constituted the major portion of the impact on construction cost and schedule.

The DAS was relocated to isolate it from a plant office area. The move made from the original location on the second floor close to the system electrical control panel to the first floor required a significant modification in the DAS wiring.

Several schedule changes were caused by changes in the collector design and equipment delivery problems. To alleviate problems with the receiver tube design encountered in previous installations, the vendor redesigned the receiver tube support hardware. The new design is superior to the previous one, but unfortunately, this change was effected after the bidding process on this job. This impacted the manifold/receiver interface piping and the labor required for installation. An 8-month delay in complete delivery of all collector hardware caused major problems in scheduling construction milestones.

Despite various field changes and time delays during construction, the actual construction cost agrees quite well with the original bid. Table II shows a breakdown of the construction costs into the major components.

Table II. Construction Cost

ITEM	BID	ACTUAL
Painting	27,248	27,608
Structural	282,446	379,186
Electrical	145,618	157,528
Mechanical	344,800	350,314
Sheet Metal	48,420	56,179
Roofing	42,950	47,495
General Contractor	310,972	176,226
SUBTOTAL	1,202,454	1,194,536
Collectors	1,242,535	1,246,144
SUBTOTAL	2,444,989	2,440,680
DAS	200,000	200,000
Management	187,000	187,000
TOTAL	2,831,989	2,827,680

During initial operation of the system a number of problems were identified. First, due to the thermal expansion of the mirrors, bearing assembly mounting plate deflections, and close mounting tolerances, a problem with the mirror/bearing assembly mounting bolts hitting the support pylon occurred that damaged a number of mirrors and receivers. To solve this problem, collars were designed and supplied by the vendor to prevent the bolts from contacting the pylons. The thermal expansion forces are now transmitted to the pylon through the bearing and result in a deflection of the pylon. This condition was deemed acceptable and no future problem is anticipated. Several minor problems with the drive and control systems were also identified. The results of these problems are hydraulic leaks and lack of dependable operation. All of these have been handled by the owner's maintenance staff. Some of the specific components have been replaced; some with identical components and some with higher quality components. These include hydraulic accumulators, hydraulic cylinders, by-pass valves and solenoids, pressure switches, four-way valves, mode selector switches, and relays.

It has been observed that the collector tracker head is placed on the mirror edge so that it is the first item on the mirror which is shaded in the afternoon. This halts the tracking operation when the collector itself could receive a significant portion of the incident radiation for approximately 30 minutes longer. Placing the tracker head at the center of the mirror area will allow a closer match between the operating time period of the control system and the collector shading time history.

Finally, inconsistent operation during haze or light cloud conditions has been observed. These conditions occur frequently at the site and the problem manifests itself in a delay of system startup until the late morning. It appears that the collector field central controller is not adequately responsive to these slightly diffuse radiation conditions, so that a change to a more suitable control system is warranted.

SYSTEM PERFORMANCE

The operational phase of the project has been active only since February 1983, and data of any kind have been retained only since November 1982. There has not been sufficient time to completely assess actual system performance in relation to performance predictions. So, only a cursory presentation can be presented here. System performance for a single, clear day is summarized in Table III. Performance predictions based on actual weather conditions monitored by the DAS and typical weather conditions given by the DOE-2 weather data base [2] are listed as well. The performance predictions are made with a computational package developed by SwRI (see Treat, et.al., [3]).

It must be noted that these performance predictions are preliminary and have not yet been accepted as reliable. They are shown here merely for the sake of illustrating the active analytical efforts.

Table III. System Performance for Single, Clear Day

Hour of Day	Collector Inlet Temperature °F	Measured Horizontal Radiation Btu/hr ft^2	Energy Collected Actual	(1)	(2)
8	--	--	--	--	5.0
9	--	--	0	0	44.4
10	187.2	75.8	0	0	73.3
11	212.1	120.6	0	0	63.8
12	218.1	139.7	10.2	10.5	59.4
13	226.7	141.7	35.1	50.6	64.5
14	227.8	115.2	17.5	27.6	74.6
15	219.9	77.1	0	0	53.9
16	--	--	0	0	4.6

(1) Thermal performance model with actual measured weather conditions used for input.

(2) Thermal performance model with typical clear day weather conditions for December from DOE-2 [2].

NOTE: Performance shown is for 12/3/82.
Model cases (1) and (2) use test stand collector performance results published by Sandia.

It must be noted that these performance predictions are preliminary and have not yet been accepted as reliable. They are shown here merely for the sake of illustrating the active analytical efforts.

Several facets of the system performance can be pointed out with the aid of Table III. First of all, it is seen that the collector inlet temperature is approximately 30°F above the design point of 195°F. This is due to the reduced load conditions discussed above. Next, it is seen that positive energy production is not observed until 12:00. This is caused by the central controller late startup problem cited above. Third, the predictions made by the thermal performance model using actual operational conditions is significantly greater than the actual observed performance. It should be noted here that, due to the manner in which radiation data are gathered on-site, direct radiation measurements are not made during non-operational periods. Thus performance cannot be predicted during the periods when the collectors may have been operated but for some reason were not. Finally, the performance prediction using typical December, clear sky weather conditions from [2] for the site are also greater than the actual case. The bimodal shape of the collected energy profile for the DOE-2 weather data case is, of course, due to the hourly incidence angle profile for wintertime at the local latitude (~37.5°).

CONCLUSIONS

In conclusion, the solar IPH system at the Caterpillar Tractor Company in San Leandro, California is proving to be a reliable system since the initial operational problems have been resolved.

Preliminary analysis of system performance, however, shows that several changes to the hardware are recommended. These recommendations include:

- Moving existing tracker head to more suitable location on the collector mirror to provide better collector drive control.
- Upgrading collector field central control to maintain operation during hazy conditions and to provide consistent startup operation.
- Investigation of low overall system performance as compared to collector test stand performance.

- o Adding thermal storage to more fully utilize collector system energy output during reduced plant production times.

REFERENCES

1. Deffenbaugh, D.M., "A Large Scale Solar Industrial Process Heat System for Caterpillar Tractor Company, Construction Report, "SwRI Project 06-5821, DOE Project DE-FC03-79CS30309, September 1982.

2. "DOE-2, Version 2.1," Lawrence Berkely Laboratories, NTIS PB80-148380, 1980.

3. Treat, C. H., et. al., "A Design Procedure for Solar Industrial Process Heat Systems," <u>Proceedings of the ASME Solar Energy Division Fourth Annual Conference, Albuquerque, N.M., April 1982, p. 249</u>.

Solar Production of Industrial Process Steam

at

The Home Cleaning and Laundry Co.
Pasadena, California

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Abstract

Start-up and operational experiences at the Home Laundry Solar I.P.H. Project are highlighted. Performance data for a typical operating day are presented. System testing programs underway as part of the operations phase are described.

I. Introduction

The Home Cleaning and Laundry Co., Pasadena, California, was selected in 1977 by the Department of Energy as one of three "Cycle Two" experimental projects dedicated to the development of the application of solar thermal energy in industry. Testing and acceptance of the constructed solar system was performed in April, 1982, and authorization to proceed into the operations phase was made effective October 1, 1982. This paper is presented as part of the Distributed Solar Collector Summary Conference and describes start-up and operational experiences, system performance, and testing programs being conducted during the operations phase.

II. System Description

Application: Production of domestic hot water or 100-110 psig steam for use in a commercial laundry.

Site: 34.2° N Latitude, 118.2° Longitude

Process Schedule: 7:00 a.m. to 3:00 p.m., Monday-Friday

Process Load Profile: 7,643 MBTU/yr; 8,062 GJ/yr

Auxiliary Fuel: Natural Gas, boiler efficiency - 70%

Collectors: 406 linear parabolic - trough concentrating collectors, mirror reflective surface (Del Manufacturing Company).
Total Aperture Area: 6,496 ft^2; 603.5 m^2
Total Gross Area: 16,025 ft^2; 1,488.8 m^2
North - South orientation; East - West Tracking
Packing Factor: 0.405

Fluid Type, Flow Rate: Water at constant flow rate of 34,847 lb/hr (4.4×10^{-3}/S) in collector loop; closed loop pressurized to 240 psig at operating temperature.

Storage: 300 gal (1.13 m^3) steel tank, 2" AP jacketed fiberglass blanket insulation.

Design Energy Delivery: 1201 MBTU/hr; 1,267 GJ/yr

II. System Description - continued

Solar thermal energy is supplied to a tube-in-shell generator to produce 100-110 psig steam at a design flow rate of 935 lb/hr (424.1 kg/hr) for use in a commercial laundry. Production of domestic hot water at 150°F is an optional operations mode. Water is circulated at a constant flow rate between the collector array and either, 1) the domestic hot water tank, 2) the high temperature storage tank, or 3) the steam generator, or any combination of the collector array and the three vessels. The storage tank is used as a buffer tank for closed loop over-temperature protection, or as a storage tank for collector receiver preheating during startup or production of domestic hot water during periods of low insolation. The system is sized to provide 20 percent of the laundry's annual steam demand.

III. System Start-up

Completion of construction of the Home Laundry Solar I.P.H. Project was officially logged March 31, 1982. Start-up of the solar system can be considered to have begun about two months prior to this date with the performance of the first piping pressure test.

Preliminary pressure testing on February 4, 1982 demonstrated that leaks through flexhoses orginally installed in the collector array were substantial enough to warrant their replacement. Subsequently, two retrofit flexhose designs were installed and tested. The most effective design was selected, and installation was completed March 10. Minor leaks were noted from storage tank handhole gaskets and one receiver tube during pressure testing March 11. Reparations were made, but although improved, results of pressure tests performed March 23 proved unsatisfactory. The remaining leakage was isolated to a compression tank vent valve. With this leak eliminated, the piping system held pressure as designed.

Concurrent with pressure testing, start-up of the collector array was begun. Each of the twenty motor groups were unstowed in sequence, with tracking and drive unit adjustments made as required. Row-to-row and module-to-module alignment was inspected, followed by alignment adjustments to trackers. Difficulty was encountered in selecting a universal sensitivity adjustment for all insolation conditions. The Delavan SUN-LOC shadow band tracker is provided with potentiometers for adjusting deadband and time delay settings in the tracker motor control circuitry. No one pair of settings appeared adequate for the range of insolation conditions being experienced. Frequent operator attention would be required to avoid excessive oscillations through solar focus or inadequate tracker sensitivity unless a solution could be found. External to the Delavan motor control circuitry, a time delay relay was being employed to protect motor directional control relay contacts. It was determined that tracker sensitivity could be maximized if a longer time delay between motor operations was imposed. In this way, adequate sensitivity was maintained in hazy or partly cloudy conditions, while the forced interval between tracking corrections eliminated oscillations through solar focus under a bright sun.

Leakage and tracker adjustments presented the most noteworthy challenges to system start-up. A variety of additional problems too numerous to detail were encountered as well. For example, a grounded wire on a datalogger printed circuit board was discovered as the cause of an improper CRT display format. The circuit board was sent to the factory for repair. Also, excessive solar pump vibration was corrected by pump/driver coupling replacement.

System testing was conducted with D.O.E. representatives April 14-16, 1982. Final acceptance of the facility was made August 31, 1982.

During the months between system testing and official authorization to proceed into Phase III, the operations phase, the solar system was operated routinely, with regular energy delivery to the laundry. Insulation of flexhoses and

III. System Start-up - continued

construction of a control area enclosure were two major tasks accomplished during this period. The datalogger - computer link was established and refined, and development of data acquisition system (D.A.S.) software was begun.

IV. Operational Experiences

Availability of the solar system since the commencement of Phase III has been 100 percent. At the request of the Home Laundry, solar system operations have been dedicated to the production of domestic hot water. Due to the failure of the Laundry's existing domestic hot water heat exchanger August 7, 1982, the only source of hot water for laundry operations is the solar system. Regular operation of the solar steam generator has been performed for equipment exercise only since the Laundry's request was made.

Data acquisition system debugging has been the single most demanding activity at the Home Laundry. Development of computer algorithms for heat and mass balance calculations was done using FORTH, a high level computer language. Before implementing this software, difficulty was encountered in data transmission between the datalogger, computer, and matrix printer. Two measures were taken to rectify incompatibility between D.A.S. components. A replacement CPU board with handshaking capability was purchased and installed. Additional algorithms were written to control I/O routines to CPU. Once on line, inconsistencies in outputted data became apparent. Revisions to computer and datalogger software were made to correct the data errors. Some inconsistencies remained. These have been determined to be a result of electronic "noise" in data transmission lines due to an unfiltered D.A.S. power supply. Installation of a filter to regulate the power supply to the D.A.S. is planned at this writing.

Maintenance requirements of the solar system have been modest. A routine preventive maintenance program consisting mainly of collector cleaning, lubricant inspection, tracker alignment inspection and adjustment, and solar steam generator feedwater treatment is ongoing. Automatic collector rain rinse orientation has been possible since adjustments to collector drive motor controls were made November 15. Preventive maintenance manpower requirements have averaged 5.3 hours per month.

Corrective maintenance thus far in Phase III has not resulted in downtime. The process schedule at the Home Laundry permits performance of corrective maintenance when the industrial plant is idle (late afternoon and weekends). Relay and cable replacement, shadow band tracker repair, matrix printer head replacement, anamometer repair, and receiver glass replacement are the corrective maintenance tasks required to date.

V. Performance

Presented as Figure 1 is the Single Day Graph for Julian Day #47, February 16, 1983. Domestic hot water production was the operating mode. Insolation greater than 100 Btu/S.F.-HR. (collector start-up threshold) was recorded from 8:12 a.m. until 4;07 p.m. Energy delivery to the domestic hot water tank was logged between 8:12 a.m. and 4:32 p.m. The collectors were unstowed and the solar fluid pump operated until 4:32 p.m., accounting for the high energy collected value relative to incident insolation available during the 17th hour. Insolation totalized from the pyrheliometer on Day 47 was 1527 Btu/S.F.

0 Direct Solar Energy (MBtu)
Δ Incident Solar Energy in the Collector Plane (MBtu)
\+ Energy Collected (MBtu)
x Energy Delivered (MBtu)
□ Parasitic Energy Use (MBtu)
∇ Collector Inlet Temperature (°F)
• Collector Outlet Temperature (°F)

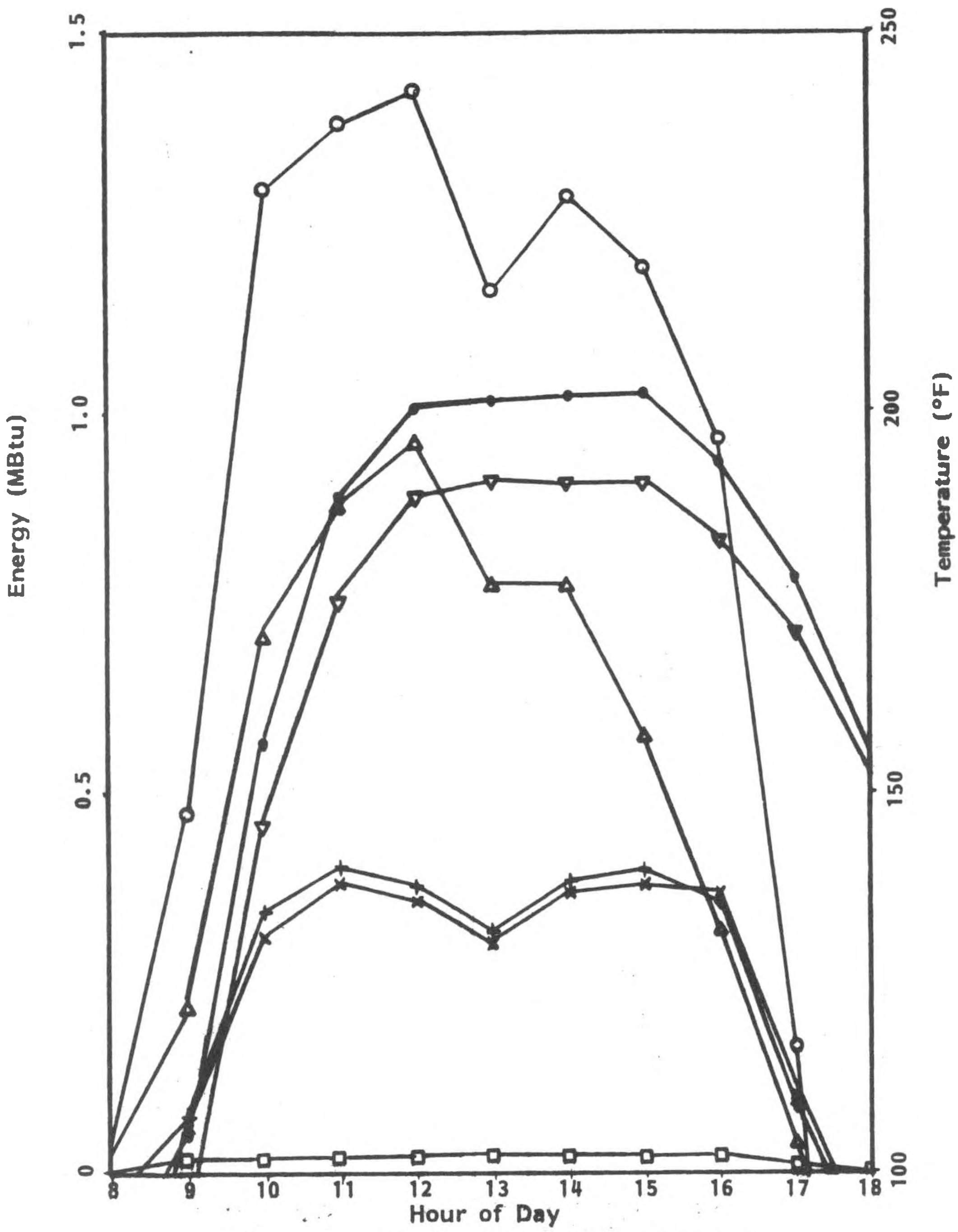

Figure 1: SINGLE DAY GRAPH, Day 47

VI. System Characterization

Seasonal variations in the availability of solar energy have to great degree dictated the testing schedule for solar system characterization. Operating experience has supported performance calculations which show that the as-built collector array cannot support steam production at winter solstice. Accordingly, system operation for domestic hot water production is being characterized during the low sun angle months of the year, while testing of steam generating capacity is reserved for summertime. Analysis of the use of the high temperature storage tank for receiver preheating during start-up and as a buffer tank during low demand periods is planned for summer, '83 as well.

Designed into the control system are automatic array and steam generator bypass control functions intended to reduce heat losses. Comparison of system performance with and without the bypass control functions is to be made to determine their value. If no distinct benefit from their use is observed, their deletion from future designs will be recommended, reducing the complexity of system controls.

A collector washing study is underway. Reflectometer readings are collected weekly, and correlation between reflectance, wash cycle period, and collector efficiency will be made. Air quality for Pasadena is being monitored, with data for total suspended particulates being recorded, in an effort to document the effects of air quality on washing requirements. Various washing strategies will be implemented, and the effects of each on system performance will be evaluated.

OPERATION OF THE SOLAR STEAM SYSTEM AT THE JOHNSON & JOHNSON PLANT IN SHERMAN, TEXAS

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System Description

The main components of the Johnson & Johnson solar steam system include 1,068 M^2 (11,520 ft^2) of parabolic trough solar collectors, a two-stage regenerative turbine pump, and an 18,900-ℓ (5,000-gal) ASME-rated flash boiler. The pump circulates pressurized water at 3.78 ℓ/s (60 gpm) through the concentrating collectors where it is heated to 202°C (395°F) under peak insolation conditions. As shown in figure 1, the heated pressurized water is throttled into the flash boiler where it flashes to 174°C (345°F) steam, flowing from there into the plant steam main for distribution to various plant processes. The boiler is located 90 m (300 ft) from the collector field. Makeup water is supplied by the plant's existing boiler feedwater system. The flash boiler retains enough thermal storage to protect the collector field from freezing, while a 15-kW standby generator is available to stow the collectors and provide freeze protection if a power failure occurs. The design incorporates conventional industrial grade steam generating equipment, easily serviced by the plant maintenance staff. A photograph of the system is shown in figure 2, and the major equipment for the solar system is summarized in table 1.

Operation Experience

Routine daily operation of the system began on January 12, 1980 and continues to date. In the first year, through January 31, 1981, the system was shutdown for 10 days for a 97 percent availability during this period. The system actually operated 70 percent of the available time; inclement weather and normal weekend downtime were the primary contributors to this utilization.

Since the end of January 1980, the system has operated automatically except for an occasional weekend in April 1980. At the end of April 1980, system operation was transferred to Johnson & Johnson personnel. Since that time, it has operated unattended most of the time, including weekends. Johnson & Johnson plant maintenance personnel have performed routine inspection and maintenance of the facility and have reported that the facility requires no special procedures and relatively little additional time added onto their existing plant responsibilities.

During the first year of operation several difficulties arose that caused a system shutdown (only 10 days total), loss of data, or less than optimum operation. The system was shutdown to remove an obstruction in the steam discharge line from the flash boiler, to replace a leaking pump seal, and to replace two leaking flex hoses. Loss of data resulted from problems with the magnetic tape recorder (22 days), and erratic behavior of the steam flowmeter and pyranometer. Instrumentation difficulties were resolved, but the instances of mag tape malfunction remain unexplained. Use of the mag tape was discontinued after the first years operation but data recording was continued at a lesser frequency on paper tape. Malfunctions in the freeze protection system (temperature sensors and the three-way mixing valve) resulted in the system coming on too early and excess heat being rejected to ambient. Also, leaking plant steam traps allowed steam to escape from the flash boiler through the condensate lines. The freeze protection system and the steam traps have been repaired.

The system had a 96 percent availability for the period February 1, 1981 through August 31, 1981. Maintenance that resulted in downtime in this period included replacement of a flex hose and repair of a manhole cover gasket on the flash boiler. Operation of the facility has continued to be automatic and unattended. Routine service of the facility

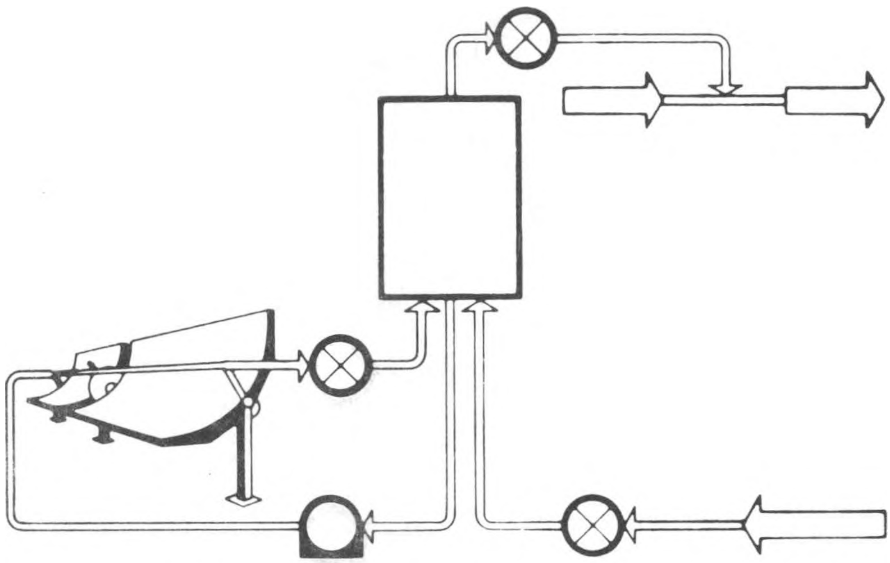
Figure 1. Solar Steam System Schematic

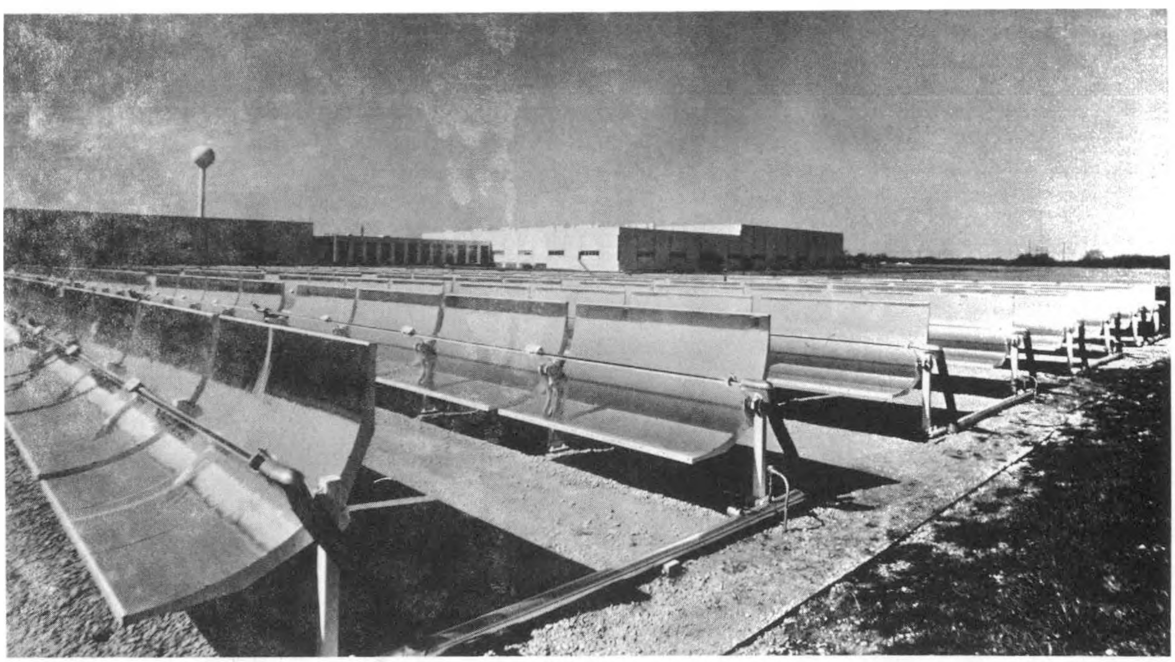
Figure 2. Photograph of the Johnson & Johnson Manufacturing Plant in Sherman, Texas

Table 1. Equipment Summary

Collector Field

- 1,068 m^2 (11,520 ft^2) in four loops with six groups/loop
- Acurex Model 3001 parabolic trough collectors
- NE/SW axis orientation

Flash Boiler

- 18,9001 (5,000 gal) capacity
- ASME Section VIII - 1,100 kPa at 188°C (160 psi at 370°F)
- Steam conditions: 825 kPa at 177°C (120 psi at 350°F) 0.15 Kg/s (1,200 lb/hr) peak

Pump

- Roth two-stage regeneration turbine
- Two speeds: 3,500 and 1,120 rpm - 3.78 ℓ/s (60 gpm) and 1.26 l/s (20 gpm)-for freeze protection
- 18.6 kW (26 hp) motor

Standby Generator

- 15-kW natural-gas-fired electrical generator
- Stows collectors and provides freeze protection

consisted of a periodic blowdown of the boiler, cleaning of the collectors, and visual inspections. More details on the system operation and its performance through August 31, 1981 are presented in references 1 through 3.

Acurex records of system operation are less quantitative since August 1981. DOE funding of the operation and performance evaluation ended in January 1981. The scope of our own efforts diminished from that time for two reasons:

- The system was operating very well with little or no attention required by Acurex

- There were other financial pressures on our discretionary funds, and no outside funds were available to support the system

Informal reports from Johnson & Johnson indicated system operation in 1982 with zero downtime through November. A small quantity of flex hoses were replaced because of leaks but no operation interruption was required.

In December another flex hose leak and an unusual set of events triggered a significant downtime period. An outline of these events follows:

- A flex hose leak occurred and went undetected. It was large enough to drain the hot water in the boiler which also serves as the freeze-protect fluid. No alarm occurred or the alarm was unnoticed or not responded to.

- That night the temperature went below freezing and because there was no water in the boiler, the freeze protect system was inoperable. Several more flex hoses burst because the remaining water froze. No alarm occurred or the alarm was unnoticed or not responded to.

- Johnson & Johnson had their local vendor make up several new flex hoses as replacements just as they had done successfully in the past.

- These were installed and the system was immediately put back into operation. But 13 of the new flex hoses were too short and caused receiver glazing breakage.

- The system was shutdown and a purchase order for glazings was sent to Acurex. The purchase order was lost in the "system" and its existence was unknown to the solar group for 4 weeks after it was sent.

- Our glazings inventory is large, but it did not include the length and diameter required by Johnson & Johnson

With some effort and ingenuity the system should again be in full operation by mid-March. The lessons to be learned are many and will not be repeated here.

The key operational problem, even in the absence of the events above, has been flex hose failures. These hoses are unique to Johnson & Johnson because it is a pressurized water system at moderate temperature. They are teflon-lined and the circular cross section of the hose tends to flatten when not pressurized. The small radius of curvature and resultant high stress at either end of the flattened section apparently encourages crack formation. Johnson & Johnson is changing all the original flex hoses to eliminate this problem.

Overall the operational experience has been very good and the system has been accepted by Johnson & Johnson simply as one of their plant steam boilers.

Closing Comments

Two general comments are appropriate to the Johnson & Johnson and other similar solar systems:

- These systems are experimental. They are serving a very important role but they must not be thought of as industrial or even prototype industry systems. Their cost, performance, size, and in some cases their location, is not representative of todays industrial requirements and the solar systems available to fill them.

- Successful system experiments such as Johnson & Johnson seem to have been lost by DOE. Continued recognition, and small funding to support operation and performance reporting, would benefit DOE, the user industry, and the solar industry.

References

1. Brink, D. F., J. M. Kendall, and S. B. Youngblood, "Solar Production of Industrial Process Steam: Phase III - Operation and Evaluation of the Johnson & Johnson Solar Facility," NTIS Report DOE/CS/31713-P1, March 1981.

2. Brink, D. F., and S. B. Youngblood, "Operation and Performance of the Solar Steam System at the Johnson & Johnson Plant in Sherman, Texas," Journal of Solar Energy Engineering, pp 139-145, Vol. 104, August 1982.

3. Brink, D. F., and S. B. Youngblood, "Performance of the Johnson & Johnson Solar Steam Facility During the Second Year of Operation," presented at ASME SED Conference, Albuquerque, NM, April 1982.

THERMAL PERFORMANCE OF THE LONE STAR BREWERY IPH SYSTEM
COMPARED TO SIMULATION MODEL PREDICTIONS

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INTRODUCTION

There are two major impediments to large scale implementation of Solar Industrial Process Heat (SIPH) systems. They are (1) the high initial construction cost and (2) confidence in the prediction of thermal performance of the system, i.e., system benefits. There are a number of efforts underway to reduce the production costs of solar collector equipment to address the first problem. Unfortunately, the second problem can only be resolved by experimental verification of existing models. The objective of the study reported here is to aid in this verification.

With accurate system modeling, performance estimates represent a realistic upper bound on energy production. These estimates can be used to gage actual system performance and pinpoint areas where changes are required to bring the actual system up to the expected performance.

The experimental facility described below was constructed as a part of the DOE SIPH program and as such is one of many such projects. It is important to provide as timely as possible a comparison of actual experimental data and the models used to predict performance. This paper provides a brief description of the facility, and thermal performance model. These descriptions are then followed by a presentation of some typical experimental data and comparison between model and data.

EXPERIMENTAL FACILITY

The solar steam system at the Lone Star Brewery in San Antonio, Texas was used to obtain the data for this study. The solar system has 15 rows, 90 feet in length, of Solar Kinetics T-700 parabolic trough solar collectors which have a total aperature area of 9450 ft^2. The collector field, shown in Figure 1, is mounted on the roof of the industrial facility. The solar system's boiler, expansion tank, fluid pump and piping are all located in the can warehouse directly below the collector field.

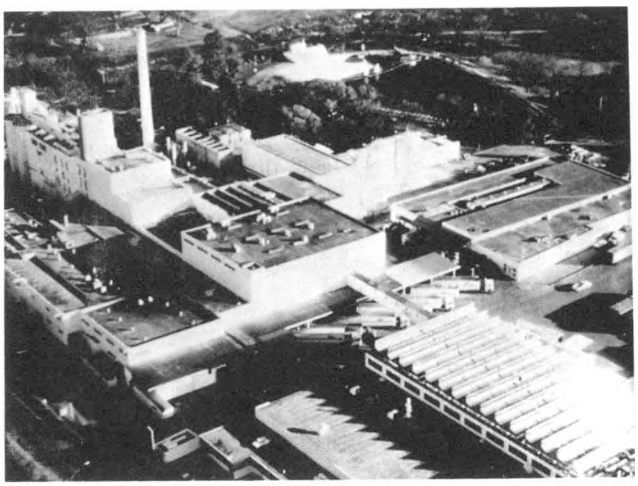

Fig. 1. Aerial Photo of Collector Field

Figure 2 shows a schematic of the system in which Therminol T-55, a heat transfer oil, is pumped through the collector field, heated, and finally passed through the tube side of a standard industrial unfired steam boiler. When the steam pressure in the boiler exceeds the pressure in the plant's main steam header a standard check valve opens and solar-produced steam is injected which reduces the load on the conventional gas-fired boilers at the plant. In this way, no storage system or sophisticated control system is required. This design provides a safe and reliable system that requires only minimal maintenance. For operating conditions of 285 Btu/hr ft^2 of radiation, and an ambient temperature of 95°F, the typical system parameters are shown in Figure 2. The maximum steam production at these conditions is 1200 lbs/hr for a total energy delivery of 1.2 x 10^6 Btu/hr.

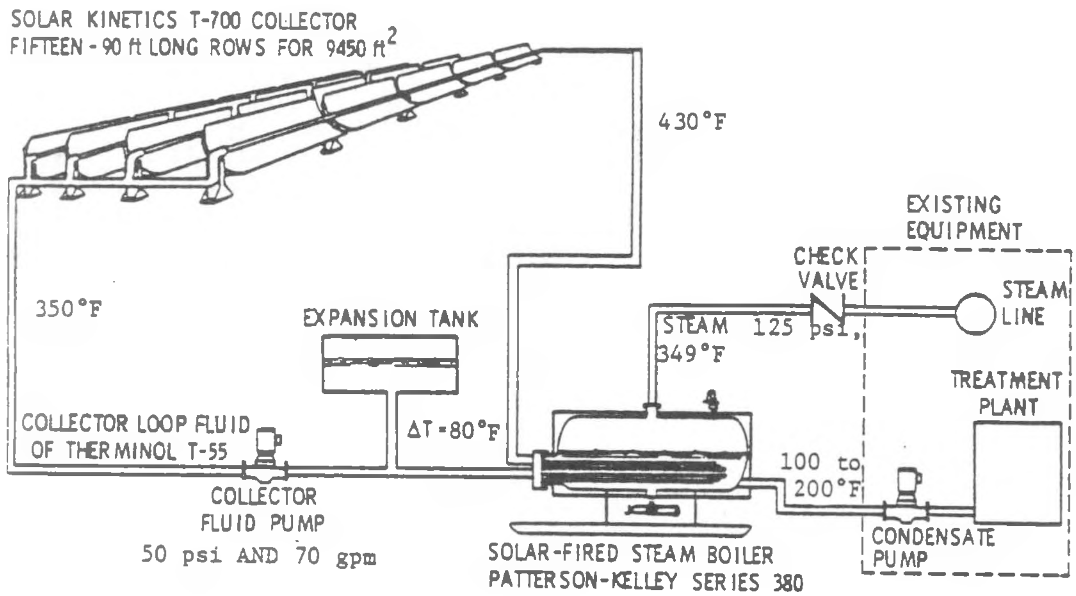

Fig. 2. Schematic of Solar Steam System

THERMAL PERFORMANCE MODEL

The computer model used in this investigation to simulate the thermal performance of SIPH systems contains portions which model collector performance, piping heat losses, and heat transport equipment (heat exchangers, boilers, etc.).

The collector performance model is based on empirical correlations of measurements of test stand performance [1,2,3]. The form of the relation chosen here to represent thermal performance is the one put forth by Lukens [1] due to its good estimate of all day performance; whereas the model used by Harrison [2] is based on idealized conditions of clear sky, near-noon radiation. The most recent of the correlations (Dudley [3]) is still under investigation for possible use in the computer routine. The Lukens correlation takes the form

$$\eta = A\,(1 + B(1 - \sec\theta))\,K \cos\theta + C\,\frac{\Delta T}{I} + D\,\frac{\Delta T^2}{I}$$

where

η = efficiency
θ = incidence angle
K = end losses and shading losses

A = 0.6849	empirically determined coefficients
B = 0.1096	for Solar Kinetics T-700 with FED
C = -0.08367	reflectors
D = -6.294E-05	

In addition to end and shading losses, the computer model will also account for losses due to dust buildup on the reflectors and receiver tubes and the frequency of washing. The dust buildup on the collector surface is modeled by a constant daily decrease in collector optical efficiency. This optical efficiency is returned to the original, clean, value at user-specified intervals.

Since piping runs between the collectors and the process interface can sometimes be substantial, a method for estimating the temperature drop in these pipes is used in the model. This method includes the length of pipe run and overall UA-valve of the heat flow path from the heat transfer fluid to the ambient air. The ambient air temperature is taken from the weather data input.

The process interface equipment considered for this investigation consists of an unfired boiler. This boiler is modeled as a parallel flow heat exchanger with two sections. One is the steam generation portion and the other a preheater to heat the condensate to steam temperature. The boiler model will account for startup transients in heating the boiler water, but once steam production begins, the model assumes quasi-steady operation. That is, the transients due to thermal mass are neglected.

The computer model also has other capabilities which are not important for the present investigation. The model is more fully discussed in [4] and [5].

The computer model is quasi-steady state in that operating conditions and performance can change hourly, but steady state operation is assumed for these hourly intervals. The model is constrained to one-hour time steps because all widely available weather data are published on an hourly basis and computing time and costs become prohibitive at smaller time steps. Any transients, then, which are short lived (i.e., less than one hour) cannot be accurately modeled. As shown below, this type of modeling technique is suitable for predicting long-term efforts but may present difficulties in short-term instantaneous predicitions.

SOLAR SYSTEM PERFORMANCE

To accurately compare actual solar system performance with simulation model predicitions the actual weather data must be input to the simulation model. Due to the method used to measure collector plane radiation at the Lone Star Brewery, actual collector plane radiation data is not available at all times, but total horizontal radiation is available. Beam radiation values were calculated from the total horizontal radiation data and compared with actual beam radiation measurements when they were available. The estimated beam radiation was adjusted to make the monthly total radiation equal to the monthly total measured radiation when measured data was available. This method tended to slightly overpredict beam radiation on partly cloudy days and slightly underpredict radiation on clear days. This method on the average gives good hourly and monthly total beam radiation estimates. The monthly totals of measured horizontal radiation and calculated beam radiation show good agreement with TMY data. Hourly averaged ambient temperature measurements were input to the simulation model. For selected days, actual hourly averaged beam radiation measurements were input to the simulation model to allow hour by hour comparisons of system performance with simulation predictions.

Measurements of collector reflectance were used to determine the decreasing optical efficiency due to dust buildup. After reflector washing with high pressure soft water, mirror reflectance was only restored to approximately 80%, not the 84.5% value of new FEK-244.

A monthly summary of the experimental solar system performance from June 1982 through December 1982 along with simulation predictions is given in Table I. All energy values are presented in Btu's per square foot off collector area. Actual energy collected is 72% of the predicted value while actual energy delivered as 125 psig steam is 51% of predicted.

Table I. System Thermal Performance Summary

Month	Energy Collected (Btu/ft^2) Actual	Energy Collected (Btu/ft^2) Predicted	Energy Delivered (Btu/ft^2) Actual	Energy Delivered (Btu/ft^2) Predicted
June	6,500	13,500	3,300	11,300
July	13,100	16,500	8,100	13,900
Aug	13,900	16,600	9,600	14,200
Sept	11,100	15,300	7,500	13,000
Oct	6,200	8,900	3,600	7,100
Nov	1,900	3,700	400	2,600
Dec	4,200	5,000	900	3,600
TOTAL	56,900	79,500	33,400	65,700

Figure 4 is a plot of actual daily total energy collected against predicted daily total energy collection for all days from June 1982 through December 1982. If actual system performance and prediction performance were identical, all the points would lie along the 45° line starting at the origin. Figure 5 presents actual and predicted daily total energy delivered to the IPH process.

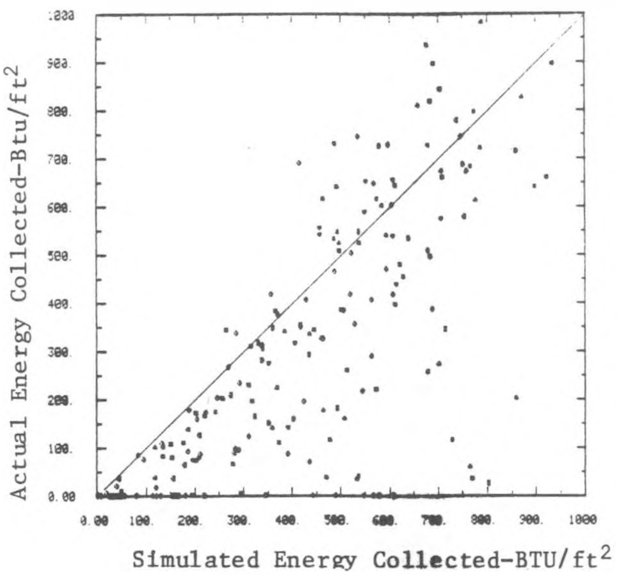

Fig. 4. Measured versus predicted daily total energy collection.

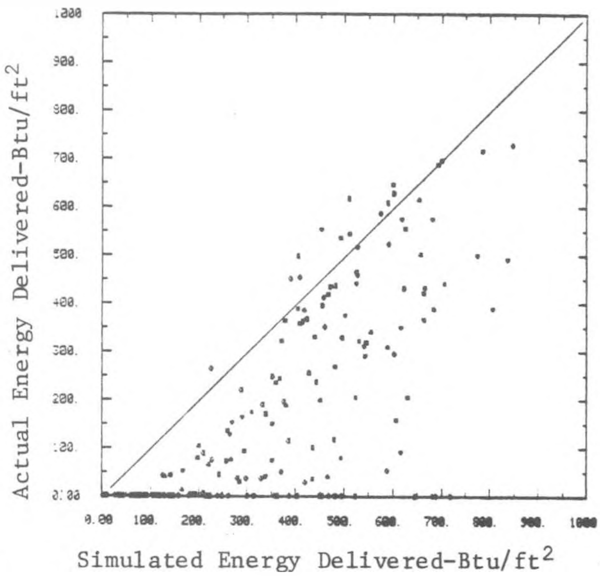

Fig. 5. Measured versus predicted daily total energy delivery.

A plot of hourly values of actual and predicted energy collected and delivered is presented in Figure 6. This plot is for clear day operation on August 24, 1982. Actual hourly averages beam radiation and ambient temperature were used in the simulation.

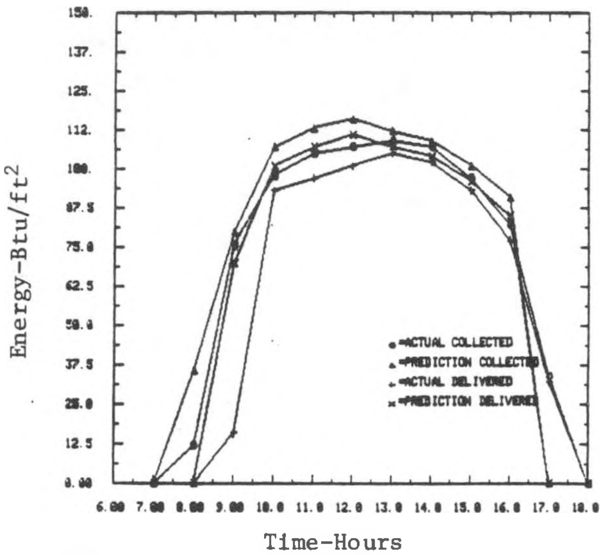

Fig. 6. Measured and predicted clear day performance for August 24, 1982

DISCUSSION OF RESULTS

Figure 6 shows very good agreement between actual and predicted energy collected and delivered for the clear day. The actual data lagged slightly behind the predicted throughout the day. Reasons for this will be given below.

Comparison of daily total energy collection data with simulation predictions shows overprediction on days with low energy collection and underprediction for days with high energy collection. The majority of this trend is due to the method used to estimate beam radiation from measured horizontal. As previously mentioned, clear day beam radiation is slightly underpredicted while estimates of beam radiation on partly cloudy days is slightly overpredicted. About one-third of the points above the line in Figure 4 come from the month of July where collector reflectance degradation due to dust buildup had to be estimated. Overestimating the collector reflectance degradation rate results in underprediction of energy collection.

The plot of energy delivered, Figure 5, exhibits the same trends as Figure 4 except the points appear to be shifted toward the bottom oΫf the graph indicating predicted energy delivered was greater than the measured energy delivery.

The considerable scatter of the data on Figures 4 and 5 is due to many causes in addition to scatter caused by simulating actual weather data. Other causes include collector tracking problems, control system delays, system downtime for repair and maintenance, equipment condition, and simulation model limitations. During solar system startup under partly cloudy conditions the collector tracking systems sometimes fail to properly locate and track the sun. Since the tracker controls have no search mode once the tracker has lost the sun, it will remain out of focus for the entire day. The actual equipment condition has been less than ideal. Problems with receiver tube glass cover breakage and selective surface degradation have resulted in higher thermal losses. As with any industrial installation, steam leaks and part failures have occurred. Delays in system startup due to cloud cover cannot be modeled due to the one hour time step in the simulation model. The present system central controller will not bring the system to operation, even when there is enough radiation to produce energy, if a long period of interrupted radiation is not received at the central light switch. This delay in system startup is necessary to assure collector row trackers will catch the sun at startup. This results in less energy collection than predicted by a simulation that cannot model short term variation in radiation due to cloud cover. In simulating system performance, perfect system operation is assumed with no downtime for maintenance or repair. This is unrealistic, particularly with an experimental installation such as this, but such a prediction sets an upper bound for system performance.

A number of simulation model limitations that affect prediction accuracy are listed below.

- o No operational thermal losses from boiler.
- o Variations in boiler feed water temperature are not modeled.
- o One-hour simulation time steps require simulated systems to be on or off for an entire hour. The simulation cannot model system operation for a portion of one hour.
- o Collector shading due to adjacent collectors is neglected if the center of the collector is not shaded at the middle of the time step.
- o Model of system thermal inertia has initial startup temperature equal to the boiler startup temperature (260°F).
- o Increased thermal losses due to wind are not considered.
- o Cloud cover effects on central control system and tracking systems cannot be accounted for.
- o Downtime for system maintenance was neglected.
- o Simulation does not model intermittent boiler feed water flow.

The effects of most of the above are hard to estimate. The high startup temperature of the system thermal inertia results in a simulation overprediction of approximately 26 Btu/ft^2 per day of operation. Boiler feed water temperature varies from 80°F to 200°F. The temperature of feed water depends on ambient temperature, feed water flow rate, and time of day. As previously shown, the simulation model accurately predicts system performance for clear days. The one-hour time step constraint precludes the accurate modeling of short term transients due to cloud cover; however, the present model is suitable for predicting long term system performance if realistic estimates of weather data, system downtime, and reflector degradation, due to dust buildup, are incorporated. The present model does tend to overpredict performance on days with low energy output. This is apparent in Figure 4 where almost all of the data are below the 45° line at values of simulated energy collection less than 400 Btu/ft^2.

CONCLUSIONS AND RECOMMENDATIONS

From June 1982 through December 1982 the solar system at the Lone Star Brewery collected 56900 Btu/ft^2 or 72% of the predicted energy. The 28% difference can be attributed to many factors. As previously discussed, collector tracking problems, downtime for maintenance, and broken receiver tube glass covers all contributed to less energy collection than possible. The simulation model does not consider increased thermal losses due to wind and the method of thermal inertia modeling results in overprediction of energy collection. No solar system downtime for maintenance on the entire system or individual parts of the system was included in the simulation model predictions.

Energy actually delivered to the IPH process as 125 psig steam was 48% less then predicted. A number of hardware related failures contributed to the reduced energy delivery. Several steam leaks went unnoticed for long time periods. Since actual energy collection was 28% less than predicted, actual energy delivery would have to be at least 28% less than predicted. Predicted energy delivery is 82% of energy collection. This is probably an optimistic prediction since thermal inertia and system thermal losses are both included in the 18% thermal losses.

Installation of new collector trackers that have the capability to search for the sun, if it is not located during startup, would help bring actual system performance closer to predicted performance. With a search mode tracker any collector row that fails to acquire the sun at startup would not be out of focus for the entire day. Tracking systems that calculate the sun's position and direct the collector to the proper tracking position would be advantageous in locations such as San Antonio where cloud cover is usually present. This type of tracker would allow earlier system startup since it would not require long periods of uninterrupted solar radiation before system startup. Other improvements that would enhance performance includes replacement of the damaged receiver tubes, installation of a more dependable light switch, and modifications to the collector drive system to make it more reliable.

The model used here to predict system performance produces good estimates of long term system performance provided that (1) accurate weather data is available, (2) degradation of the optical properties of reflective surface and transparent receiver cover due to dust buildup are considered as well as washing techniques and frequency, and (3) realistic estimates of system downtime are incorporated.

Finally, to improve the thermal performance model, it is recommended that short-lived system dynamics be more closely investigated. These include boiler and piping heating, perturbations due to intermittant cloud cover and control system errors. To account for these phenomena, the effects should be approximated on an hourly basis or the performance model should be changed to more accurately follow these dynamic behaviors with a smaller time-step.

REFERENCES

1. Lukens, L. L., Experimental Trough Collector Performance Characterization, Sandia National Laboratories, SAND 81-0313, 1981.

2. Harrison, T. D., Midtemperature Solar Systems Test Facility Predictions for Thermal Performance Based on Test Data, Sandia National Laboratories, SAND 80-1964/7, 1980.

3. Dudley, V. E., "The Effect of Solar Radiation Level on Efficiency of a Concentrating Solar Collector," Proceedings of the ASME Solar Energy Division Fourth Annual Conference, Albuquerque, N.M., April 1982.

4. Treat, C. H., et. al., "A Design Procedure for Solar Industrial Process Heat Systems," Proceedings of the ASME Solar Energy Division Fourth Annual Conference, Albuquerque, N.M., April 26-29, 1982.

5. Treat, C. H., et. al., A Design Procedure for Solar Industrial Process Heat Systems in Texas, Final Report, Southwest Research Institute Project 02-6516, Texas Energy and Natural Resources Advisory Council, EDF-056, Austin, Texas, August 1981.

SOLAR ENERGY FOR HEATING FRYING OIL AT ORE-IDA FOODS, INC.

Richard D. Fogerson

Introduction

The solar energy project began on May 17, 1978 when Ore-Ida Foods, Inc. signed a contract with Energy System Management Division of TRW as the recipient of an industrial solar energy demonstration system funded by the Department of Energy (DOE). This project resulted from DOE's desire to test the potential of solar energy in supplying high quality energy to an industrial process.

The project was defined by three phases. During Phase I, CH2M Hill completed the overall design of the system and TRW with assistance from another contractor completed design of the computer control software and hardware.

Phase II constituted construction of the system which was completed officially on July 17, 1981 with the system's dedication. The piping was done by Home Plumbing & Heating, the electrical was done by Tri-State Electric, Inc., the mirrors were fabricated by Sun Tech, and construction management was accomplished by CH2M Hill.

Phase III, the performance testing of the system, began on October 20, 1981 and was scheduled to last for 15 months, January 19, 1983.

Description

Water from the plant's boiler system is circulated through the collector field under 600 psig pressure and is heated to 480°F. in passing through the collectors. The collectors are parabolic trough mirrors having a total surface area of 9,300 ft^2 and located on 1/2 acre of land. Constructed of hexel material and coated with a reflectorized mylar film, they concentrate the sun's energy by a factor 60 on the black water pipe running the length of the mirror. The mirrors track the sun in an east to west rotation and turn face down in the stow position automatically when either the wind velocity reaches or solar insolation drops to a specified value for a specified time.

The flash tank and main pump are located in the factory. Water at 480°F. and 600 psig flashes to steam at 417°F. and 300 psig. It is then combined with factory boiler steam where it is piped to heat exchangers to heat oil for a french fry line. The entire solar system is computer controlled and all pertinent data is automatically stored on magnetic tape and printed hard copies by the data acquisition system (DAS).

Performance

Collector efficiency and system efficiency were estimated to be 46% and 29% respectively. Based on these efficiencies and the projected operating days it was calculated that 2,000 #/hour of steam would be generated amounting to 2.6 billion BTU's annually. This would be equivalent to about a $9,300 annual savings in deferred natural gas costs.

The system was not started up until the beginning of good weather on February 24, 1982. From that date through the end of the originally scheduled performance test period, January 19, 1983, the system operated a total of only 23 out of a possible 329 days. Also, keeping in mind that we have only very limited test data, the measured efficiencies appear to be only about half of that originally estimated. Excessive heat losses and dirty mirrors and receiver tubes are the reasons but the contribution of each to the loss in efficiency is unknown at this time. Because of the reduced efficiencies and reduced operating days, the dollar value of the natural gas saved amounted to only about $350. Of the remaining days, bad weather contributed 48 days of downtime and pump and computer problems contributed 258 days.

Maintenance record

Maintenance costs resulting from work done by Ore-Ida amounted to $2,485 for this period. These costs probably are not very useful though for any estimating purposes because of the large number of startup problems, the small amount of actual operating time, and the fact that some costs TRW also incurred are not included.

Numerous mechanical and computer problems were experienced. Some examples are: pressure relief valve failures, computer programming bugs, DAS failure (hardware and software), main pump failure (due to faulty installation), field to factory pipe bracket failures (due to faulty installation), broken collector receiver glass, mirror surface failure, flexible line failure. These all contributed to the excessive downtime while the loss of efficiency was mainly due to the lack of good mirror and receiver cleaning equipment and techniques. It should be noted here too that the Ore-Ida facility was reported as one of the cleaner areas in a mirror cleanliness study made by McDonnell Douglas.

Conclusions

At the time of the writing of this paper, DOE has expressed interest in supplying the funding for certain modifications to the solar system to bring its actual efficiency closer to the original estimated value and for critical spare parts to prevent the long periods in downtime experienced to date. A statement of work received recently outlined several proposed modifications. These might include: (1) insulation of flexible hoses, flash tank, pipe supports, valves, and other hot spots, (2) spare main pump and other critical components, (3) upgraded DAS, and (4) high pressure deionized water system for mirror cleaning.

Although the operating experience has not been good to date, Ore-Ida Foods, Inc. feels that we are very close to realizing a workable system and therefore it is well worth the relatively small amount of money necessary to upgrade the system and it is well worth Ore-Ida Foods' time to operate the system to obtain valuable data on the commercial viability of an industrial solar installation of this type.

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Southern Union

PAPER NOT AVAILABLE AT TIME OF PUBLICATION

THERMAL LOSS EXPERIENCE FROM SOLAR FIELD EXPERIMENTS

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INTRODUCTION

Distributed collectors of solar thermal energy, whether they be line focusing devices such as troughs or parabolic dishes, must rely on a piping network to deliver a heated fluid from the receiver of the solar collector to the point of use. The installed cost of this thermal transport system and the efficiency with which it performs its function are key parameters in the economics of solar energy systems. The performance of the thermal transport system is a higher leverage parameter than its cost because a Btu saved is a Btu earned." Any improvement in the efficiency of delivering energy to the point of use will result in a proportional decrease in the size of the solar collector field needed to achieve a given annual production capacity. Therefore, a relatively high cost can be accommodated effectively for incremental improvements in the performance of the thermal transport system.

In recognition of the importance of developing an understanding of key issues of thermal transport and of accumulating operating experience, the DOE, in setting up its Solar Thermal Field Experiment Program, included instrumentation which could measure engineering performance parameters such as system thermal losses. Credible data from field projects in substantial amounts are not yet available to compare with design values but some preliminary information will be reviewed. An exception to the last statement is the Coolidge Solar Irrigation Project which operated for three years beginning in late 1979 and for which carefully conducted tests have been documented.[1,2]

DESIGN CONSIDERATIONS

Conservation of thermal energy is the watchword in the design of thermal transport systems. Liberal use of high quality insulation would seem to be an obvious approach to a low-loss piping network but of more importance is the treatment of fittings and components and the minimizing of system heat capacity.

The straight runs of insulated pipeline are the least of the designer's problems. Pipe supports should not provide an conductive path to the atmosphere and their spacing should be as far apart as possible. Spacing well in excess of handbook distance - even to the extent of tolerating some sag - is probably cost-effective. Valves, flanges, and other fittings should be carefully insulated - even if it means that access for service and maintenance will be less

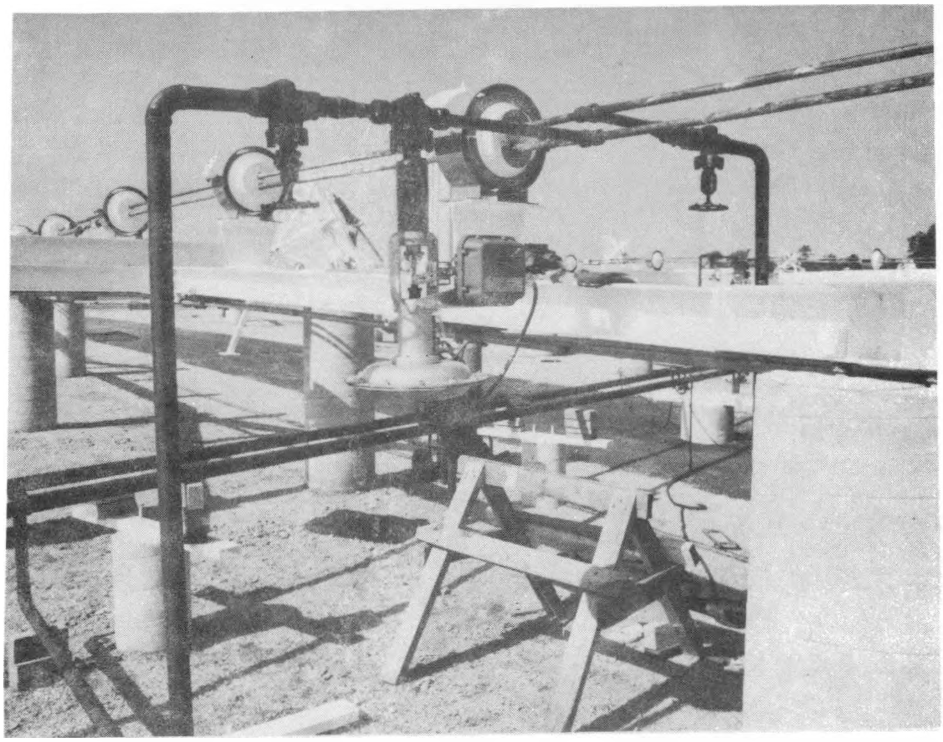

Figure 1 Nested branch line piping at Shenandoah. Note downward orientation of valves and the anti-siphon connections to the main manifold.

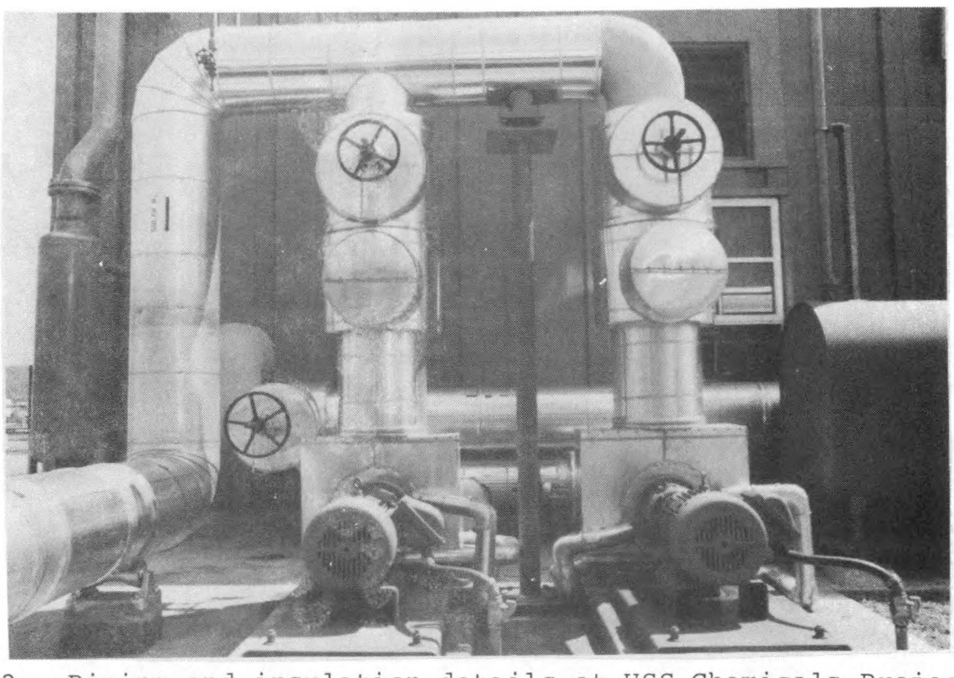

Figure 2 Piping and insulation details at USS Chemicals Project.

convenient. Valve handles should be oriented downward to reduce thermosiphoning and convenience fittings such as handvalves for branch shutoff and drainvalves should be eliminated altogether or included only after careful scrutiny. These and other energy conservation measures are practical if one appreciates the diurnal nature of a solar energy plant. A normal process plant which operates 24 hours a day must be shut down for maintenance or the sections to be maintained must, at least, be valved off. Time is money to a 24 hour per day operation so convenience fittings and easy access features are important. A solar plant operates at most only about 2000 hours of the 8800 hours in a year*, so there is plenty of time for scheduled maintenance to take place when the sun is not shining.

Thermosiphoning should be reduced by proper routing of piping so that thermal communication between hot sections and cold sections is minimized. This is often possible simply by routing pipes downward for a foot or so. These considerations are also somewhat more important for a diurnal system than for a 'round the clock system since nighttime cooldown can be reduced by such practice. For the same reason, a good piping network design should minimize heat capacity so that morning startup can be shortened. The heat capacity of the system is an energy tax that must be paid on each system start, and one which does not pay back in full at the end of the day.

The piping network at Shenandoah was designed with the above principles in mind and adequate temperature sensors have been incorporated to measure the thermal losses throughout the system. The branch lines at Shenandoah (Fig. 1) feature nested piping. The cold inlet line (260°C) and the hot return line (400°C) are enclosed in a single insulated envelope. Molded calcium silicate blocks provide support and low conductivity at each pipe support and pipe anchor point.

Figure 2 illustrates the meticulous manner in which piping design nd insulation has been carried out at the U. S. Steel Chemical plant in Haverhill, Ohio. When data is available it will be most interesting to compare the thermal performance of Shenandoah with USS Chemicals since both have about 50000 ft^2 of collectors and both have been carefully designed and insulated with the major difference being that Shenandoah uses parabolic dish collectors and USS Chemicals uses troughs.

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* At least the collector field does. Storage and hybrid plant concepts would result in higher operating fractions for the thermal utilization equipment.

FIELD PROJECT EXPERIENCE

Three projects will be examined as to the design values of thermal loss and the comparison of the predicted solar energy collection with these thermal losses. The three projects are the Coolidge Solar Irrigation Project near Coolidge, Arizona, the Southern Union Refinery IPH Project near Lovington, New Mexico, and the Shenandoah Solar Total Energy Project near Atlanta, Georgia. The Southern Union project serves process steam applications while the other two feature electrical power generation. Thermocline stoage is included in the system at Coolidge and Shenandoah, but not at the IPH projects. Finally, the Shenandoah Project employs parabolic dish collectors while the other two are parabolic trough systems Table 1 contains additional pertinent descriptive information for each project.

	Shenandoah	Southern Union	Coolidge
Collector Type	Dish	Trough	Trough
Collector Field Aperture (ft^2)	47200	10080	23040
Collector Field Outlet Temp.(°F)	750	450	550
Number of Branches or Strings	12	6	8
Collector Field Row Orientation	Not Applicable	E-W	N-S

Table 1 - Solar Thermal Field Project Descriptions

The designers of the Shenandoah Project (Fig. 3) have predicted

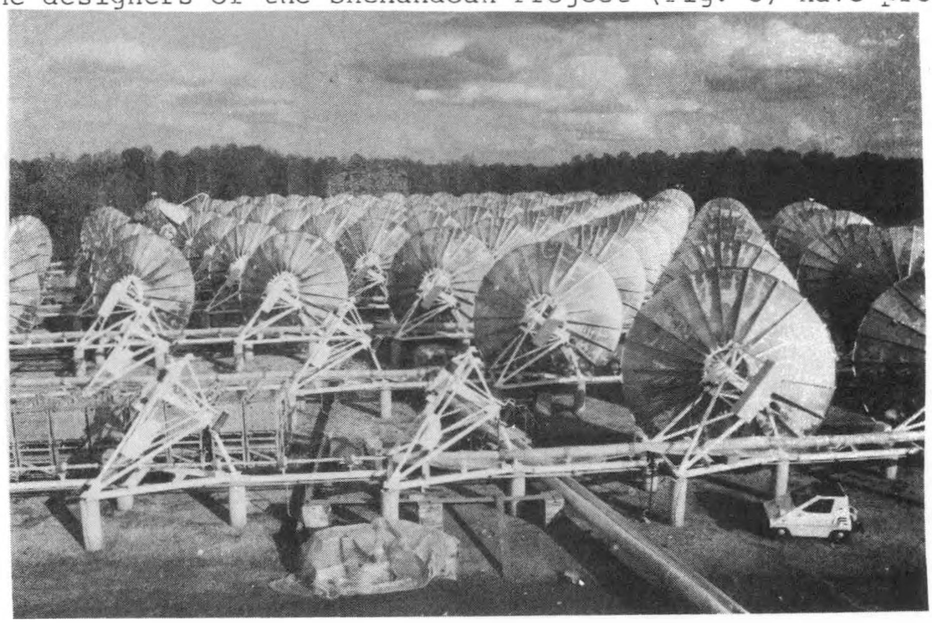

Figure 3 - Construction scene at Shenandoah showing center-field manifold and branch piping.

that the system will deliver 11000 MBtu/yr. On the basis of a unit of aperture this would be 233,000 Btu/ft^2-yr. The expected insolation in Georgia is about half that of the American southwest and the reflective surface employed on the Shenandoah dishes, aluminized acrylic, is about 10% less reflective than silvered glass. Thus a more ideal dish system in a high insolation climate would be expected to produce in excess of 500,000 Btu/ft^2-yr. An idealized trough system in the southwest would produce about 400,000 Btu/ft^2-yr assuming it tracks the sun in only one axis. The predicted thermal losses for the Shenandoah system are 27000 Btu/ft^2-yr. This would amount to about 10.4% of the collected energy. Carefully measured values are not yet available for Shenandoah but preliminary figures indicate that the predicted values will be close to actual. It will be seen that the thermal loss predictions for a dish-thermal system are higher than for a trough system. This is because dish systems, being modular, must be connected by piping in two axes. Also, because dish systems must be deployed at a lower packing fraction, they will require relatively more length of interconnecting piping. The evaluation testing at Shenandoah will include detailed characterization of these losses.

The design of the Southern Union trough system (Figure 4) calls for the collection of 337,000 Btu/ft^2-yr. and a reduction of this value due to thermal losses of 15400 Btu/ft^2-yr. This loss figure would be only 4.6% of the collected energy. The "measured" values of thermal loss at Southern Union, as at most IPH projects are derived values which are based on temperature measurements at insolated surfaces and on comparisons between

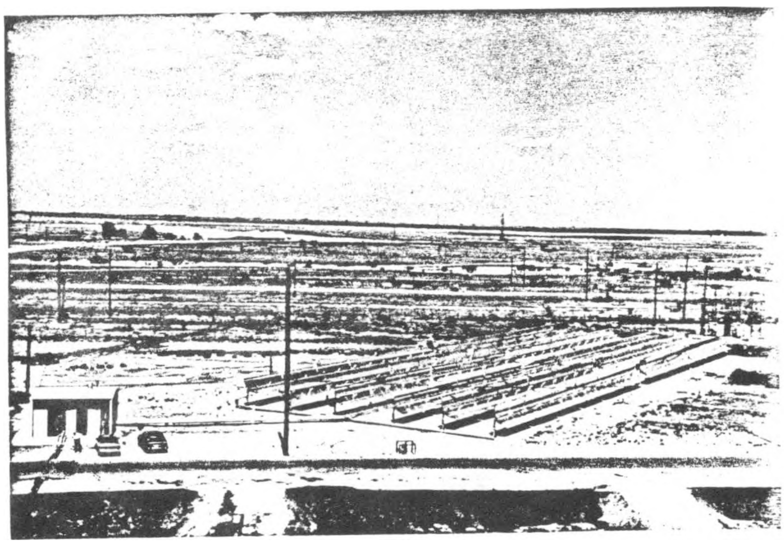

Figure 4 Collector field and control and equipment enclosure at the Southern Union IPH Project.

measured energy gained in the collector field and the steam rate delivered to the load. Expressed as a percentage of energy collected on clear days the thermal loss measurements at Southern Union have ranged from 5 to 8% in the summer and from 9 to 14% in the winter when total energy collected is low. A sampling of data from clear days was[2] extrapolated to annual normalized losses of 14000 to 28000 Btu/ft^2 - yr.

The most careful thermal loss measuurements in the field[1] to date were conducted at Coolidge (Figure 5) in April, 1980.[1] These tests were conducted along the lines used in the MISR systems in which the collectors were turned away from the sun toward clear sky but also into a position such that the receiver tubes were shaded. Heated fluid was then pumped through the field and its temperature drop measured. After adjusting the total losses to account for receiver tube losses the piping losses were calculated to be about 8% of the springtime clear day energy collection capability.[3] An annual thermal loss extrapolation of 22000 Btu/ft^2-yr. has been calculated.

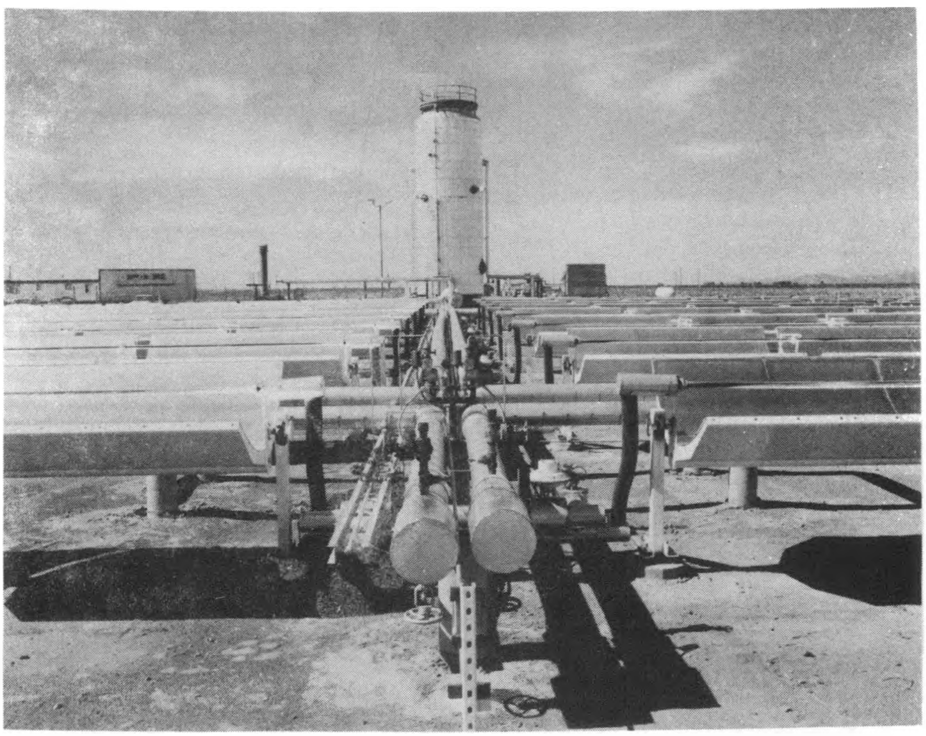

Figure 5 Center manifold piping at the Coolidge Project

Conclusions

Conclusions based on hard data cannot be made at this time because of the quality and quantity of the data. A sound perception would be that most systems are experiencing thermal loss in excess of design values and that improvements can and will be made. A most important aspect of the analysis and evaluation of all the solar thermal field projects will be to quantify the performance of existing thermal transport systems, compare the performance with predictions, identify the reasons for discrepancies, and where possible, to modify the systems to improve thermal performance.

The process described above takes place in parallel as well as series. Solar energy system designers have already capitalized on the lessons learned in the field experiments now in operation. New system designs in construction and on the drawing boards today are more sophisticated than those in the field and, as feedback from operating systems is assimilated, further improvements will doubtless be realized.

References

1. L. E. Torkelson and D. L. Larson, Sandia National Laboratories and the University of Arizona, "1980 Annual Report of the Coolidge Solar Irrigation Project," SAND80-2378, February 1981.

2. L. E. Torkelson and D. L. Larson, Sandia National Laboratories and the University of Arizona, "1981 Annual Report of the Coolidge Solar Irrigation Project," SAND82-0521, June 1982.

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