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Final Report on the Modification and 1978 Operation of the Gila-Bend Solar-Powered Irrigation Pumping System

G. Alexander, D.F. Busch, R.D. Fischer, W. A. Smith
Battelle's Columbus Laboratories

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FINAL REPORT

on

THE MODIFICATION AND 1978 OPERATION OF THE GILA BEND SOLAR-POWERED IRRIGATION PUMPING SYSTEM

to

SANDIA LABORATORIES
ALBUQUERQUE, NEW MEXICO
(P.O. 07-7231)

and

THE NORTHWESTERN MUTUAL LIFE INSURANCE COMPANY
MILWAUKEE, WISCONSIN

by

G. Alexander, D. F. Busch, R. D. Fischer
W. A. Smith

December 29, 1978

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

TABLE OF CONTENTS

TABLE OF CONTENTS - Continued

TABLE OF CONTENTS - Continued

TABLE OF CONTENTS - Continued

TABLE OF CONTENTS - Continued

LIST OF FIGURES

LIST OF FIGURES - Continued

LIST OF TABLES

LIST OF TABLES - Continued

EXECUTIVE SUMMARY

The 1978 program for modification and operation of the solar-powered irrigation system at Gila Bend, Arizona was intended to upgrade the system using state-of-the-art components, modify the system to achieve more mature capabilities, and use the system to evaluate operating and maintenance requirements.

Five separate tasks were undertaken to achieve these goals. Three of the tasks involved physical alteration of the system, the fourth involved developing extensive evaluation capabilities, and the final task, which was in progress through the majority of the program, was to operate the facility to obtain maintenance and operating experience.

Some of the collector unit absorber tubes and housings were replaced with new components, and some of the original tubes were recoated with an improved compound. Insufficient data is available to judge the relative efficiency of these new components, but operating life and mechanical performance appear to be superior to the original units. Experience indicates that visible deterioration may not indicate serious loss of performance.

A new tracking system was placed on order to reduce the requirements for operator attention and adjustments. After delivery and spending substantial time making modifications in the new system and trouble shooting it--both of which caused a serious loss in overall system operating time--the new system, to date, does not appear to be any better than the system it replaced. The problems in the new system are not the same problems that existed in the original system; however, satisfactory progress towards unattended operation was not made.

Design work was completed and components were purchased to allow the irrigation pump to be driven by either the solar system, an electric motor, or both simultaneously. The electric motor and the gearbox required to drive the pump were installed, and operation on solar-power-only and on electric-power-only was demonstrated. Leakage in the turbine/gearbox unit prevented operation in the hybrid mode. Resolution of this leakage problem and installation of remaining components were postponed to permit operation for the duration of the season, since initial problems with the electric motor and irrigation pump had further reduced operating time.

An extensive system of instrumentation and data recording and tramsmission equipment was installed and verified. A computer procedure for automated storage and analysis of data was developed. Although several deficiencies still exist in this area, these capabilities, developed for this program but applicable to programs with similar requirements, proved valuable for monitoring and evaluating the performance of the equipment.

The problems associated with various subsystems still in development and, surprisingly, with components of proven reliability, seriously affected the total amount of operating time during which useful operating data could be gathered. Even so, the solar-powered irrigation system was operated for 188 hours and pumped 32.8 million gallons of water, and significant information was gathered on hardware performance, component life, and maintenance requirements.

Economics aside, modest development work and extensive field testing operations are still required before the farmer accepts solar-powered irrigation hardware as a part of his irrigation system.

The Gila Bend facility will be maintained, at no cost to the government, in a temporary shutdown condition for 6-12 months to facilitate the initiation of any follow-on program or demonstrations in connection with additional work.

FINAL REPORT ON THE MODIFICATION AND 1978 OPERATION OF THE GILA BEND SOLAR-POWERED IRRIGATION PUMPING SYSTEM

BACKGROUND OF THE PROJECT

Hundreds of thousands of irrigation pumps are currently in use throughout the United States, powered by natural gas, electricity, liquified natural gas, and diesel fuel. These conventional fuels are projected to become increasingly costly and scarce. Recognizing the urgent need for alternative energy sources, The Northwestern Mutual Life Insurance Company (NML) and Battelle Memorial Institute (BMI) joined in a cooperative venture to develop practical applications of solar energy. The NML/BMI solar-powered irrigation project was initiated in 1975, and the system was installed at the NML Paloma Ranch near Gila Bend, Arizona, in early 1977.

Operation during 1977 demonstrated that irrigation pumping using solar energy was feasible. Initial system problems were resolved and unattended operation, under the care of ranch personnel, was demonstrated. Although the projected capital cost indicated that there would not be an immediate viable market for the system, the functional requirements for practical solar irrigation systems became evident during operation. Several modifications were needed to allow the system to meet these requirements.

Under the joint support of Sandia Laboratories and NML, the solar-powered irrigation system was modified to address these requirements, and operating during 1978. The operation, maintenance, and modification of the system during 1978 are presented in this report.

DESCRIPTION OF THE APPLICATION

The solar-powered irrigation pumping system is located on Paloma Ranch, a commercial agricultural operation owned by NML. The ranch is located outside Gila Bend, Arizona, approximately 70 miles southwest of Phoenix (see Figure 1). The local climate is excellent for the application of solar irrigation equipment, as the Gila Bend area receives high levels of insolation throughout the year.

The solar irrigation pumping system was designed to serve the needs of intensive, irrigated agriculture. Operations at Paloma Ranch include the cultivation of cotton, sugar beets, and wheat. The local growing season extends from April to October and irrigation is required throughout the season. The ranch has nearly 30,000 acres under irrigation, the majority of which is served by a system of concrete-lined distribution ditches.

The solar irrigation pumping system serves to return tail water from a collection sump to these distribution ditches. Water is supplied to the irrigation system from a series of deep wells. The water is applied to the fields from the distribution ditches by siphons, in an amount approximately 10 percent in excess of that required by the crop, and the resulting 10 percent runoff is recovered from the graded fields in a series of tail water ditches. The solar irrigation pump returns the tail water, which collects in a sump, to irrigation ditches, servicing an area of approximately 5000 acres. The lift from the tail water sump to the distribution ditches varies daily, ranging from 7 to 12 feet.

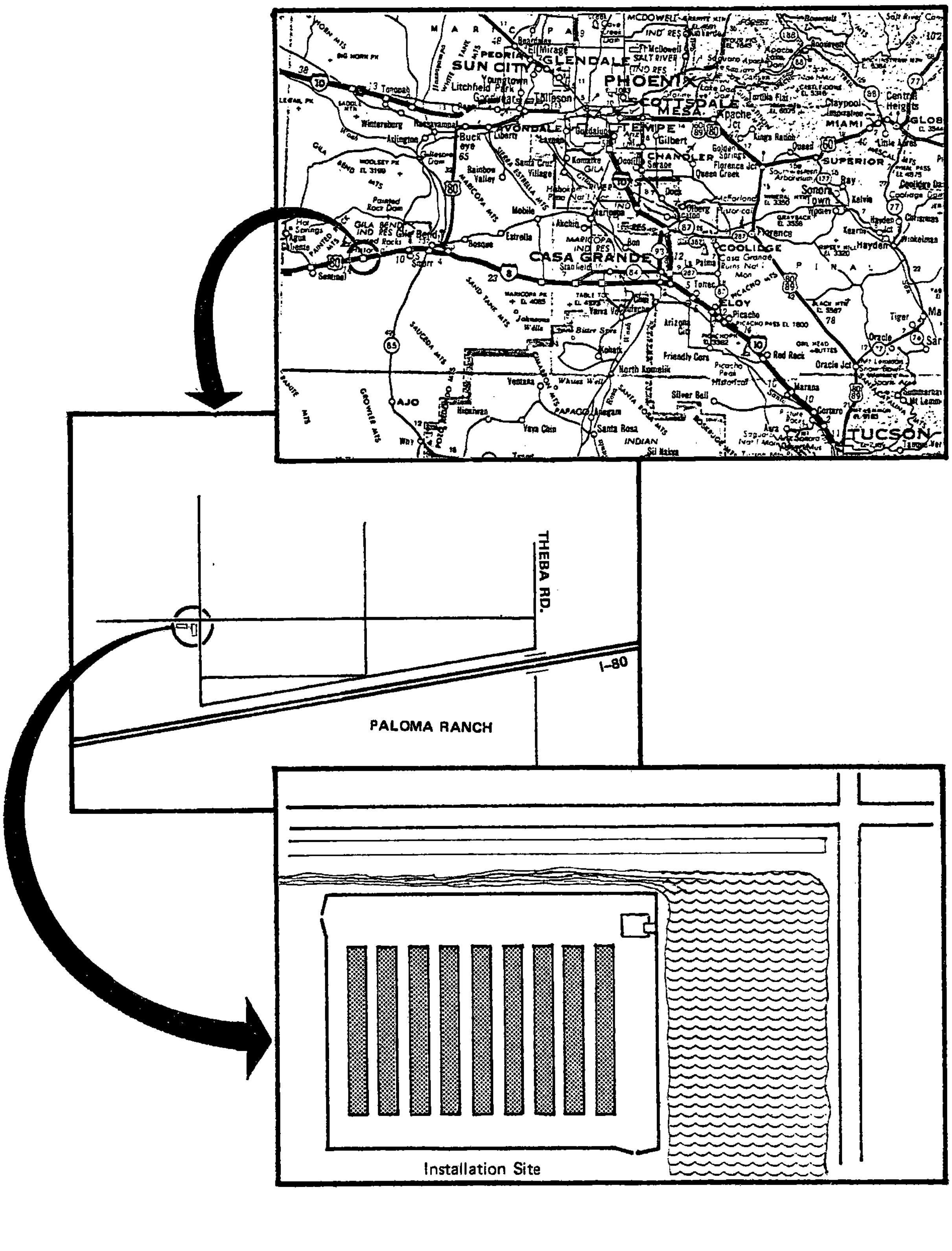

FIGURE 1. LOCATION OF NML/BMI SOLAR-POWERED IRRIGATION SYSTEM

ACKNOWLEDGEMENTS

Funding for the tasks described in this report, including operation of the system during the 1978 irrigation season and upgrading and modification of components of the system, was provided by Sandia Laboratories and The Northwestern Mutual Life Insurance Company.

Sandia Laboratories provided funds for the operation of the system and for upgrading of major components.

The Northwestern Mutual Life Insurance Company provided funds for modifications necessary to achieve hybrid operation, as described in the body of this report.

The initial development of the solar-powered irrigation system was a cooperative venture between NML and Battelle Memorial Institute (BMI). In addition, NML provided funds for the 1977 operation and maintenance of the system.

The staff of Paloma Ranch were extremely cooperative throughout the program, providing facilities, services and advice in connection with installation and operation of the pumping system.

OBJECTIVE OF THE PROGRAM

The objective of the 1978 program was to use the solar-powered pumping system to obtain data and information on operating characteristics, maintenance requirements, and component reliability. The program covered operation; parts replacement; minor modifications; hybrid electric conversion; data gathering, reduction, and analysis; and reporting. Six specific tasks were planned to meet the objectives:

Task 1. Operate the solar-powered facility at the Gila Bend Paloma Ranch during the 1978 irrigation season

Task 2. Improve the tracking system

Task 3. Replace the absorber tubes and receiver housings

Task 4. Design, develop, and install components required for conversion to hybrid electric operation

Task 5. Modify the sensors and instrumentation, and gather, reduce, and analyze data

Task 6. Report.

DESCRIPTION OF THE SYSTEM AT THE BEGINNING OF THE PROGRAM

The 1978 program was based on modification and operation of the system developed and installed during 1976 and 1977. The features of this system, operating experience during the 1977 irrigation season, and the status of the equipment at the end of this period are discussed below.

Features

The NML/BMI solar-powered irrigation system, shown in Figure 2, consists of a field of parabolic sun-tracking collectors, a turbine engine power package, and an irrigation pump unit--all installed on approximately one-quarter acre of land. The system in place at the beginning of the program is described below in terms of its operating capabilities, controls, and safety features.

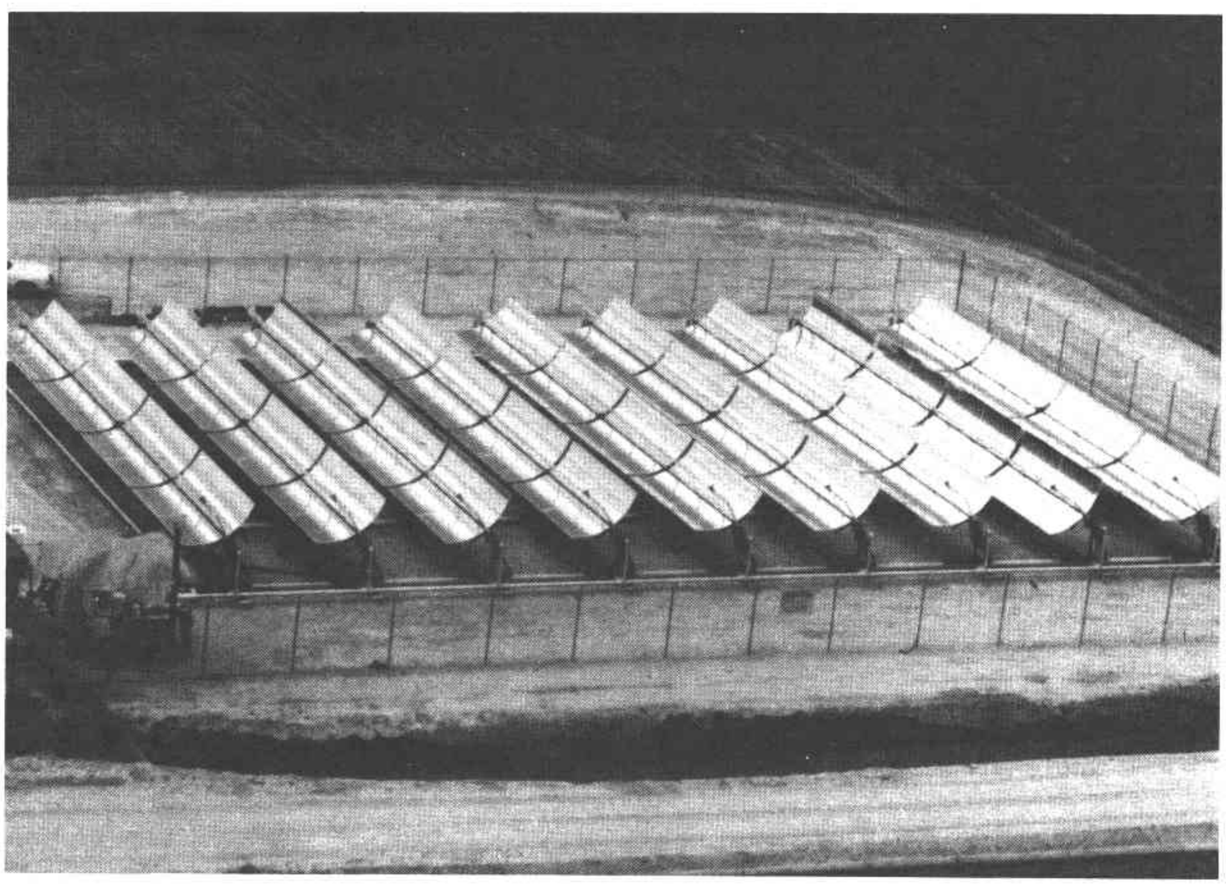

FIGURE 2. THE NML/BMI 50-HORSEPOWER SOLAR-POWERED IRRIGATION SYSTEM: 1977

Design Operating Capabilities

The Rankine-cycle turbine engine delivers a design maximum of 50 horsepower to the irrigation pump, which can deliver a maximum of 10,000 gallons of water per minute to the ranch's water-distribution system. The system, intended for completely automatic operation, has manual override controls.

The system begins operating in the morning when the sun is at the correct elevation to supply the energy necessary to operate the boiler. In late afternoon, when the sun is too low to supply the necessary energy, the collectors automatically rotate to their stowed positions and the system shuts off. The system is so designed that it will continue to operate when the sun is momentarily hidden by passing clouds; however, dense cloud cover will cause the system to shut down and the collectors to stow. Although the system will not operate under solid cloud cover, it will automatically commence operation when the cloud cover passes on.

This solar-powered system is best described in terms of its energy-collection and energy-conversion loops. In the descriptions that follow, the operating temperatures, pressures, and flow rates represent design operating conditions.

Energy-Collection Loop. The solar-collector field consists of nine rows of collectors, each row 80 feet long, erected on north-south axes. As shown in Figure 3, direct sunlight reflected from an aluminized acrylic reflector surface is concentrated onto a 1-5/8-inch copper collector tube, which has a black absorptive coating on the outside surface.

Water flowing through the collector tube is heated from an inlet temperature of 274 F to an outlet temperature of 302 F, and is maintained at a pressure of approximately 100 psig to ensure that it remains a liquid. This hot water is pumped at a rate of 32,000 lb/hr to the boiler in the skid-mounted power package (see Figure 4), where it loses 16 degrees while vaporizing the working fluid (R-113), hereafter referred to as Freon. After passing through the boiler, the water loses 12 degrees in the preheater, where the working fluid is heated before it is pumped into the boiler. The water is then pumped from the preheater back to the collector inlet, completing the water loop.

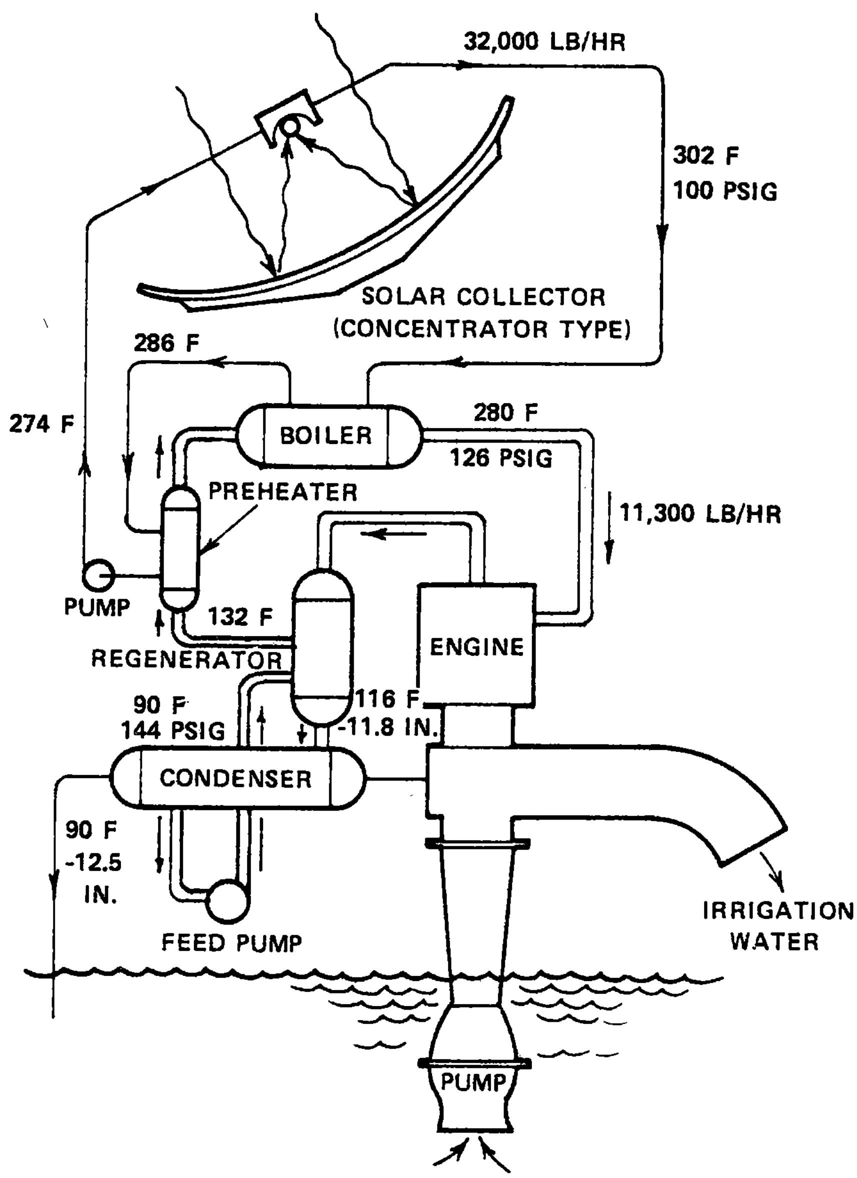

FIGURE 3. A SCHEMATIC OF THE SOLAR-POWERED IRRIGATION SYSTEM: 1977

The figures are design values.

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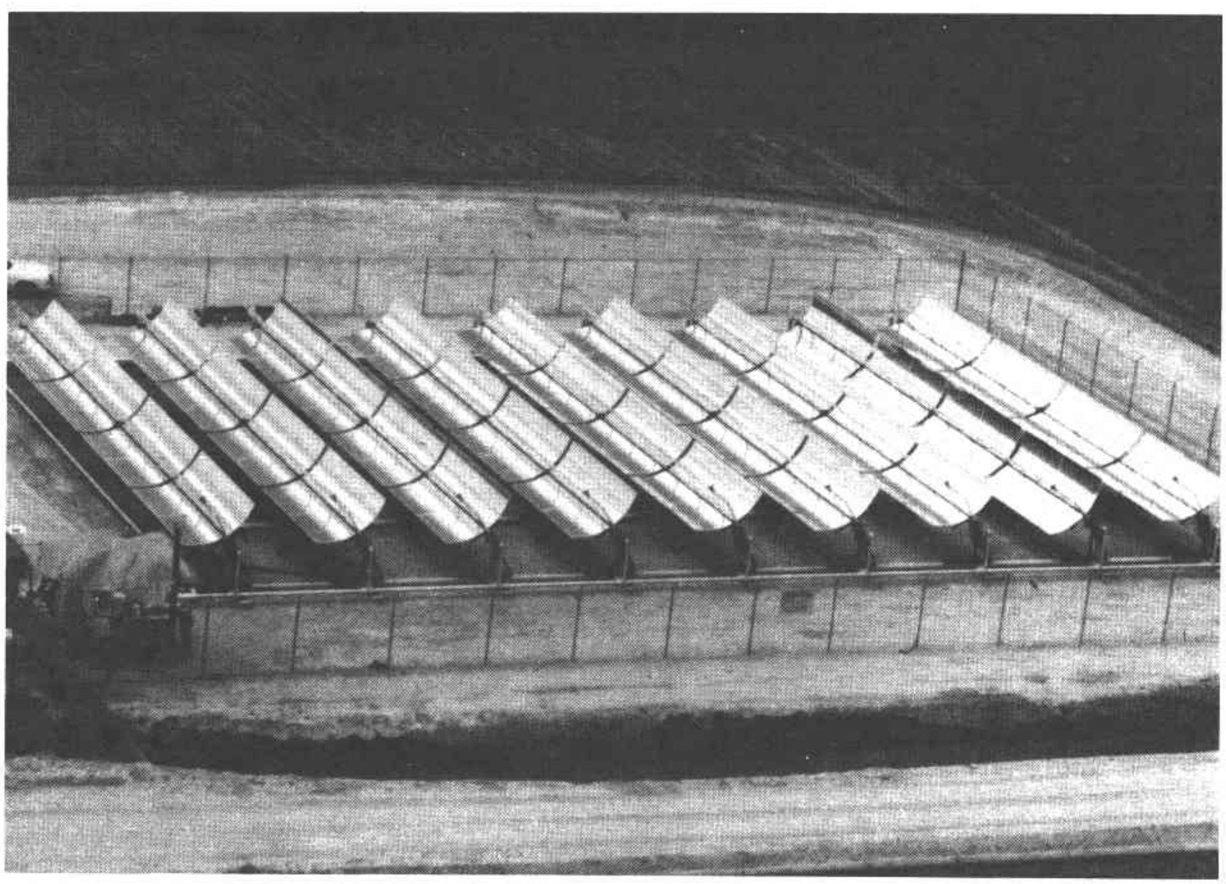

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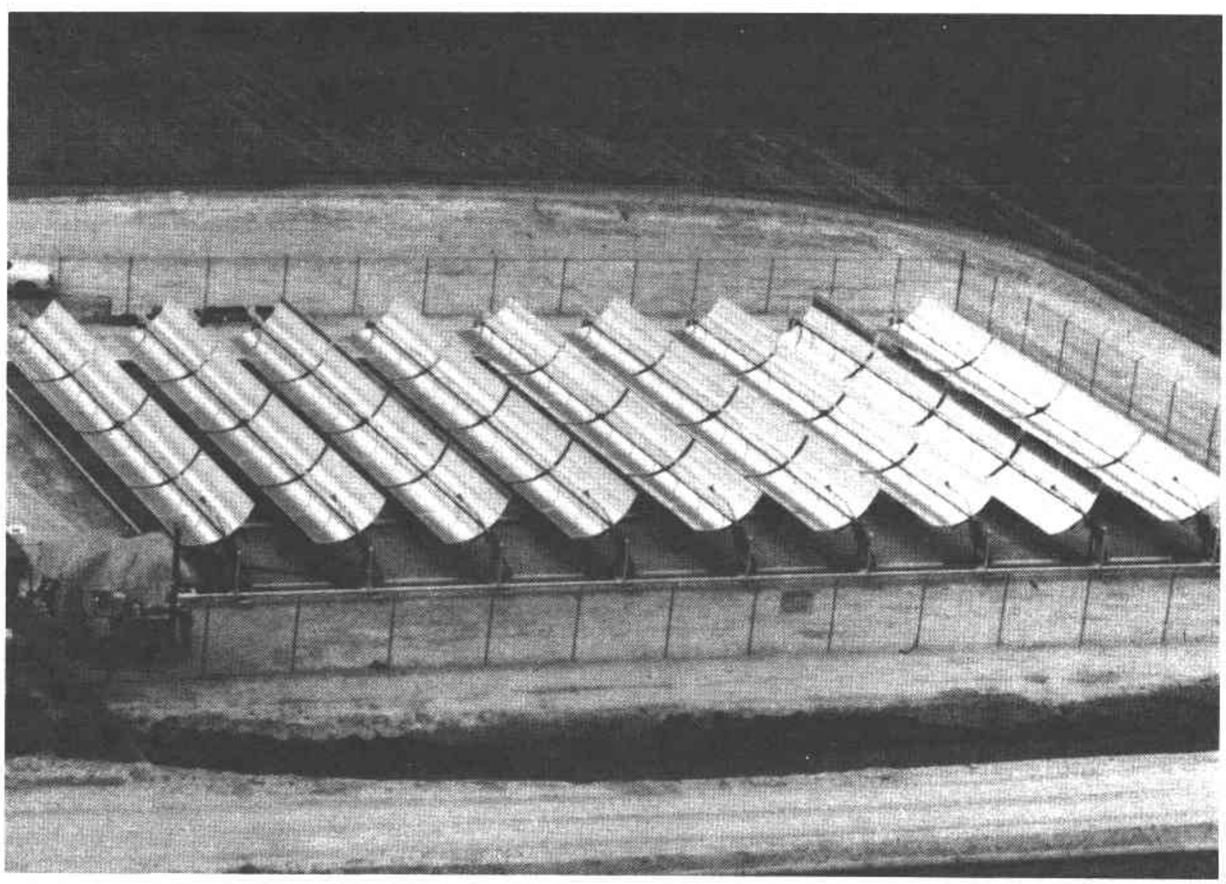

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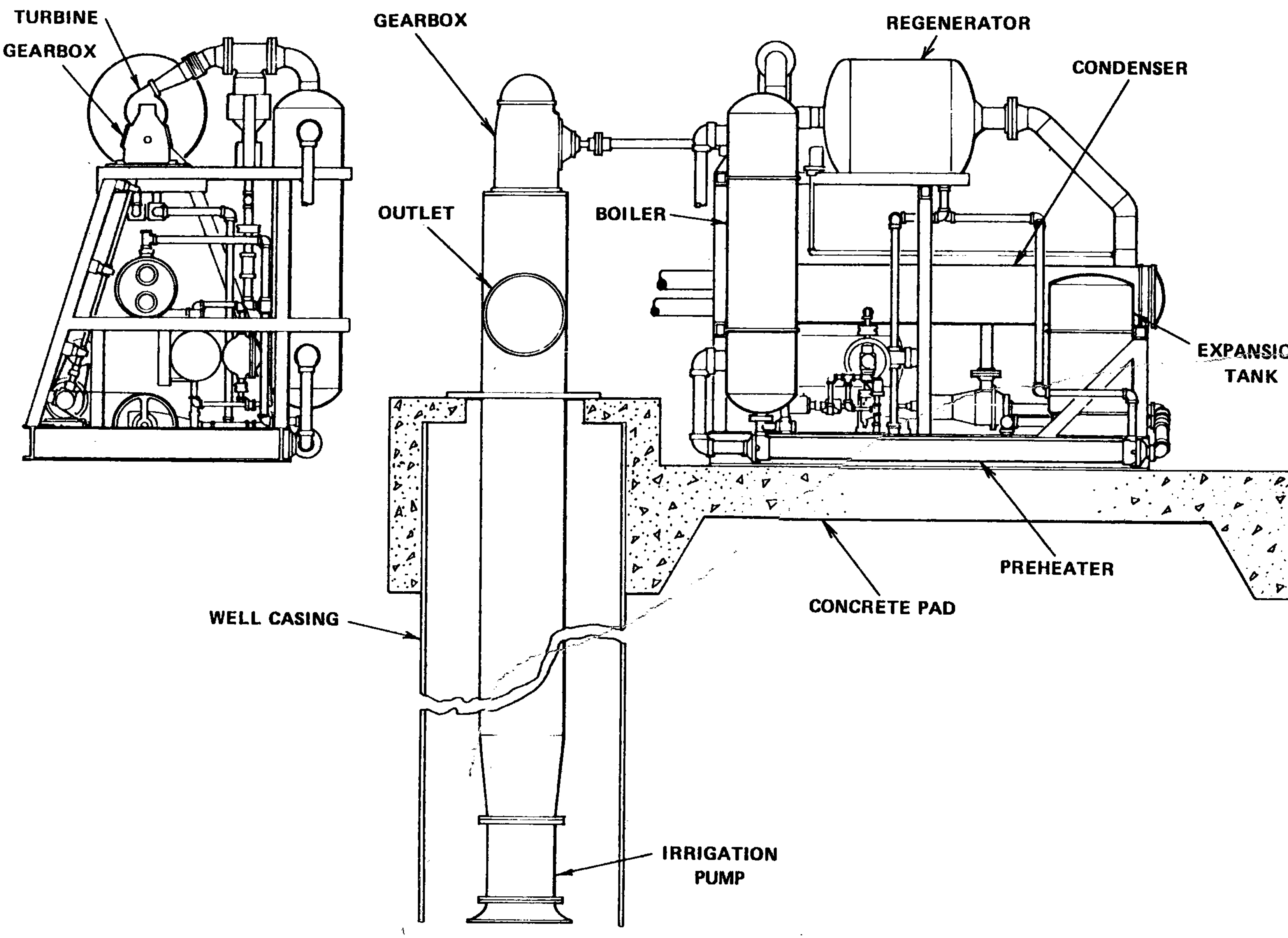


FIGURE 4. THE SKID-MOUNTED POWER PACKAGE: 1977

The expansion tank shown in Figure 3 allows thermal expansion of the water during temperature changes from ambient to about 300 degrees. Relief valves, temperature sensors, and pressure transducers around the loop ensure that the temperatures and pressures do not exceed specified limits. Corrosion inhibitors prevent corrosion in the hot-water loop. A flexible, high-pressure steam hose between the collector and header allows the collectors to rotate approximately 270 degrees while the supply and return headers remain stationary.

Energy-Conversion Loop. The Freon working fluid, flowing at a rate of 11,300 lb/hr, leaves the boiler as a vapor at a temperature of about 280 F and a pressure of 126 psig. After passing through a separator where any fluid droplets are removed, the Freon enters an expander where its temperature and pressure are decreased while its velocity is increased. This high-velocity gas stream is then directed against the vanes of an impeller within the turbine; this rotates an output shaft and converts the energy of the moving vapor to shaft horsepower. A gearbox reduces the turbine output shaft speed of 30,700 rpm to the drive shaft speed of 1775 rpm (nominal 1800 rpm).

The Freon vapor then passes from the turbine into a regenerator, where it transfers heat to the liquid Freon pumped from the condenser. The Freon vapor, now at a temperature of 116 F and a pressure of -11.8-inch Hg, enters the condenser where it is cooled to a liquid using water from the sump. The now-liquid Freon leaves the condenser at 90 F and a pressure of -12.5-inch Hg and drains into a receiver tank, which maintains a positive liquid head on the feed pump to prevent feed-pump cavitation. A float valve maintains the proper liquid level in the receiver tank and, therefore, in the boiler. The feed pump transfers the Freon into the regenerator at 90 F and 144 psig. Here it is heated to 132 F. It then flows to the preheater, which heats it to the boiling point. Then it flows through the boiler where it is vaporized, completing the working fluid loop.

The drive shaft from the turbine gearbox supplies the power to a conventional 50-horsepower irrigation pump, slightly modified to supply cooling water to the condenser. The turbine gearbox output shaft is double ended, which provides a power takeoff for auxiliary systems, in particular for the feed pump and the collector water pump. A small electric starting motor with overrunning clutches provides the initial power to the feed pump and collector water pump to start the system. After a preset speed is reached, the turbine output shaft supplies the power and the electric starting motor is automatically turned off.

System Control

The system in place at the beginning of the 1978 program was controlled by a combination of electronic and mechanical devices. Normal operation of the system required that the collector field and skid package be active at the appropriate times, that each collector row track the sun properly, and that the flow rate of each working fluid be matched to the incident solar energy and to the load.

Startup and shutdown of the system, under normal operating conditions, were controlled by sensors which detected the presence of sufficient sunlight for operation. A manual switch was also provided for this purpose. (Safety features were provided, as described below, which were also capable of shutting the system down.)

Each collector row was equipped to track the sun independently, once the system was activated.

The rate at which Freon was circulated through the energy conversion loop was controlled so as to regulate the level of liquid Freon in the boiler; any excess feed pump output was bypassed back to the receiver tank. If this level was correctly maintained, the rates at which collector water and condenser cooling water were pumped were inherently matched to system requirements (above the preset speed for starting motor cutout), and the system was self-regulating.

Safety Features

Automatic features were incorporated for safe operation in the unattended mode. In addition, certain features were included for manual monitoring and shutdown of equipment.

Active automatic safety functions were designed into the system to prevent damage to the components. Thus, the system will shut down (by rotating the collectors to their stored position), or will not start, whenever:

- Oil pressure is insufficient and the turbine is operating above a certain set speed
- The water level in the sump basin falls below a certain minimum level
- The turbine exceeds a certain maximum speed
- The wind rises above a certain velocity
- The ac power fails or is intentionally shut off
- The collector-water circulant pump fails to rotate while the system is activated.

Individual solar-energy collectors will track independently and automatically when so allowed by the master controller, but each will automatically return to its stored position if the temperature in that collector row rises above a certain level. Manual reset is required to operate a row which has shut down due to elevated temperature.

The system is passively protected from the effects of overpressure in both the collector water system and the Freon system. In the latter, a relief valve will transfer Freon from the high-pressure side to the low-pressure side of the Freon loop to reduce the pressure to a preset level. If this measure is inadequate, Freon will vent to the atmosphere by means of rupture discs on both the high- and low-pressure sides. A pressure-relief valve, venting to the atmosphere, protects the collector water system.

Visually-monitored instruments installed around the working-fluid loops indicate pressures, temperatures, and flow rates. Sight glasses are installed in a number of locations for verification of flows and liquid levels. A manual emergency shutoff valve is located between the high- and low-pressure Freon loops; opening this valve equalizes pressures across the turbine, causing it to rapidly coast to a stop.

Summary of 1977 Operations and Performance

Operation of the solar-powered irrigation system during 1977 generally showed good correlation with design goals. However, several shortcomings were discovered during operation of the system.

Collector Field. After a relatively short period of operation, a severe accumulation of dirt developed on the inner and outer surfaces of the glass which covered the absorber tubes, seriously reducing the efficiency of the collectors. Performance tests comparing the efficiency of absorber assemblies with and without glass covers showed that the glass covers provided no significant improvement in performance, even if clean. Consequently, the covers were removed from several of the collector rows and the system was operated for the remainder of the season in this configuration.

After several weeks of operation, some collector rows began to show degradation of the coating on the absorber tubes, including flaking, peeling, and powdering. By the end of the season, this degradation had spread to all rows and there was an apparent deterioriation in performance.

Two rows were severely damaged late in the season when they steam locked, overheated, and the overtemperature sensors failed to cause the rows to rotate to the stored position. As a result, the absorber tubes and housings were severely warped, and the tube coating damaged.

The reflective surfaces of the collector units showed no significant deterioration. They had been cleaned on three occasions, and maintained their reflectivity well.

In spite of the mechanical damage sustained by two rows, and the degradation of the absorbtive coating, all rows were operational at the end of the 1977 irrigation season, although performance was apparently reduced.

Tracking System. The most serious tracking system problem was related to accuracy and stability under variable cloud cover. With either clear, hazy, or cloudy sky, the system tracked consistently and accurately; however, a change in the type of cloud cover resulted in unacceptable tracking performance unless manual adjustments were made.

Another problem involved the switching of current to the tracking motors. The relays initially installed in the system were undersized for the loads they were required to carry, and had to be replaced. The new relays subsequently installed were not fully reliable. Their sticking (resulting from arcing and welding of the contacts), although intermittent, was a periodic problem and required the presence of an operator for repairs and replacement.

Skid-Mounted Power Package. The skid-mounted power package was found to operate satisfactorily after minor modifications were made in the field. No major component failures occurred during 1977. However, one problem which prevented unattended operation involved maintaining adequate cooling water flow to the condenser. The cooling water, drawn from the flow of tail water through the irrigation pump, contained significant amounts of agricultural debris which tended to plug a coolant line check valve. Modifications were made to allow the check valve to be flushed manually as required. Although needed infrequently, this required the presence of an operator to monitor the temperature rise through the condenser and flush the check valve.

System Performance. Overall system performance throughout the 1977 operating season proved to be satisfactory. Although the design peak power output was not achieved, irrigation water output of over 9000 gallons per minute was achieved on several occasions. A total of 323 hours of operation were accrued during the 1977 season; the average water output during operation was 3790 gallons per minute. Maximum efficiency achieved by the entire system was in the range of 4-5 percent. This compared to 5.5 percent design efficiency.

TASKS 2-5: MODIFICATIONS DURING 1978

As described under "Objectives of the Program", Tasks 2, 3, 4, and 5 of the program involved modification of the system through addition to or upgrading of existing components. Task 1, Operations, was carried out to the extent possible while these tasks were under way, and is discussed under "Task 1: Operations and Maintenance During the 1978 Irrigation Season". The following discussion includes the rationale for each modification of the original system, the modification(s) chosen in each case, installation and trouble-shooting experience, and performance of the modified subsystems.

Task 2. Improve Tracking System

Task 2 of the 1978 program involved improving the tracking system. The system required upgrading to achieve reliable unattended operation.

The 1977 Tracking System

The original tracking system installed in 1977 was specified and provided by Hexcel Corporation, the manufacturer of the collector units. Specifications were based on the requirements of the collector system, including accuracy of tracking, coordination of individual collector rows, and fault indication. Hexcel chose Delevan Electronics, Inc., as the supplier of the tracking hardware. It appeared that the standard features of the system that Delevan had under development would meet most of the requirements of the NML/BMI installation. Table 1 summarizes these features.

The standard features of the Delevan tracking system promised to allow unattended operation of the collector field. The single master controller was designed to control system startup at the appropriate time each morning, temporary shutdown for the duration of heavy cloud cover during the day, and shutdown each evening. In addition, the master controller included provisions for monitoring the operation of any associated

TABLE 1. TRACKING SYSTEM SPECIFICATIONS

Manufacturer:	Delevan Electronics
Configuration:	Centralized master controller; sun sensor and individual controller on each collector row
Power Supply:	24 VDC, internally regulated
Enclosures:	NEMA 12 (oil tight, dust tight)
Accuracy:	$\pm$ 1/4°

Logic Functions:

Master Controller

- Generates an uninterruptable "Store" signal continuously while monitoring a negative condition (LED indicates "Store")
- Generates an uninterruptable "Store" signal for a settable time period after all negative conditions have ceased. (LED indicates "Store Timer")
- Generates an "Out of Store" signal for a settable time period after a "Store" signal has ceased. (LED indicates "Out of Store Timer")
- Reacts to the following as negative conditions: (LED indicates each condition)
  (1) Low solar radiation (variable set point)
  (2) High wind (variable set point)
  (3) Low a-c voltage signal (variable trip point, variable delay, manual reset)
  (4) Closure of N.O. contacts (1 circuit)
  (5) Opening of N.C. contacts (2 circuits, 1977; 3 circuits, 1978)
  (6) Closure of Manual-Store Switch.
- Energizes 110 VAC relay (N.O. and N.C. contacts) whenever "Store" signal is not in effect.

Individual Controllers

- Tracks sun unless signaled "Store" or "Out of Store" by Master Controller. (LED indicates Store, Out of Store, or Null Condition)
- Manual override switch on each row controls motion of collector
- Manual deactivate switch on each row allows any row to be individually immobilized in any position
- Overtemperature sensor sends individual row to store (manual reset)
- Audible signal sounds if row is deactivated due to overtemperature
- Limit switches in motor power circuit to prevent runaway.

components for fault conditions. Individual electronics packages, mounted on each collector row, controlled tracking throughout the day. Indication of overtemperature in a collector row was designed to send that row to the stored position. Thus the tracking system provided overall system control functions as well as directing the tracking of each collector row.

The logic functions of the "standard" Delevan tracking system fulfilled most of the needs of the solar-powered irrigation system. Modifications installed by Delevan prior to delivery addressed some of the remaining requirements; additional fault monitoring capability was added to the master controller, and a 110-VAC relay was installed to control the skid package starting-motor circuitry.

The features included in the Delevan tracking system made it suitable for use in the solar-powered irrigation system. However, upon installation and initial operation it became evident that the system did not perform as expected.

Installation of 1977 Tracking System. The tracking system was placed in service early in 1977; several shortcomings were immediately obvious.

The torque available to rotate the collector rows through their travel was inadequate for high wind conditions. The tracking motor power supply was converted from rectified, unfiltered 24-volt ac to a rectified and filtered 24-volt system. Since this modification still did not add adequate torque, the 24-volt system was then converted to a 36-volt dc, battery-supplied system, with rectified ac used for battery charging. This provided adequate torque for any anticipated wind loading.

A second problem occurred when these modifications were completed. The relays which switched the motor current had originally been sized for current draw based on rectified, unfiltered 24-volt ac. With the modified power supply, and the highly inductive loads (90-volt dc motors), these switching relays could not handle the power. Larger relays were substituted, substantially increasing the current carrying capacity.

Performance of 1977 Tracking System. Operating experience after the completion of on-site development of the tracking hardware showed that system control was satisfactory, including adequate protection against faults in the skid package, and that tracking accuracy was acceptable if adjusted properly for any constant level of cloud cover.

However, two serious deficiencies existed, based on operating experience. Variation in the level of cloud cover required manual adjustment of the tracking system deadband to obtain satisfactory accuracy and stability. The second major inadequacy was the performance of the relays used for motor switching. Even after upgrading these relays, as described above, occasional welding and sticking of contacts occurred, resulting in continuous operation of the tracking motors. Repair or replacement of these relays was required at relatively frequent intervals.

At the end of the 1977 irrigation season, all components of the tracking system were functional but the system required an operator to maintain satisfactory performance over a long period.

1978 Tracking System

At the conclusion of the 1977 irrigation season, it was determined that improvements could be made which would eliminate the two problems described.

Discussions with Delevan indicated that the required manual adjustment of tracking controls resulted from variation in the signal-to-noise ratio within the tracking system as cloud cover varied. In 1977 the tracking system used a "Bang-Bang" control system, switching each tracking motor on and off in response to variations in the error signal generated by two half-shaded phototransistors. Under conditions of bright sunlight, a wide deadband was required in order to minimize overshooting, which lead to instability. However, under cloudy conditions, a wide deadband allowed unacceptable tracking error. Thus, it was necessary to narrow the deadband whenever the ratio of diffuse radiation to direct radiation increased. With a narrow deadband setting, a return to predominately direct radiation resulted in limit-cycle oscillation of the collector.

One method of eliminating this problem was to modulate the collector tracking speed, in proportion to the magnitude of the error signal. Slowing the rotational speed of the collector as it approaches focus would help eliminate overshoot, and it was felt that this modulation would allow a constant deadband setting, regardless of cloud cover. Delevan had under design at the end of the 1977 program a revised control system incorporating pulse-width-modulation, which acts as semiproportional control, modulating collector tracking speed but avoiding problems associated with full proportional control. The new Delevan design also promised to eliminate contactor problems by incorporating semiconductor power switching.

An order was placed with Delevan in early April, 1978, for a revised control system conforming to the specifications of the original control system with respect to features and performance, but adding semiproportional control and solid-state power switching. A new master control unit, new row controllers, and new 24 volt dc motors were to be provided. All hardware was designed for 24 volt operation. The tracking motors were not available on schedule; therefore delivery of the control system was delayed. The system was not delivered to the Gila Bend site until the end of June.

Installation of 1978 Tracking System. Prior to installation of the new control system, revised control and power distribution conduit and wiring were installed. This work was conducted before the original control system was removed, in order to reduce system downtime. A local electrical contractor was hired to remove the old system, and installation and connection of the new hardware began on July 15, 1978. Installation was completed approximately July 19.

A variety of problems were encountered during installation of the revised system. Wiring diagrams provided with the new hardware were found to be incorrect, and documentation of the system was generally inadequate. It was necessary to reverse polarity of the phototransistors and the battery charger in order to adapt components of the old system to the new hardware.

After the new components were completely installed, the rows were run independently to complete minor debugging operations on the wiring. At this point, the system components were interconnected and the new tracking system was operated for the first time. Erratic operation ensued.

Battelle and Delevan personnel participated in troubleshooting, modifying and debugging the revised system. During this process a variety of minor problems were corrected, including incorrectly sized ground leads, audible overtemperature indicators which had been miswired, chatter of small signal switching relays, inadequate battery charger output, and initial component failures. Several major problems were corrected after numerous iterations of troubleshooting and modification.

- Torque available for rotating the collector rows was inadequate; this resulted in nonuniform operating speeds and an unsatisfactory margin for coping with high winds. Torque was increased by modifying current limiting circuits within the row controllers to increase the current available to the motors.
- A potentially hazardous problem (unreliable choice by the row controllers between store and out-of-store signals) was corrected by installing lock-out circuitry in the master controller, which guaranteed that store and out-of-store signals could never be generated simultaneously. The store signal (the system response to a fault indication) was given precedence over the out-of-store signal.
- Initial experience showed that even slightly cloudy or hazy conditions resulted in unacceptable tracking accuracy. This problem was traced to inadequate current flow through the phototransistors, and was alleviated by modifications to the individual row control circuitry.
- Initial operation of the revised system led to a rash of failures of the power transistors which control current flow to the tracking motors. The failure rate associated with these components was unacceptable. Midway through the program, Delevan provided larger capacity switching transistors; these upgraded components have apparently resolved the excessive failure rate experienced earlier.

- Failures in which the master controller did not respond to fault indications from the skid package were addressed by several modifications which Delevan personnel installed in the master control circuitry. Although the failures observed at the time have been corrected, behavior of the system near the end of the program indicated that some problems still exist in this area.

Performance of the Revised Tracking System. After expending significant effort to correct the initial problems and obtaining approximately 55 hours of operating experience with the system in its present configuration, it is apparent that some of the goals of the modification have been attained, but significant problems still exist.

The power switching problems encountered in the 1977 version of the tracking system are apparently solved. The solid-state switching used in the 1978 system has eliminated the problems associated with the use of relays, and substitution of larger transistors for the original 20 amp components has enabled the circuitry to handle the required current without an excessively high failure rate.

Tracking performance is unsatisfactory in several respects, however. Variation in cloud cover still requires manual adjustment of the deadband and delay settings on the individual row controllers. This appears to be due to mismatch between the sun sensors (which were retained from the original control system) and the semiproportional circuitry installed with the revision, as little or no pulse width modulation occurs as the concentrator moves toward its focused position. Whereas the tracking performance of individual rows is adequate on hazy or moderately cloudy days, stability is now marginal on cloudless days, requiring long delay and wide deadband settings. Furthermore, an unacceptable steady-state offset is generated under cloudy or hazy conditions, if the long delay required for stability on clear days is used. (This steady-state offset is a phenomenon new to the revised system--it was not encountered on the previous version of the tracking system.) As a result of the conflicting adjustments required for clear and cloudy or hazy conditions, it is impossible to strike a compromise setting which is even minimally satisfactory. Readjustment is required at least as frequently as with the original tracking system, and is more complex.

Also of concern are several failures of the safety functions incorporated in the master controller. Simulated failure of the circulant pump (which provides vital water flow to the absorber tubes in the collector units) has, on at least one occasion, not resulted in sending the collector units to their stored position. At the conclusion of the field work in 1978, this problem had been tentatively diagnosed as a failed integrated circuit chip, but the problem had not been corrected.

The torque available for tracking with the revised system is less satisfactory than with the original tracking system. It appears to be adequate for any anticipated windloading, but an increase in available torque of approximately 50 percent would provide a more suitable margin.

Operating experience with the revised system leads to the conclusion that, although in certain respects the new system shows improved reliability, its performance is still not satisfactory.

Current Status

The tracking system, in its present condition, is functional. All rows will track with satisfactory accuracy if adjusted properly for ambient cloud conditions; however, stability is marginal for all rows on clear, bright days.

The master controller is operational, although the status of some safety functions is uncertain. The apparent failure of an integrated circuit component in the master controller has thus far not impaired its ability to operate under normal circumstances, but poses a safety hazard regarding protection of the collector system from circulant failure.

Two other features of the system still present obstacles to unattended operation. Operating procedure specifies that proper functioning of the oil-pressure-fault circuit be verified by manually testing the oil pressure sensor at system startup each day. The system is capable of operating without utilizing this procedure, but then a less than totally fail-safe logic is incorporated. Also, the sensors which monitor absorber tube temperature on each row are of questionable reliability. The routing of the sensor lead wires leaves them susceptible to thermal damage, should the collector row lead or lag in tracking the sun. The mode of operation of the sensors is such that overheating the sensor leads could result in a constant indication of normal operating temperature, even though the absorber tube might be at a dangerously high temperature.

Task 3. Replace Absorber Tubes and Receiver Housings

Task 3 of the 1978 program involved replacing the absorber tubes and receiver housings of the Hexcel collector units. These modifications were required in order to replace damaged components and to upgrade the collectors using the improved materials and designs which became available.

1977 Components

The collector system was installed during February and March, 1977. The components were supplied by Hexcel Corporation of Casa Grande, Arizona. Figure 5 illustrates the original absorber assembly configuration.

Based on the high peak, high average, and high percentage-of-direct insolation available in the Phoenix-Gila Bend area, and on the requirements of the skid package design, nine rows of parabolic trough, single-axis tracking collector units were installed. Each row was composed of four modules, each 20 feet long, for a total installed area of 5785 sq ft. The associated support structure and tracking system components were included in the purchase.

Performance of 1977 Components. The Hexcel concentrating collector system performed well, in many respects, throughout the 1977 program. The honeycomb reflector panels proved to be very strong, light, and stable. The reflective surface itself, an acrylic film with a second-surface reflective coating, showed good durability. The thermal performance of the collector units closely approached the specified value, achieving approximately 95 percent of claimed design output.

By the end of the 1977 project, however, it was apparent that major repairs and improvements were needed. As described previously, failure of temperature sensors had allowed two absorber assemblies to overheat, causing mechanical damage to the assemblies on Rows 4 and 7. This warping and the severe deterioration of the absorptive coating substantially affected the power output of these two rows.

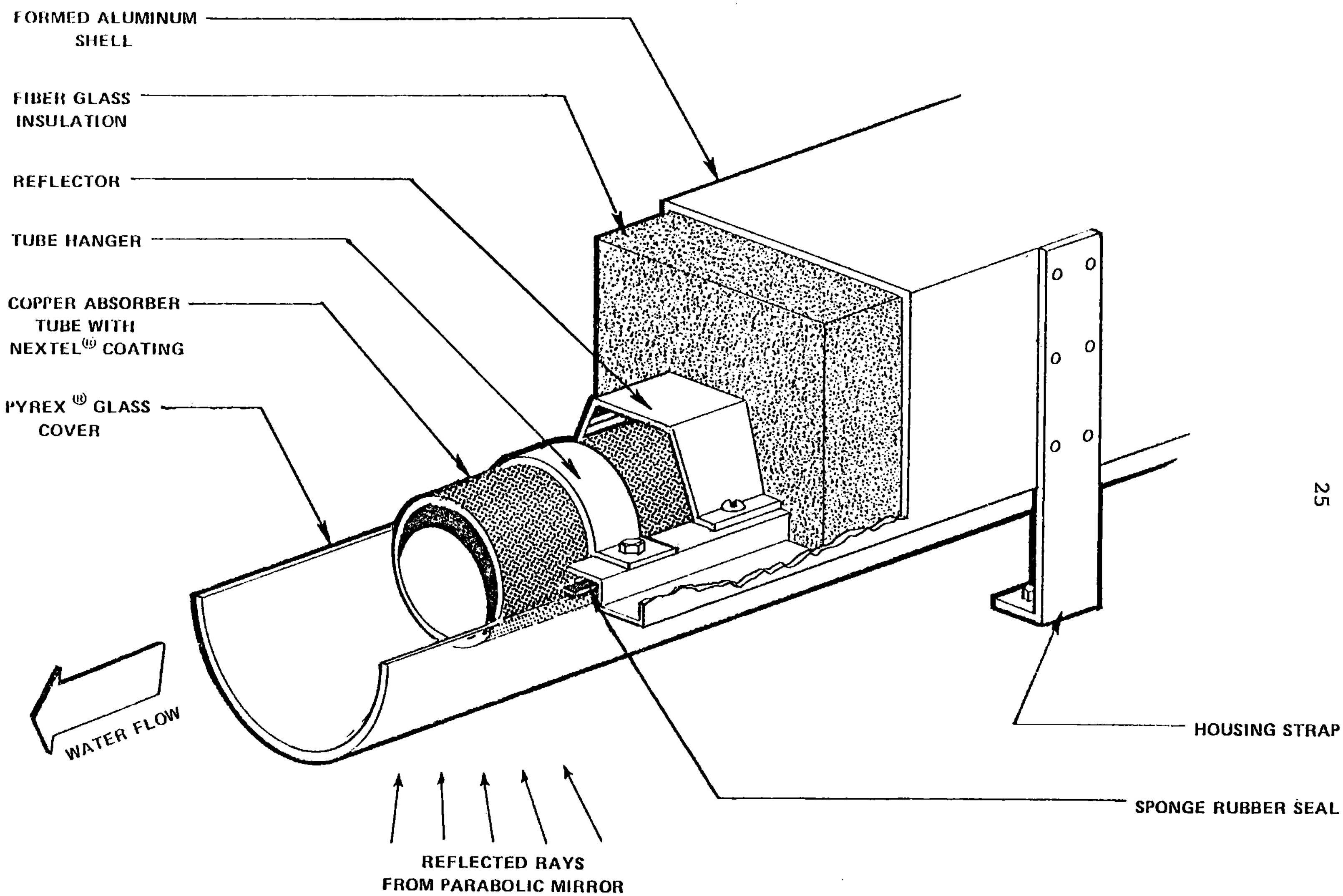


FIGURE 5. ABSORBER ASSEMBLY 1977 VERSION, AS SUPPLIED BY HEXCEL

The absorptive, nonselective coating on the absorber tubes had shown significant deterioration during the 1977 operating season. Flaking, peeling and powdering were first observed on two of the nine units. By the end of the 1977 program, similar deterioration was beginning to show on all units. An "apparent" loss of performance accompanied this physical degradation of the coating.

The housings around the absorber tubes (see Figure 5) were found to be susceptible to damage from overheating, should the collectors lead or lag in tracking the sun. Also, removal of the glass convection-radiation covers provided an improvement in performance.

Status of Collector System, September 1977. At the end of the 1977 program, although certain deficiencies had appeared in the equipment, all collector units were in operating condition. The mechanical integrity of the supporting structure and reflectors remained excellent, except for some minor damage to the main torque tubes, resulting from roll-forming by the roller bearings. The flexible hoses joining the rotating portion of the collector units to the stationary header pipes showed no significant deterioration or weathering. The reflector surface itself showed no substantial abrasion or any degradation other than the collection of dust. The reflector surfaces had been cleaned three times during the 1977 program, using spray application of deionized water. The absorptive coating on the absorber tubes of all rows showed serious degradation. In some instances, only bare copper pipe remained. Glass had been removed from Rows 2, 3, 5, 6, and 7 during experiments evaluating the effect of the glass covers. The remaining glass was very dusty. The seals installed in the receiver housings were not effective in excluding dust and moisture during thermal cycling of the collector units. The absorber tubes and receiver housings in Rows 4 and 7 were mechanically warped during a serious overheat condition resulting from a sensor failure.

1978 Components

Investigation revealed that components were available from the original supplier to repair and upgrade housings and absorber tubing. Hexcel was producing a redesigned receiver assembly (see Figure 6).

The housing was an aluminum extrusion with a secondary reflector of specular-polished aluminum. A wind shield was incorporated in the revised housing design to reduce convection losses, and no glass was utilized. The revised absorber assembly included a copper absorber tube with black chrome selective coating. The revised design, due to the reflector, promised to reduce the possibility of distortion due to overheating from inaccurate tracking.

The manufacturer of the original absorptive coating (3M) was contacted regarding the failure and they indicated that it was probably the result of combining temperatures at the high end of the compound's operating range with ultraviolet exposure. As a result of these inquiries, a new compound was developed by the manufacturer and offered for experimental evaluation. The manufacturer suggested that the old absorber tubes be cleaned and recoated to evaluate the performance of the new experimental absorptive coating.

Recommendations for Upgrading. The original recommendations for upgrading the solar-powered pumping system during the 1978 program included installation of the revised Hexcel absorber assemblies on all nine rows. The performance of the black chrome selective coating was predicted to be superior to the performance of paint-on coatings. Increased efficiency was also expected to result from the revised housing design, since the specular reflector behind the absorber tube was designed to recover some of the energy previously lost due to inaccurate tracking. The wind protection provided by the revised housing was also expected to aid the efficiency of the unit.

Experimental results derived early in the 1978 program indicated that the efficiency of the collector rows was reduced to a surprisingly

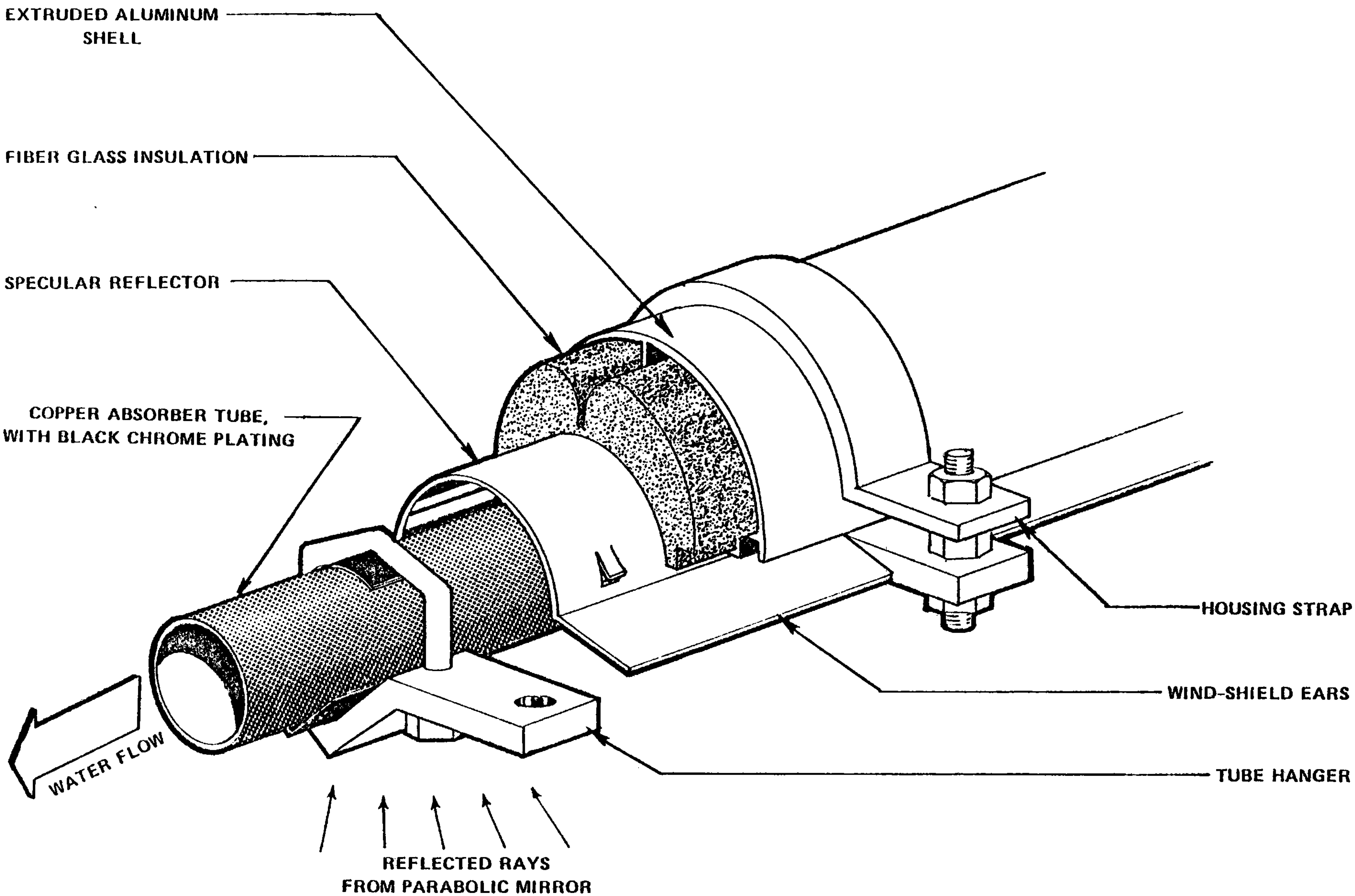


FIGURE 6. ABSORBER ASSEMBLY 1978 VERSION AS SUPPLIED BY HEXCEL

small extent by the deteriorated absorptive coating. Since this had significant economic implications on the maintenance and replacement costs associated with solar operations, Battelle and Sandia agreed to a modified replacement plan for the housings and absorber tubes. It was believed that the possibility of achieving economically satisfactory efficiency, using either degraded and weathered coatings, or lower performance, but lower cost, materials, should be evaluated.

A matrix approach was suggested to use the collector system as a test bed to evaluate combinations of the receiver assembly components. Two versions of housing and three versions of coatings were available: the receiver housing was available in its original configuration, and in the revised housing design available from Hexcel Corporation; the original coating was in place in a weathered conditions on all nine collector rows at the beginning of the 1978 program, the new Nextel® coating was available from 3M and could be applied to the original absorber tubes after cleaning, and black chrome selective coating was available, on new absorber tubes, through Hexcel.

Installation. Five of the six possible combinations were recommended and eventually installed in the field. Installation of the revised absorber components was carried out one row at a time to minimize the downtime of the entire system. Table 2 lists the combinations of housing and coating installed on each row, and the date when installation of each combination was completed.

To allow proper comparison of the performance of each combination, uniform focus and structural stiffness was required in each row. The initial design of the revised absorber housing made no provision for installation of guy wires to stabilize the absorber assembly. When these details became available the guy wires were installed; installation of guy wires and final focusing were completed in mid-September.

Performance of Revised Components. The revised housing showed good stiffness and light weight. The reduced weight, compared to the original design, would require less counterweight and would aid in reducing

TABLE 2. RECEIVER HOUSING/ABSORBER COATING COMBINATIONS

Coating \ Receiver Housing	Original Design	Revised Design
Original Nextel®	Row 8; April 1977 Row 9; April 1977	Row 1; June 1978 Row 2; June 1978
Experimental Nextel®	Row 3; June 1978 Row 4; June 1978	Row 6; Aug. 1978 Row 7; Aug. 1978
Black Chrome	(Not Planned)	Row 5; Aug. 1978

the total rotational inertia of a new collector system. Installation is less complex than for the 1977 version. The new housing design is less sensitive to damage from overheating than the original design. This is primarily due to the protection afforded the receiver assembly by the specular reflector and windscreen. The simple design of the revised housing should allow a significant reduction in cost.

Evaluation of collector efficiency in 1977 and early 1978 was based on the assumption of approximately equal division of the total collector-water flow between the nine rows. This assumption was necessitated by the lack of instrumentation for measuring individual flows, and was rationalized on the grounds that the flow paths were designed for approximately equal pressure drops. However, the installation of flow venturis on each row during 1978 allowed the individual collector flows to be measured and, on the basis of limited data, the assumption of uniform flow appears to represent a poor approximation. Measurements indicate that flow through an individual row may vary by ± 8 percent or more from the average flow rate. This is not unexpected, and occasional verification of the flow division at various total flow rates allows the nonuniform division to be incorporated in the analysis. However, variations of ± 7 percent were found within a single row, at a fixed total flow rate; this was an unexpected phenomenon, and suggests that frequent flow measurements will be required to properly evaluate collector performance.

Meaningful evaluation of the efficiency of the various collector components is severely restricted by the limited number of these detailed measurements of individual flow rates which are available for the period of operation with well-focused rows and installed guy wires. The performance of the various components is not markedly different, and thorough long-term comparisons will be required to adequately evaluate relative efficiencies.

Current Status

All receiver assemblies are currently operational. A combination of original and new receiver housings, and original Nextel®, experimental Nextel®, and black chrome receiver tubes are in place as indicated in Table 2. All rows have guy wires in place, and are well focused. As described under "Task 5", a flow meter and thermocouples are in place on each row, allowing measurements of collector performance.

Task 4: Conversion For Hybrid Electric Operation

The solar-powered irrigation pump program funded by NML was designed to demonstrate the technical feasibility of using solar energy for pumping water; in this regard that program was successful. The next step was to design a system to maximize the utility of solar energy and to pump water on demand--day or night, still having a system which could be operated by ranch personnel.

Though there are a number of ways to achieve the above, a fairly straight-forward approach was to add an electric motor to drive the pump at its design speed, and use available solar energy to reduce electrical energy requirements. There are several advantages to this approach.

- Such a system can meet the farmer's irrigation requirements upon demand.
- It is a simple system requiring neither thermal nor hydraulic storage.
- For a given collector field, all available solar energy is used to pump water.

Because of the need and the availability of the NML system, a hybrid electric conversion was planned for the 1978 irrigation season. Figure 7 illustrates the incorporation of the electric motor into the solar system.

Rationale. The integration of a pumping station into a large irrigation system places stringent requirements on the performance of the pumping equipment. Irrigation pumping is required on a 24-hour, 7-day-a-week basis, as full utilization of equipment reduces the large capital investment required for pumping stations, wells, and ditches, and reduces the labor required to operate the irrigation system.

The NML/BMI solar-powered pumping system was not designed for 24-hour operation. It is believed that using the electrical grid to "back up" the solar-powered pumping system improves the reliability and flexibility of the system, and that early commercial equipment for use in the United States will be designed to use this approach.

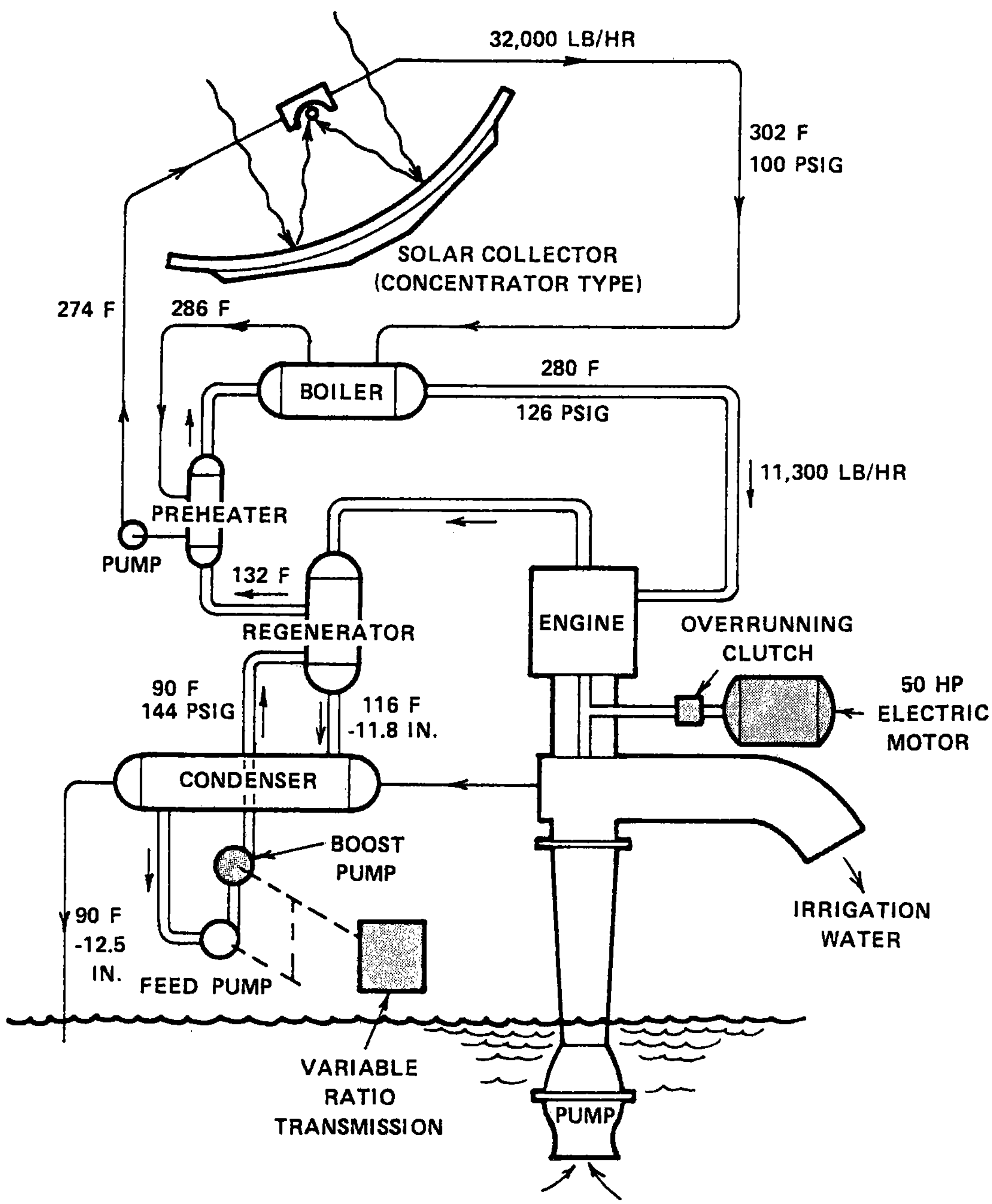


FIGURE 7. A SCHEMATIC OF THE SOLAR-POWERED IRRIGATION SYSTEM: HYBRID CONFIGURATION

Operation in the hybrid mode also improves the efficiency with which solar energy is used. Low speed operation of the irrigation pump results in low efficiency, due to tare and head losses. Commercial irrigation pumps are generally turbine-type pumps, due to their low cost and the adaptable configuration of this design. However, the efficiency of a turbine pump drops rapidly as input power and speed drop.

Constant speed operation, maintained by an electric motor, permits the pump to operate at its peak efficiency. Solar energy, when available, could reduce the total electrical energy used for driving the pump, allowing all of the available net solar power to be used to reduce pumping costs. In this mode, total losses are held to a minimum, productive use is made of all solar and electrical inputs, and the resultant constant output has greater utility to the farmer. (A new design based on the hybrid use of solar-electrical power for irrigation pumping would also allow the solar components to be sized for best economy, rather than on the basis of maximum flow requirements.)

Design Work

Design work was undertaken at the beginning of the 1978 program to add the hybrid electric system. Considerations included adapting the skid package to constant, full-speed operation and controlling the system under varying conditions of solar heat input.

A 1200 rpm, 3-phase, 50 HP electric motor was selected to drive the irrigation pump through a new gear box which replaced the original right-angle drive (see Figure 8). The new gear box contained a right-angle input for the drive shaft from the skid mounted power package, and incorporated a speed reducer to match the 1800 rpm output of the skid package to the 1200 rpm operating speed of the irrigation pump. An overrunning clutch mounted between the gear box and the drive shaft from the turbine allows the solar system to pick up load from the electric motor, but prevents driving the turbine with the electric motor when solar power is not available. An antireverse ratchet is incorporated in the adapter unit between the electric motor and the gear box, so that

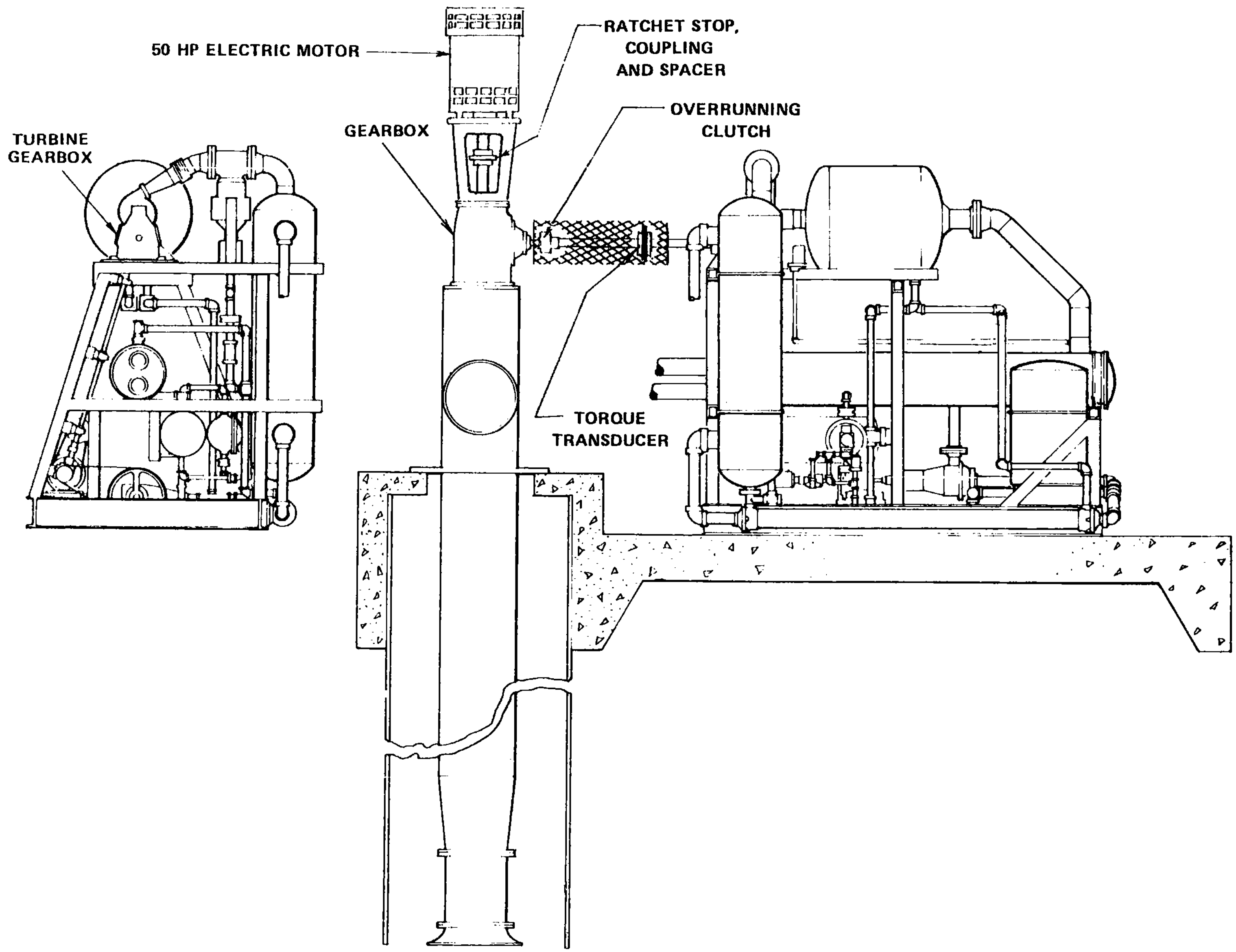


FIGURE 8. THE SKID-MOUNTED POWER PACKAGE: 1978

backflow through the pump on shut-off cannot reverse-drive the pump, motor and turbine. The electric motor was fitted with standard, manual motor-starter controls.

Operation in the hybrid mode results in full-speed operation of the turbine and associated components at all but the lowest power levels, since the skid package carries only circulation and friction loads until irrigation pump load is picked up from the electric motor. Operation at constant full speed was believed to present no problems with the turbine, heat exchangers, and other components, but it was projected that full-speed operation at design heat input would require Freon flow in excess of the capability of the feed pump.

During 1977, feed pump cavitation problems occurred, resulting from inadequate net positive suction head at the feed pump inlet. The feed pump was modified at the time to improve its cavitation resistance, and the static head at the pump inlet was increased. The resultant improved capacity of the pump proved adequate for all conditions of steady state operation experienced during the remainder of 1977. However, maximum output during this period was approximately 90% of peak design power, and there was serious doubt as to the adequacy of the feed pump for full speed, full power operation. To achieve the required Freon flow rates, the net positive suction head available at the feed pump had to be significantly increased. A turbine-type pump was located which was specifically designed to pump fluids with entrained gases. This boost pump was chosen to operate in series with the original feed pump to raise the pump inlet net positive suction head.

An additional requirement for operation in a hybrid configuration is that control of the skid package must be maintained under varying rates of heat input. In the 1977, non-hybrid system, the skid package was regulated by maintaining a constant Freon level in the boiler, bypassing unneeded Freon flow from the feed pump outlet back to a reservoir. Turbine speed (and hence collector water flow rate and feed pump flow rate) stabilized at an equilibrium point determined by the pressure and temperature at the inlet to the turbine, the condenser pressure acting on the exhaust from the turbine, and the irrigation pump load.

Analysis showed that the same system of control was valid for constant speed operation. However, in the hybrid mode, even when operating at low heat input the turbine and feed pump operate at full design speed, and Freon flow would be maximum although only a low flow was required. The losses generated in bypassing this excess flow were unacceptable. Therefore, a variable-speed drive was selected to control the operating speed of the feed pump and boost pump, allowing the output of the feed pump to be matched to the boiler requirements. Bypassing is required only at extremely low rates of heat input, and during startup. The flow of Freon through the modified skid package is schematically illustrated in Figure 9.

The resulting design for the modified system requires no alterations when switching between hybrid, electric-only, or solar-only modes of operation:

- For electric-only operation, the electric motor and pump run at 1200 rpm, while the skid package and collector field are inactive.
- For hybrid operation, the electric motor and pump run at 1200 rpm, and the skid package output shaft runs at 1800 rpm. The skid package carries whatever proportion of the load it can sustain, thus reducing the overall electrical load by the full net solar output.
- For solar-only operation, the skid package runs at whatever equilibrium speed it can maintain, given the incident sunlight and other performance parameters within the system. The electric motor idles along with the pump, contributing only windage losses, and neither produces nor uses electrical power.

Equipment Required/Ordered

The equipment required to convert the skid package to the hybrid configuration was specified and ordered during May and June 1978.

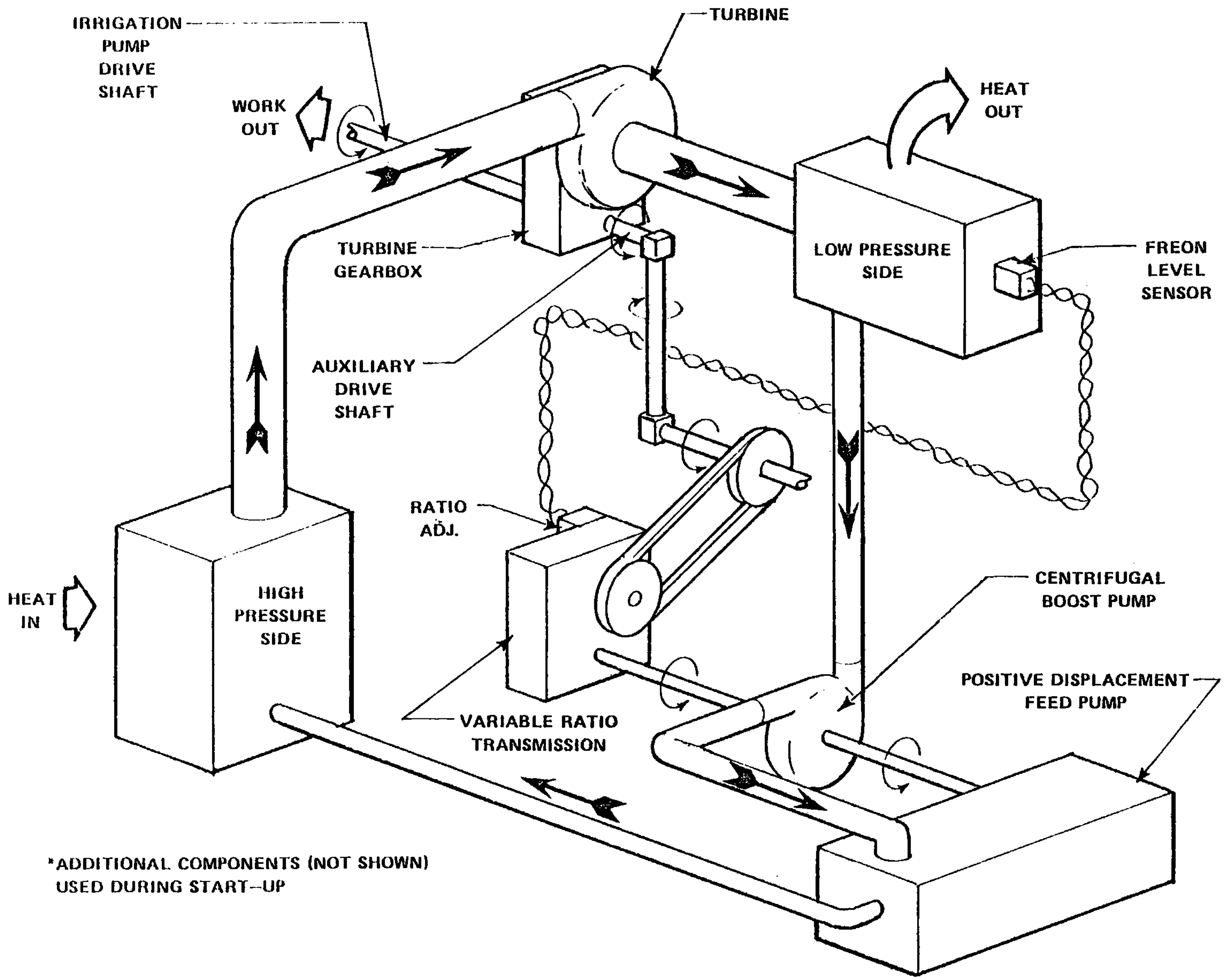


FIGURE 9. SOLAR POWERED IRRIGATION PUMPING SYSTEM FREON FLOW SCHEMATIC*: HYBRID CONFIGURATION

The electric motor, a standard item for irrigation applications, was ordered along with controls, starter relays, etc. A 3-shaft right-angle gear box (not a standard agricultural item in this geographical area) was ordered through a Phoenix supplier. The boost pump, variable speed transmission and a float controller for the transmission were also ordered, along with the required sheaves, belts, and other incidental hardware.

Installation

The irrigation pump and gear box were removed May 24, 1978, and the new gear box, the pump, and the electric motor were installed on June 5, and checked out on electric power only. During the second week in June, the system was checked out on combined solar and electrical power.

Turbine Oil Leakage. Problems were encountered with operation in this hybrid mode. The system was brought up to 75 percent power on solar energy, and then the electric motor was brought into hybrid operation for the first time. A serious loss of turbine gear box oil occurred in two to three minutes. The skid package was immediately shut down, and no damage was experienced. Investigation showed that oil was lost through the turbine shaft seal into the Freon side of the turbine housing at speeds above 1700 rpm.

The turbine and its attached gear box were removed from the skid package and shipped to the manufacturer (Barber-Nichols Engineering, Arvada, Colorado) for evaluation. Inspection in their laboratories, using an abbreviated test, failed to duplicate the leakage. However, certain features of their test procedure do not duplicate the normal operating condition of the turbine. Test bed operation at Barber-Nichols was conducted under vacuum, without load, by driving the turbine rotor through the gear box. Previous investigations by Barber-Nichols had failed to duplicate leakage problems on this unit. (Early in the 1977 program, during fabrication and assembly of the skid package, a similar leak had been detected in the turbine. At this time, the seal was modified by the manufacturer in an attempt to cure the problem. No instances of oil loss had been noted since the installation of the turbine and skid package at the site, prior to the problems which arose on June 13, 1978. However, the turbine was never operated at full speed during this period.)

The turbine was returned to the field site and reinstalled on July 11. Evaluation by a Barber-Nichols engineer, at the site, indicated that the seal leakage could be stopped by increasing back pressure, and was possibly excited by associated mechanical components on the skid package. (Increasing back pressure is an unacceptable cure for the leakage, but indicates that the problem indeed lies in a marginal seal.)

Electric Motor Failure. Diagnosis of the cause of the turbine leak was hindered by failure of the 50 HP electric motor installed on the irrigation pump. The irrigation pump was run by the ranch on electric power between June 29 and July 9, to satisfy irrigation requirements. On July 9, a circuit breaker in the motor control box tripped, with no apparent cause. After investigating, ranch personnel reset the circuit breaker and continued operation. On July 10, Battelle staff arrived and found the motor inoperative.

The motor supplier was contacted, and his personnel found a manufacturing defect. The motor was replaced on July 14, with operation continuing on a solar-only basis from July 10 to July 14.

Irrigation Pump Inspection. On July 21, the irrigation pump sounded unusually noisy, and on July 22, a circuit breaker for the electric motor tripped when the pump was operated. Troubleshooting indicated high current draw: operations continued on a satisfactory basis on solar only, but the noises continued. On August 8, the pump was removed for repair. When the pump was removed, a collapsed inlet screen was found, which may have been responsible for cavitation and a higher actual pumping head than anticipated. On August 17, after checkout at the supplier, the pump was reinstalled in the field. Very high current draw was noted when operation was initiated, and the motor circuit breaker again tripped. It was found that on reassembly of the pump, a key included to prevent rotation of the shaft retention nut had not been replaced, and the shaft nut had tightened, binding the pump. The pump was again removed and returned to the supplier for repair. The irrigation pump was finally reinstalled on August 22, without the inlet screen, which was felt to be the cause of the initial problem.

Postponement of Remaining Conversion Tasks. The unanticipated problems with the tracking system, the turbine, the electric motor, and the irrigation pump adversely affected operating time. Attempts to resolve the turbine gear box leakage problem would further reduce operating time. A decision was made, therefore, by Battelle and the Sponsors to place emphasis on obtaining operating time and not to complete the hybrid conversion task.

Current Status and Operating Characteristics

The electric motor, gear box and irrigation pump are installed and operating satisfactorily. The boost pump and variable speed transmission have not been installed. and the oil leak in the turbine has not been corrected. Therefore, the system can operate on solar power alone or electric power alone; it cannot operate in the hybrid mode.

Operation on solar power alone has not, to date, resulted in rapid loss of oil from the turbine gear box. However, given the consequences of such a loss, the oil level in the turbine gear box should be monitored at frequent intervals when running at high power levels.

Task 5: Instrumentation, Data Collection, and Data Transmission

Reviewed below are those portions of Task 5 related to modification of sensors, instrumentation, and data collection hardware, and to development of capability for direct data transmission. Portions of Task 5 related to development of data analysis capabilities are discussed under the heading "Data Analysis Program".

Systems Status - End of 1977

The instrumentation and data collection systems in place at the end of 1977 were organized to provide raw data suitable for manual analysis or possible future computer analysis. The majority of the measured system parameters were sampled at regular intervals by an automated data logger, while the remaining parameters were periodically sampled manually by field personnel.

Instrumentation sensors were in place to monitor the collector field, the skid mounted power package, the environment and the system output. Table 3 lists the components which were in place during the 1977 and 1978 programs.

Collector Field Sensors. The instrumentation in place on the collector field monitored water flow to the field, water temperatures at the inlet and outlet of the collector field, water temperatures at the inlet and outlet of each collector row, and pressure in the collector water loop.

Skid Package Sensors. The skid package was instrumented to record temperatures of collector water in and out of the skid package heat exchangers, temperatures and pressures around the Freon loop, Freon flow rate through the feed pump, and cooling water temperature at the inlet and the outlet of the condenser. The speeds of the turbine gear box output shaft and of the Freon feed pump were also recorded. An elapsed-time meter indicated total hours of operation.

TABLE 3. INSTRUMENTATION SYSTEM COMPONENTS

Table 3a. Sensors

1977	1978	Location/Parameter	Number of Sensors	Component Description	Comments
		Collector Field			
•	•	Water flow to field	1	Barco #BR12480-40-31, Setra #228	Manually read in 1977, 1978, using magnehelic gage #5005. Setra transducer added 1978, but not operational.
	•	Water flow through each row	9	Barco Venturi #448, Barco Master Meter, 0-100"	Manually read in 1978, using Barco meter.
•	•	Water temp., in/out of field	2	Type K thermocouple	
•	•	Water temp., in/out each row	18	Type K thermocouple	
•	•	Water loop pressure	1	Bell & Howell #4-326-0001	
		Skid Package			
•	•	Water temp., boiler inlet	1	Type K thermocouple	
•	•	Water temp., boiler outlet	1	" " "	
•	•	Water temp., preheater outlet	1	" " "	
•	•	Water temp., expansion tank	1	" " "	
•	•	Water temp., condenser inlet/outlet	2	" " "	
•	•	Freon temp., between each component	12	" " "	
•	•	Oil temp., turbine gear box	1	" " "	
•	•	Freon pressure, preheater inlet	1	Bell & Howell #4-326-0001	
•	•	Freon pressure, boiler outlet	1	Bell & Howell #4-326-0001	
•	•	Freon pressure, turbine inlet	1	Bell & Howell #4-326-0001	
•	•	Freon pressure, turbine exhaust	1	Bell & Howell #4-326-0003	
•	•	Freon pressure, condenser	1	Bell & Howell #4-326-0003	

Table 3a. Sensors (Continued)

1977	1978	Location/Parameter	Number of Sensors	Component Description	Comments
•	•	Freon flow rate, through feed pump	1	Barco #BR12427-24-31. Setra #228	Manually read in 1977, 1978, using Barco Master Meter. Setra transducer added in 1978, but not operational
•	•	Output-shaft speed	1	Madison #300-4-RPM-1800	Shaft encoder and digital-to-analog converter prepared, but not installed.
•	•	Feed pump speed	1	Biddle hand-held tachometer	Manually read. Shaft encoder and digital-to-analog converter prepared, but not installed.
	•	Output-shaft torque	1	Lebow #1228-H-2K Daytronix #878 AC signal conditioner	
•	•	Total operating hours	1		Manually read
		<u>Environment</u>			
•	•	Ambient temperature	1	Type K thermocouple	
•	•	Instrument temperature	1	" " "	
•	•	Wind velocity	1	Maximum #41 anemometer	
•	•	Total radiation	1	Epply pyranometer Model PSP	Horizontal surface
•	•	Diffuse radiation	1	Ditto	Horizontal surface, shawdow-band
•		Sun elevation east	1	Shadow post	Manually read
•		Sun elevation south	1	Shadow post	Manually read
		<u>Irrigation Pump Outlet</u>			
•	•	Irrigation water flow	1	Brooks #11-4B04-04	Instantaneous flow rate and total flow--manually read
•	•	Water level in sump	1	Float line	Manually read

Table 3a. Sensors (Continued)

1977	1978	Location/Parameter	Number of Sensors	Component Description	Comments
•		Static pressure at pump	1	Manometer	Manually read
•		Static pressure at fence	1	Manometer	Manually read
		50 HP Electric Motor			
	•	Electrical power draw	1	OSI #PC5-54C Watt transducer	

Table 3b. Data Collection and Transmission Hardware

1977	1978	Item	Number of Components	Component Description	Comments
•	•	Data Logger	1	Esterline-Angus PD2064	• 64 channel capacity • Direct conversion of thermocouple output to engineering units • Paper tape output • Programmable sampling interval • Alarm network added in 1978 • Non-volatile memory added in 1978
•	•	Digital cassette recorder	1	Techtran #815	
	•	Computer Terminal	1	Techtronix Silent 700	300 BAUD transmission rate
	•	Modem	1	A-J #242 Acoustic Coupler	

Environment Sensors. The environment of the solar irrigation pumping system was instrumented for ambient temperature, wind speed, total radiation, diffuse radiation, solar angle, and standard time and date.

System Output Sensors. The output of the irrigation pump was instrumented for lift height, dynamic head, irrigation flow rate, and irrigation total flow.

Data Collection Hardware. The output of the instrumentation system was sampled at programmed intervals, or on demand, by the data logger. The resulting channels of data were printed onto paper tape and recorded on magnetic tape. The magnetic tape cassettes were mailed back to Battelle for future use.

Desired Improvements

A number of improvements were sought, including (a) sensors for individual collector evaluation, (b) sensors for measurement of skid package output and for evaluation of hybridization, (c) improved sensor performance and conversion of manually sampled data to automatic sampling, (d) improved data logger performance, and (e) capability for immediate transfer of data between the site and Columbus, Ohio.

Collector Evaluation Capability. Additions to the instrumentation and data collection system were required to allow for evaluation of collector performance. The system in place in 1977 was capable only of measuring flow rate through the entire collector field; to evaluate accurately the performance of individual collectors, it was necessary to measure the flow rate through each collector row.

Hybrid Skid Package Evaluation Capability. Additional instrumentation was also required for evaluation of the skid package. Since irrigation flow is not a meaningful performance measurement in the hybrid mode, sensors were required to measure the output of the skid package in terms of shaft horsepower, and instrumentation was needed for measuring the electrical power drawn by the 50 HP electric motor. Also, since modifications to the skid package involved control of the feed pump flow rate, evaluation required automated instrumentation for monitoring feed pump speed.

Upgrading and Automation of Sensors. Several improvements were required to correct shortcomings found in 1977 instrumentation.

The tachometer used to measure skid package output-shaft speed had not been fully satisfactory because the output of the transducer carried significant ripple and some offset at low rpm.

Both the collection of complete, accurate and consistent data, and the need for unattended monitoring required that all important parameters be automatically recorded. The flow rate of collector water into the field and the flow rate of Freon through the skid package were recorded manually in the 1977 version of the system; these parameters needed to be instrumented for automatic recording. Since the output of the skid package would be measured directly as shaft horsepower, irrigation flow parameters would be of decreased importance and would continue to be recorded manually. In 1977 sun angle had been recorded for easy manual verification of the analysis procedure; this was discontinued in 1978.

Data Logger Expansion. In order to improve the effectiveness of its operation, additions to the data logging device were required. A nonvolatile memory was needed to avoid the necessity of reprogramming the data logger in the event of a power interruption (a fairly common occurrence). An alarm network was available for the data logger which would provide added safeguards on system operation, and allow a lesser degree of operator attention to system performance indicators.

Data Transmission Capability. To make full use of the computer data analysis program described below, capability for rapid transmission of information was required. Daily transmission of recorded data and return transmission of analysis results (with 24 hour turn around, and interactive capabilities) would allow on-site operators to verify, correct, or modify equipment in "real time". Hardware was required to allow rapid transfer of information between magnetic tape cassettes at the site and computer memory at Battelle's Columbus, Ohio facility.

System Description - 1978

The automated instrumentation, data collection and data transmission systems installed during 1978 included all of the functions incorporated in the automated portion of the 1977 instrumentation and data collection systems plus the capabilities addressed in the section above.

Venturi meters were added at the output of each collector row so the flow rates through the collector rows could be read manually with a differential pressure gauge. This allowed periodic readings to determine the division of flow between the nine parallel collector rows.

Several additions were made to evaluate the hybrid skid package. A torque transducer and an AC signal conditioner were added to monitor output shaft torque. This transducer gives an instantaneous reading of shaft torque which may be combined with shaft rpm to calculate output shaft horsepower. The AC excitation of the torque transducer minimizes slip ring noise and reduces transducer maintenance requirements. A power transducer was installed on the 50 HP motor, to indicate the instantaneous electrical power drawn by the electric motor. Feed pump speed was to be sensed using a digital shaft encoder and a digital-to-analog converter, producing an analog signal suitable for input to the data logging device; this hardware was completed and ready for installation at the end of the 1978 program, but it was not installed since the hybridization was not completed.

Several additional improvements were planned to overcome shortcomings of the equipment used in 1977. Digital hardware, similar to that for measuring feed pump shaft speed, was to measure skid package output shaft speed. Hardware was purchased, and ready for installation, but implementation was delayed until the other hybrid components are installed, since a common signal conditioning unit is used for both circuits. Manual recording of the collector water flow rate and the Freon flow rate was to be replaced by the use of automated differential pressure sensing devices. Two differential pressure transducers were purchased and installed to sense the pressure drop across venturis in the collector water loop and the Freon loop. Problems arose with the use of these differential pressure transducers, however; one was defective at installation. After extensive field testing, the unit was returned to the factory for evaluation, and repair or replacement. At the end of the 1978 program, the unit had not yet been returned. Also, the frequency response of both transducers was extremely high, resulting in spurious inputs to the data logger. A signal conditioning unit. incorporating low pass filters to remove the spurious signals, was developed. Initial problems with these new filters, resulting from ground loops, required extensive troubleshooting.

Since more direct methods of measuring skid package power output were used, as described above, measurement of irrigation flow rate, sump water level, and total irrigation flow were manually recorded as convenient verifications. Measurements of dynamic head and solar angle were discontinued for 1978.

A nonvolatile memory was added to the data logging system, to prevent program loss in the event of power failure. An alarm network was also added, which monitored selected channels at each programmed scan, and gave a dual level alarm: high, higher; high, low; low, lower. This alarm network adds the capability of sounding an alarm when a problem is indicated, or of sending a fault signal to the system control logic when a failure is imminent.

Table 3 summarizes the configuration of the instrumentation, data collection and transmission systems at the end of 1978.

Figure 10 illustrates the flow of data from on-site instrumentation, through data analysis, to operator feedback. As in 1977 a

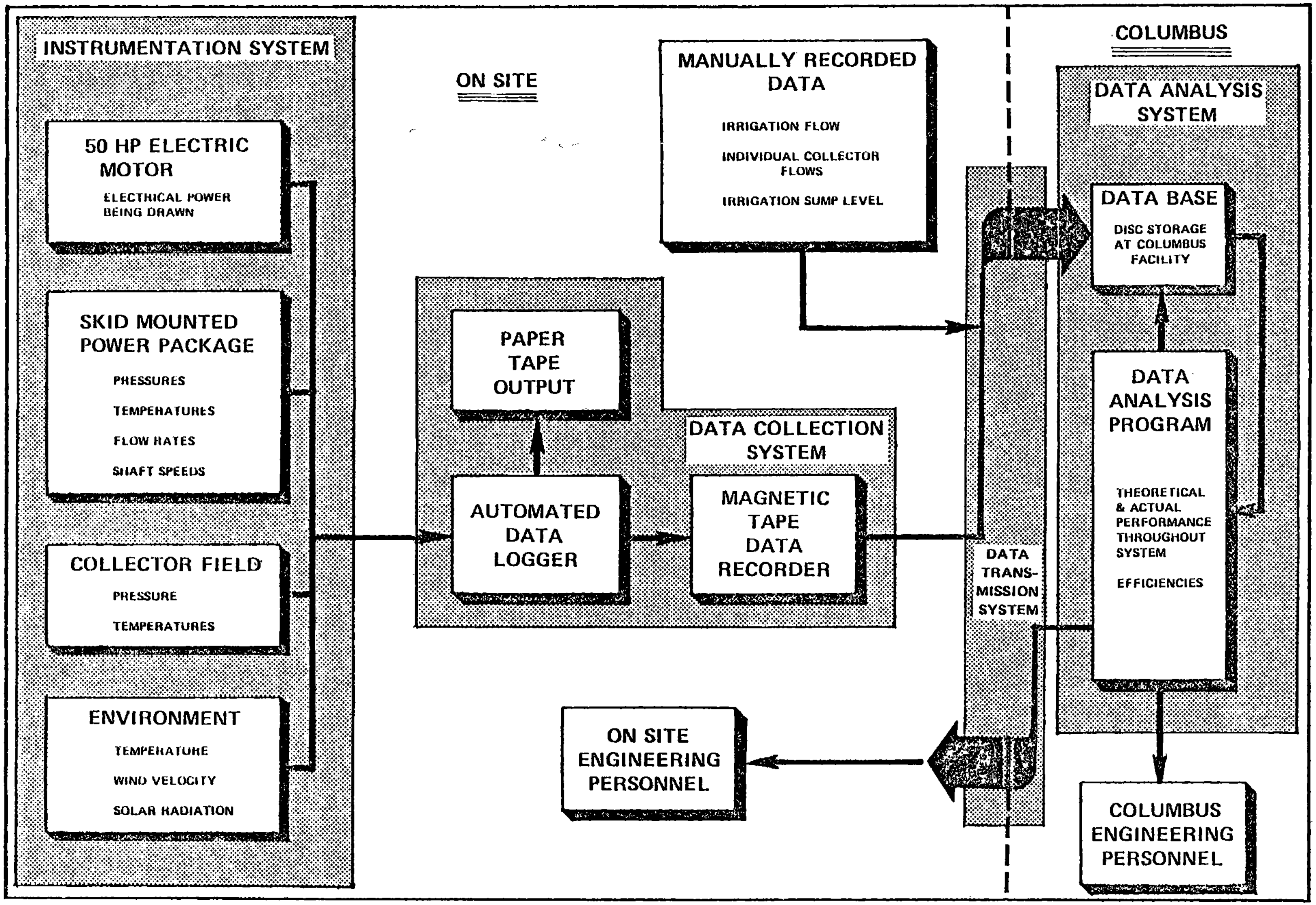


FIGURE 10. INSTRUMENTATION, DATA COLLECTION, TRANSMISSION AND ANALYSIS SYSTEMS: 1978

digital cassette recorder was utilized, in parallel with the paper tape output device, to provide a data recording format suitable for direct computer utilization. Instead of mailing these cassettes and then manually analyzing data, a portable computer terminal and a modem device were acquired to transmit data directly to Columbus computer facilities for analysis. Further details on the transmission and processing of data are included in the section entitled "Data Analysis Program".

Task 5: Data Analysis Program

Operating data on the solar irrigation pump provides

- A means of monitoring system performance
- A historical record of system performance.

Since the solar irrigation pump is self-regulating, the operator does not need system information to "operate" the pump. Rather, he utilizes such information to evaluate the effect of minor adjustments or changes to the system and to indicate the need for initiating corrective actions which have not yet been automated, such as bleeding air from the condenser, replenishing working fluid, or backflushing the check valve in the condenser-cooling-water supply. A log of long-term system performance information provides the project engineer and system designers with a basis for initiating major system changes to improve performance and evaluating the effect of such actions.

A historical record of system performance provides information for relative comparison of the performance of the system with conventional systems and with other solar irrigation systems.

Description of the Data Analysis Procedures at the End of 1977

During the first year of operation, data reduction was conducted with programmable calculators by the on-site engineer or operator. The data logger selected for recording performance data printed temperatures in engineering units on a paper tape. Other values were displayed as voltage signals; meaningful values in engineering units were obtained from these voltages by multiplication with appropriate calibration factors.

Calculation sheets were prepared to aid in the calculation of significant performance parameters which required consideration of multiple input values. Property values for the working-fluid and heat-transfer media were obtained by manual interpolation of tabulated property values. The effort required for calculation of some system parameters, such as power-system efficiency and solar collection efficiency, was substantial even with the aid of a programmable calculator.

Need for Automating the Data Analysis Procedures

The need for an automated data analysis procedure was based on cost and time constraints. The large volume of data (approximately 65 values at 20 minute intervals throughout each operating day) and the relatively complex analysis required (interpolation of property valves, many intermediate calculations for flows, etc.) made complete manual analysis prohibitively expensive. Also, it was felt that the operator and/or project engineer would benefit from timely access to the analysis results, and experience showed that the time lag involved in manual analysis was unacceptably long. To achieve the rapid turnaround desired, and to allow complete analysis of the recorded data, the automated analysis procedure described in the next section was prepared.

Description of the Data Analysis Program

The data analysis procedures were set up to utilize the large computer installation at Battelle's facility in Columbus, Ohio. Data for each day was read from a Techtran cassette recorder into a file on the CDC 6500 computer, using a modulate-demodulate device (modem) and a private telephone line installed in the Paloma Ranch office. Before or after the data on a cassette was transferred, the operator could input any manually recorded data from the keyboard of a Texas Instruments Silent-700 terminal, and key each data-point to an appropriate time-dependent data-point label.

Figure 11 shows a diagram of the data-analysis procedures. Computer programs to accomplish these procedures include:

- One large program (approximately 2000 source cards) for all operations above the dashed line on Figure 11
- A program to store the sorted input data and processed output data in a conveniently accessible random-access data base
- A program to retrieve up to 15 columns of data for a series of consecutive data points. (Data from

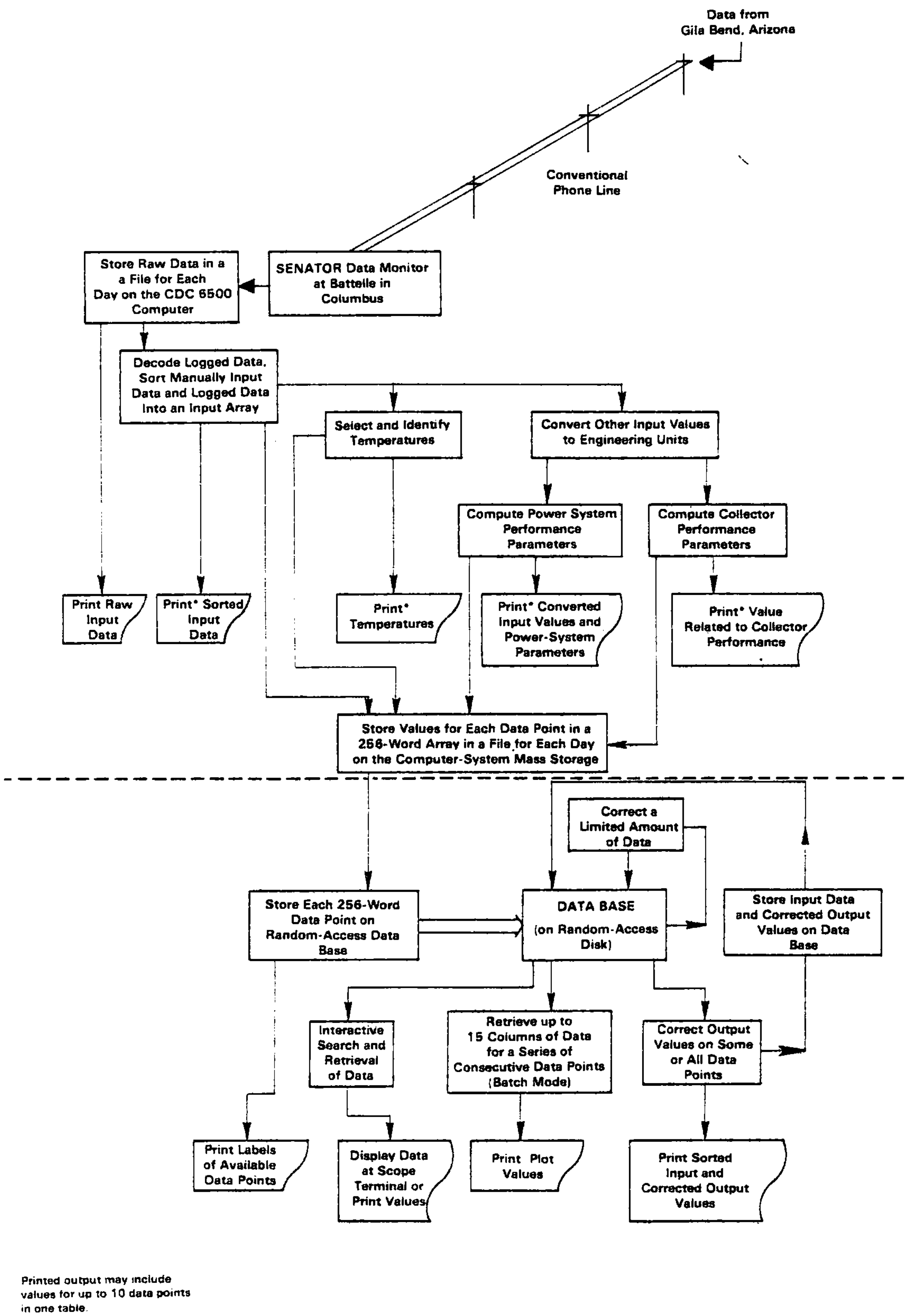


FIGURE 11. FLOW CHART: DATA-ANALYSIS PROCEDURES

some or all of the data points on the data base can easily be retrieved with this program.)

- A program to permit interactive search and retrieval of data
- A program to correct a limited amount of data
- A program to correct output values on some or all data points in the data base.

Equations used in the data analysis section of the program are provided i·, Appendix B. The text with these equations provides an explanation of the use of periodically input values. All property data for the working fluid (Freon R113), the collector heat-transfer media (water-additive mixture), and the pumped water are accessed by one or two-dimensional polynomial equations (fitted to the data by least squares regression analysis), so as to fully automate the analysis by eliminating manual interpolation from tabulated values.

Description of the Information Available

Measured or calculated parameters which are stored on the data base include: pressures, temperatures and flows throughout the system; insolation and weather data; temperature differentials, heat transfer rates, and mechanical and electrical powers; and efficiencies. These parameters quantitatively record the performance of the solar irrigation pumping system at twenty minute intervals throughout the operating day, or at times when data collection was initiated manually.

A typical example of the standard three-page output of the analysis program is shown in Tables 4-6. Measured and calculated values are printed as a tabulation versus time-code. Raw input data and sorted input data are also printed with each analysis (see Appendix, Tables A-1 and A-2).

Description of Program Capabilities

Cataloged procedures are used to analyze and store data to minimize the labor required to process the daily input. If desired, the

PAGE NO 1

DESCRIPTION /TIME	06231000	06231020	06231040	06231100	06231118	06231120	06231140	06231200	06231220	06231240
R-113 FLUID TEMPERATURES,F										
TURBINE INLET	235.7	243.0	241.7	246.3	248.2	237.3	255.5	259.2	260.4	263.9
TURBINE OUTLET (NO 1)	170.1	178.2	178.5	182.1	183.8	177.1	189.2	0.0	193.2	196.5
TURBINE OUTLET (NO 2)	170.3	177.8	176.3	180.6	182.9	177.1	187.2	190.1	192.7	195.4
REGENERATOR OUTLET (VAPOR)	107.4	112.5	114.5	116.7	118.4	116.2	120.8	122.5	123.7	125.2
CONDENSER OUTLET (LIQUID)	88.0	90.7	91.6	92.4	92.9	92.5	93.9	95.0	95.6	96.6
FEEDPUMP INLET	89.0	91.7	92.6	93.4	94.2	94.2	95.1	96.0	96.8	97.7
REGENERATOR INLET (LIQUID)	89.0	91.6	92.4	93.5	94.2	94.1	95.1	96.0	96.7	97.6
PREHEATOR INLET (LIQUID)	133.8	138.7	139.3	140.6	142.4	137.5	144.0	146.0	147.7	149.4
PREHEATOR OUTLET (LIQ+VAP)	228.0	232.7	231.2	235.4	236.3	224.9	243.5	247.2	246.8	248.6
BOILER OUTLET (VAPOR)	240.5	248.5	248.1	251.6	253.3	237.2	261.1	265.6	264.9	269.1
WATER TEMPERATURES,F										
CONDENSER INLET	78.9	79.0	79.3	79.4	80.1	80.2	80.6	80.8	81.6	82.5
CONDENSER OUTLET	84.2	87.1	88.2	89.1	90.0	89.0	91.4	92.4	93.5	94.5
WATER-ETHYLENE GLYCOL TEMPS,F										
BOILER INLET	[illegible]	254.2	251.8	256.2	250.7	254.0	268.1	271.0	273.5	275.2
BOILER OUTLET	234.0	239.6	236.8	242.1	245.2	230.7	253.0	257.4	259.9	261.5
PREHEATER OUTLET	228.9	234.8	233.9	236.8	239.9	225.3	246.9	250.9	253.1	254.2
EXPANSION TANK	183.5	175.0	136.7	144.9	148.8	169.0	198.6	164.6	157.2	149.0
COLLECTOR FIELD INLET	227.5	234.1	235.8	237.9	239.1	236.0	245.2	249.8	253.0	254.0
NO 1 COL ROW INLET	119.5	123.1	123.4	125.1	127.6	127.7	128.1	128.6	131.4	131.9
NO 2 COL ROW INLET	125.6	130.2	131.7	133.8	206.2	234.7	243.6	245.5	249.3	251.3
NO 3 COL ROW INLET	222.2	228.9	231.8	232.9	236.2	235.9	243.4	245.3	250.1	251.4
NO 4 COL ROW INLET	224.7	230.8	233.4	235.0	236.6	237.0	243.5	246.6	250.5	251.7
NO 5 COL ROW INLET	225.3	231.1	233.8	235.4	237.2	237.5	243.6	246.8	251.3	252.3
NO 6 COL ROW INLET	225.1	231.7	234.0	235.3	237.3	237.2	244.0	247.1	251.6	252.5
NO 7 COL ROW INLET	224.7	230.7	233.0	234.0	236.5	236.5	243.0	246.3	250.8	251.9
NO 8 COL ROW INLET	224.9	230.8	233.1	234.7	235.9	236.3	242.5	246.6	250.7	251.6
NO 9 COL ROW INLET	224.9	231.6	232.9	234.5	236.5	235.7	242.6	246.7	250.4	251.6
NO 1 COL ROW OUTLET	118.9	121.9	121.9	123.1	125.1	125.2	125.6	125.5	126.9	128.9
NO 2 COL ROW OUTLET	119.9	122.9	120.9	121.0	128.5	226.9	263.7	266.6	269.9	273.4
NO 3 COL ROW OUTLET	241.7	249.4	248.5	251.0	255.1	259.8	265.6	267.0	269.4	272.2
NO 4 COL ROW OUTLET	244.6	250.9	248.4	252.5	255.8	261.8	266.4	267.2	270.1	273.2
NO 5 COL ROW OUTLET	247.5	253.2	251.0	254.9	257.6	263.5	268.9	269.3	272.8	275.1
NO 6 COL ROW OUTLET	249.9	256.3	253.2	257.8	260.6	267.3	271.5	271.6	275.6	278.4
NO 7 COL ROW OUTLET	246.8	254.6	250.9	256.4	258.2	265.4	269.0	268.1	271.8	275.9
NO 8 COL ROW OUTLET	248.0	254.9	251.7	255.7	258.5	264.3	268.2	269.5	273.4	274.0
NO 9 COL ROW OUTLET	245.5	251.7	249.4	253.2	256.0	259.6	264.9	266.5	270.6	271.5
MISCELLANEOUS TEMPERATURES,F										
RUPTURE DISC (LOW)	104.9	108.6	110.7	114.0	116.5	116.3	118.5	119.7	118.5	118.7
RUPTURE DISC (HIGH)	219.6	221.9	221.2	225.3	227.6	218.0	231.6	233.3	234.0	237.6
INSTRUMENT AMBIENT	87.1	86.1	88.7	87.1	86.5	86.5	86.2	86.1	85.6	86.2
TURBINE GEARBOX NO 1	174.6	188.8	194.6	200.0	203.7	202.9	207.7	211.1	210.2	212.1
BLANK	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BLANK	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BLANK	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 4. TYPICAL PAGE 1 OUTPUT

PAGE NO 2

DESCRIPTION /TIME	06231000	06231020	06231040	06231100	06231118	06231120	06231140	06231200	06231220	06231240
PRESSURES										
PREHEATER INLET, PSIA	80.6	85.9	84.4	87.9	90.7	79.4	96.4	102.7	101.4	102.0
BOILER OUTLET , PSIA	76.9	81.5	80.8	83.9	85.8	75.3	93.5	95.3	97.8	98.6
TURBINE INLET , PSIA	78.0	82.8	82.2	85.1	87.2	76.6	94.7	97.7	98.9	99.8
TURBINE EXHAUST, PSIA	8.8	9.5	9.7	9.8	10.1	9.6	10.5	10.9	11.2	11.5
CONDENSER , PSIA	8.8	9.6	9.7	9.9	10.2	9.7	10.6	11.0	11.3	11.6
EXPANSION TANK , PSIA	73.3	75.4	75.5	76.6	77.4	77.8	81.1	82.0	83.1	83.4
LIQUID LEVEL,FT										
TAILPOND SUMP	9.5	9.5	9.5	9.5	9.5	9.5	9.3	9.3	9.3	9.3
R-113 FLOWS										
FLOW-VENTURI ,LB/MIN	0.0	0.0	112.6	0.0	0.0	0.0	133.3	0.0	0.0	0.0
TURBINE-NOZZLE ,LB/MIN	107.4	113.3	112.6	116.1	118.9	105.3	128.5	132.1	133.7	134.6
FP FLOW/TUR NOZ FLOW	0.0	0.0	99.9	0.0	0.0	0.0	103.7	0.0	0.0	0.0
FEEDPUMP (ACTUAL) ,GPM	0.0	0.0	8.8	0.0	0.0	0.0	10.4	0.0	0.0	0.0
FEEDPUMP(100 PCT V.EFF),GPM	11.1	11.4	11.5	11.7	11.9	10.8	12.7	12.7	12.8	12.8
FEEDPUMP VOL EFFCY,PCT	0.0	0.0	99.2	0.0	0.0	0.0	99.9	0.0	0.0	0.0
COLLECTOR FLOW,GPM	42.6	38.9	49.9	35.9	42.9	41.4	55.4	49.6	53.1	54.7
WATER FLOWS ,GPM										
IRRIGATION-PUMP	0.0	0.0	4200.0	0.0	0.0	0.0	5500.0	0.0	0.0	0.0
CONDENSER-COOLING	127.1	75.3	83.9	56.9	33.0	118.5	92.1	26.3	75.5	79.9
WEATHER DATA										
AMBIENT TEMP, F	100.7	99.4	100.7	101.8	102.3	103.0	103.8	104.4	107.2	107.5
WIND VELOCITY,MPH	.2	.3	.3	.2	.3	.2	.2	.2	.3	.2
SOLAR RADIATION,BTU/(HR-FT2)										
H TOTAL (HORIZ)	246.6	255.8	265.7	277.2	281.3	284.1	290.1	295.6	299.0	300.6
H DIFFUSE (HORIZ)	32.2	30.8	38.3	32.1	30.1	31.6	28.2	28.7	29.4	28.3
R-C SOLAR POWER SYSTEM										
OUTPUT SHAFT SPEED, RPM	1239.8	1270.0	1280.0	1299.9	1318.1	1195.8	1410.0	1409.9	1415.9	1413.1
OUTPUT TORQUE, LB-FT	88.6	88.0	86.7	89.6	90.8	81.6	98.7	102.1	102.5	101.4
OUTPUT POWER, HP	20.9	21.3	21.6	22.2	22.8	18.6	26.5	27.4	27.6	27.3
ELECT AUX POWER INPUT,KW										
50-HP MOTOR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IRRIG PUMP HYDRAULIC POWER,HP	0.0	0.0	10.1	0.0	0.0	0.0	12.9	0.0	0.0	0.0
TEMPERATURE DIFFERENTIALS,F										
BOILER (E.G.-WATER)	14.0	14.4	13.0	14.1	5.5	23.3	15.1	13.6	13.6	13.7
PREHEATER (E.G.-WATER)	5.1	5.0	4.9	5.3	5.3	5.4	6.1	6.5	6.8	7.3
BOILER + PREHEATER	19.1	19.4	17.9	19.4	10.8	28.7	21.2	20.1	20.4	21.0
CONDENSER (WATER)	5.3	8.1	8.9	9.7	9.9	8.8	10.8	11.6	11.9	12.0
IDEAL CONDENSER PRESS,PSIA	8.2	8.7	8.9	9.0	9.1	9.0	9.3	9.5	9.6	9.8
EXCESS CONDENSER PRESS,PSI	.6	.9	.8	.9	1.1	.7	1.3	1.5	1.7	1.8
HEAT TO BOILER,BTU/SEC	108.5	110.1	118.5	92.2	61.4	158.0	155.6	131.9	143.3	151.9
HEAT REJECTED IN COND,BTU/SEC	93.4	84.5	103.5	76.4	45.3	144.5	137.8	42.3	124.5	132.8
TURBINE POWER(INTERNAL),HP	21.4	22.1	21.3	22.4	22.9	19.1	25.2	126.8	26.6	27.0
TURBINE EFFICIENCY,PCT	60.7	59.4	58.2	58.3	58.3	57.5	57.9	283.5	59.0	59.7
POWER SYSTEM EFFCY,PCT	14.0	15.6	12.7	17.1	26.3	8.5	11.4	67.9	13.1	12.6
POWER SYS+IRRIG PUMP EFFCY,PCT	0.0	0.0	6.0	0.0	0.0	0.0	5.8	0.0	0.0	0.0
DT COND(R113 O-WATER O),F	3.6	3.6	3.4	3.3	2.9	3.5	2.5	2.6	2.1	2.1
DH SEPARATOR(PCT OF DHACT)	-.2	-.3	-.3	-.3	-.3	-.3	-.3	-.1	-.3	-.4
BLANK	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BLANK	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 5. TYPICAL PAGE 2 OUTPUT

PAGE NO 3

DESCRIPTION	/TIME	06231000	06231020	06231040	06231100	06231118	06231120	06231140	06231200	06231220	06231240
NUMBER OF ACTIVE COL ROWS		7.0	7.0	7.0	7.0	7.0	8.0	8.0	8.0	8.0	8.0
COLLECTOR-FIELD FLOW,LB/MIN		345.8	313.7	402.5	288.8	345.2	335.3	444.7	397.3	424.9	437.4
HB NORM TO SUN,BTU/(HR-FT2)		254.3	261.9	254.4	265.6	265.9	266.7	271.3	272.9	273.8	276.3
HBN NORM TO APER		253.9	261.0	253.0	263.6	263.4	264.0	268.2	269.3	270.0	272.4
HEAT INC ON COL ROW,BTU/SEC		46.7	48.0	46.5	48.5	48.4	48.6	49.3	49.5	49.7	50.1
(TOUT-TIN),F	ROW										
DELTA T	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DELTA T	2	0.0	0.0	0.0	0.0	0.0	-5.8	20.1	21.1	20.6	22.1
DELTA T	3	19.5	20.5	16.7	18.1	18.9	23.9	22.2	21.7	19.3	20.0
DELTA T	4	19.9	20.1	15.0	17.5	19.2	24.6	22.9	20.6	19.6	21.5
DELTA T	5	22.2	22.1	17.2	19.5	20.4	26.0	25.3	22.5	21.5	22.8
DELTA T	6	24.8	24.6	19.7	22.5	23.3	30.1	27.5	24.5	24.0	25.9
DELTA T	7	22.1	23.9	17.9	22.4	21.7	28.9	26.0	21.8	21.0	24.0
DELTA T	8	23.1	24.1	18.6	21.0	22.6	28.0	25.7	22.9	22.7	22.4
DELTA T	9	20.6	20.1	16.5	18.7	19.5	24.1	22.3	19.8	20.2	19.9
DELTA T	AVG	21.7	22.2	17.3	20.0	20.8	22.5	24.0	21.9	21.1	22.4
DELTA T	FIELD	20.5	20.1	16.0	18.3	11.6	16.0	22.9	21.2	20.5	21.2
COL ROW FLOW ,LB/MIN											
FLOW	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FLOW	2	0.0	0.0	0.0	0.0	0.0	41.9	55.6	49.7	53.1	54.7
FLOW	3	49.4	44.8	57.5	41.3	49.3	41.9	55.6	49.7	53.1	54.7
FLOW	4	49.4	44.8	57.5	41.3	49.3	41.9	55.6	49.7	53.1	54.7
FLOW	5	49.4	44.8	57.5	41.3	49.3	41.9	55.6	49.7	53.1	54.7
FLOW	6	49.4	44.8	57.5	41.3	49.3	41.9	55.6	49.7	53.1	54.7
FLOW	7	49.4	44.8	57.5	41.3	49.3	41.9	55.6	49.7	53.1	54.7
FLOW	8	49.4	44.8	57.5	41.3	49.3	41.9	55.6	49.7	53.1	54.7
FLOW	9	49.4	44.8	57.5	41.3	49.3	41.9	55.6	49.7	53.1	54.7
COL ROW EFFCY ,PCT	ROW										
EFFCY	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EFFCY	2	0.0	0.0	0.0	0.0	0.0	-8.2	37.4	34.9	36.4	39.9
EFFCY	3	33.9	31.5	33.9	25.4	31.7	33.9	41.3	35.9	34.1	37.5
EFFCY	4	34.6	30.9	30.5	24.5	32.2	35.1	42.6	34.1	34.7	38.8
EFFCY	5	38.6	33.9	35.0	27.3	34.2	36.8	47.1	37.3	36.0	41.1
EFFCY	6	43.1	37.6	39.0	31.5	39.1	42.6	51.2	40.6	42.4	46.7
EFFCY	7	38.4	36.7	38.4	31.4	35.4	40.9	48.4	35.1	37.1	43.3
EFFCY	8	40.1	37.0	37.8	29.4	37.9	39.7	47.8	37.9	40.1	40.4
EFFCY	9	35.8	30.9	33.5	26.2	32.7	34.1	41.5	32.8	35.7	35.9
EFFCY	AVG	37.8	34.1	35.2	28.0	34.9	31.9	44.6	36.2	37.3	44.5
EFFCY	FIELD	36.1	31.3	32.9	26.0	19.7	23.0	43.0	35.4	36.5	38.6
AVG VALUES											
COL OUT TEMP,F (AVG)		246.3	253.0	250.4	254.5	257.4	258.9	267.5	268.2	271.7	274.2
COL IN TEMP,F (AVG)		224.5	230.8	233.1	234.5	236.6	236.4	243.3	246.4	250.6	251.8
FIELD VALUES											
COL OUT TEMP,F (FIELD)		248.0	254.2	251.8	256.2	250.7	254.0	268.1	271.0	273.5	275.2
COL IN TEMP,F (FIELD)		227.5	234.1	235.8	237.9	233.1	238.0	245.2	249.8	253.0	254.0
DT OUT(AVG-FIELD),F		-1.7	-1.2	-1.4	-1.7	6.7	4.8	-.8	-2.8	-1.8	-1.0
DT IN(FIELD-AVG),F		3.0	3.3	2.7	3.4	2.5	1.7	1.9	3.4	2.4	2.2

TABLE 6. TYPICAL PAGE 3 OUTPUT

data analysis and storage programs can be automatically initiated to process any new data on file each day at 11:00 p.m., using cataloged procedures.

A second analysis program was prepared for time-sharing use at terminals within Battelle or at the terminal at Gila Bend, for timely feedback of analyzed data to the operator or project engineer. Also, an interactive data retrieval program was prepared for use by the operator at Gila Bend for printing portions of data for any historical data point in the data base.

Optional analysis features are available for the following purposes:

- To limit the printed output to any or all of the pages shown in Tables 4 through 6. This feature is particularly useful when printing data at a time-sharing terminal--for example, to surpress the printing of all the raw input data
- To limit the analysis to selected data points within any daily file. This feature is particularly useful for limiting the printout at a time-sharing terminal to interesting data points such as in the vicinity of maximum power for the day
- To specify the number and identity of active collector rows
- To manually read data into the daily file along with the logged data
- To revise channel numbers changed as a result of instrumentation failure.

In addition, secondary options are available for automatically accommodating collector-row information or manually input data entered in the file along with the logged data. These two features have made it possible to add to the daily files all information unique to the data in the file and thereby limit the unique input data required when processing the data to a value for the month in which the data were recorded. Data for any day on file can then be reprocessed at any time without concern for inputting collector-row information or manually input data associated with the data, because it is already on the file and will be utilized in processing the data.

A major effort was expended to eliminate all known bugs in the data analysis program before setting up the data base, to ensure that only correct data was stored. However, well into the year, after considerable data was entered into the data base, errors in the solar radiation calculations and in property values at the inlet to the turbine were discovered. A program was written to correct these errors on all the data on the data base and rebuild a corrected data base. This program accessed the decoded and sorted input data on the data base to reduce the computing time associated with character conversion and sorting. Other corrections to stored data can be made in the future, if needed, with relatively little effort by making minor changes in this program.

A procedure for retrieving historical data from the data base using the terminal at Gila Bend was prepared. The program retrieves any number of specific rows of data, for any one data point, and prints it in the format as shown in Tables 4 through 6.

Another retrieval procedure, for use at Battelle, was prepared to list, in a single table, the value of up to 15 measured or calculated parameters for any selected set of data points. This program produces tables as shown in Table 7. With minor modification this program can store data for subsequent plotting or sorting. The input data needed is minimized by requiring only the label for the first data point in the table and the number of consecutive data points to be included in the table. Values from a portion or all of the data points in the data base can be easily retrieved with this program.

Utilization of the Data Analysis Program

Examples of printed data from the data-analysis program and from a retrieval program are shown in Tables 4 through 7. Appendix A includes data analysis results for representative time periods, and

FIRST DATA IN LIST IS 09201220

TIMOD,HR	189	190	191	192	193	194	195	196	197	198	199	224
					ARRAY NUMBER							
12.33	16.9	16.2	22.7	22.2	25.6	25.9	23.8	22.9	22.8	22.1	19.3	-.1
12.67	22.0	17.4	22.8	19.8	22.2	22.2	20.6	19.8	20.3	20.6	20.1	-2.9
13.00	20.0	18.1	21.2	18.5	20.2	21.1	20.5	20.0	20.2	20.0	20.1	-3.7
13.33	16.7	13.3	21.3	17.1	19.7	19.7	19.7	18.6	18.7	18.3	20.3	-6.4
13.67	21.7	16.6	22.4	17.7	20.9	22.0	20.6	19.7	20.3	20.2	19.8	-4.1
14.00	21.7	18.9	21.3	17.7	21.2	21.8	20.8	21.0	21.8	20.7	20.6	-3.7
14.33	22.7	18.5	23.5	19.8	19.9	20.6	20.9	20.7	21.9	20.9	21.2	-4.2
14.67	18.0	15.1	21.9	18.5	19.8	21.1	20.5	20.8	23.5	19.9	21.2	-5.3
15.00	17.7	14.4	20.6	15.4	19.7	20.4	19.6	19.3	21.9	18.8	20.7	-5.7
15.33	21.6	17.3	22.4	18.1	22.0	22.6	21.6	21.6	22.4	21.1	20.3	-2.9
15.67	24.3	13.4	24.8	20.2	23.2	24.3	22.3	21.5	22.8	22.5	21.2	-2.5
16.00	16.9	13.1	20.7	14.3	18.9	20.3	16.6	19.3	25.7	18.4	21.5	-6.5
16.33	1.8	2.3	3.1	1.9	4.5	4.0	3.8	4.7	4.9	3.4	12.9	-6.0
16.67	2.7	3.1	3.6	.7	1.5	.6	1.2	1.9	1.9	1.9	9.6	-5.8

189 TO 197-DELTA T FOR COLLECTOR ROWS 1 TO 9,F
198-DT AVG, 199-DT FIELD
224-DT OUT(AVG-FIELD),F 225-DT IN(FIELD-AVG),F

TABLE 7. TABULATED OUTPUT

accompanying comments on the significance of the specific values. Several examples of the application of analysis results to monitoring system performance are also included.

TASK 1: OPERATION AND MAINTENANCE DURING THE 1978 IRRIGATION SEASON

Introduction

Meaningful evaluation of the solar-powered irrigation pumping system is best based on the performance of the system and its subsystems. Interrelationships between components produce results which are not necessarily predicted on the basis of the isolated performance of each component. Task 1 of the program entailed operating and maintaining the system during the 1978 irrigation season to obtain data on required maintenance, hardware life, and component performance.

Two factors should be considered in any long term evaluation of performance. One factor is the total elapsed time since installation, which relates to weathering, corrosion, erosion, etc. The second factor is total accumulated operating time, which relates to wear, thermal cycling, fatigue, component life, deposits, fluid stability, etc. Many components, of course, are affected by both factors; flexible hoses, V-belts, rupture discs, and seals are typical examples.

The economic implications of solar irrigation system maintenance requirements are critical to the overall feasibility of future solar applications. Prior to installation of the Gila Bend facility, no data was available regarding actual maintenance costs for in-service equipment receiving normal agricultural maintenance. The solar powered irrigation system installed at Paloma Ranch has been operated under the care of ranch personnel, although not for extended periods. Both ranch and experimental operating experience indicates that certain conclusions may be drawn regarding requirements for agricultural use.

Accrued Operating Time

The solar-powered irrigation system was installed between February and April of 1977. By the end of the 1977 irrigation season, the system had been operated 323 hours; approximately 73.5 million gallons of water had been pumped. Between April and October of 1978, 188 additional hours of operation were accumulated, and 32.8 million gallons

Table 8. Breakdown of Operating Hours and Downtime: 1978 Irrigation Season

Month	Staffed (days)	Potential[1] Operation (hrs)	Weather[2] (hrs)	Actual[3] Operation(hrs)	Routine[4] Maintenance(hrs)	Repair[5] (hrs)	Modification[6] (hrs)	Business[7] (hrs)
May	13	117.0	7.0	50.0	3.6	31.0	7.0	18.4
June	19	171.0	0.7	60.5	3.0	23.4	57.3[8]	26.1
July	21	189.0	22.0	9.4	0.9	9.9	143.3[9]	3.5
August	19	171.0	9.0	11.0	0.9	132.9[10]	14.5	2.7
September	10	85	8.4	57.1	3.0	6.0	2.0	8.5

(1) As the system was not reliable for unattended operation, potential operation = staffed days x daily potential operating time (9.0 hrs/day, May through August, 8.5 hrs/day in September).

(2) System downtime due to cloud cover.

(3) From hour meter

(4) System downtime for checking oil levels, verifying proper operation, etc. (does not include purging or check valve flushing)

(5) System downtime for repair of in-service equipment

(6) System downtime resulting from installation of modifications.

(7) System downtime resulting when operator off-site for communications, etc.

(8) Installation of electric motor, gear box, and irrigation pump.

(9) Installation of tracking system.

(10) Repair of pump and tracking system.

of water were pumped on solar power alone. Table 8 lists the operating hours accrued during each month of the 1978 program, shows the distribution of potential operating time into actual operation, maintenance, modifications, and other activities, and notes major periods of downtime and the basic causes of each.

Summary of Operating and Maintenance Experience

The operation of the solar-powered irrigation pumping system has yielded significant experience with system and component maintenance requirements, operating performance, and life. The following discussion of these factors is broken down by major subsystems.

Collector Field

The collector field subsystem can be subdivided into five major areas: support structure, reflectors, receiver assemblies, flexible hose connections, and collector drive components.

Support Structure. The support structure consists of foundations, collector row stanchions, the longitudinal torque tube, and strongbacks which support the collector panels. The support structure is essentially sound with no observed deterioration. There is some minor damage to the torque tubes where they were "roll formed" by roller supports at the stanchions.

Reflectors. The reflectors are a honeycomb structure, with a reflective coating bonded to an acrylic overlay. The reflector surface has survived weathering without noticeable degradation. A recent evaluation by a representative of the manufacturer (3M) indicated that essentially no deterioration in the reflectivity of the collector surface has taken place. The current reflectivity when cleaned is estimated to be better than 82.7 percent which compares well with the design reflectivity of 85-87 percent.

The reflective surfaces were cleaned three times during the 1977 operating season, using deionized water applied with a high pressure spray gun. The efficiency improvement which resulted from cleaning the collector units was negligible; therefore, during 1978, the collectors were not cleaned. Though the reflectors appear dirty, it is not apparent that they actually get dirtier during the course of a year. This year, the effect of omitting the cleaning operations has not been accurately evaluated, due to the modification of the absorber assemblies.

Generally, the physical structure of the reflective surface shows no sign of weathering or exposure-related deterioration. One area was found where surface delamination has occurred, but representatives of Hexcel indicate that this is probably the result of a manufacturing defect and can be repaired. One area on another collector module was severely torn when it came into contact with an electrical enclosure door. In an area where it was not resealed properly after this physical damage humidity and stress-induced failures were noted in which the acrylic film separated from the crazed aluminum vapor coating. Also, on all collectors some color change and embrittlement of the extruded plastic edging around the reflector modules has been noted.

The reflector focus adjustments (at the guy wires, strong backs, and absorber supports) appear to be stable and durable. Rows 8 and 9 were focused early in the summer of 1977, and have thus far not required refocusing.

Receiver Assemblies. The receiver assemblies consist of absorber tubes (copper pipe with an absorptive coating) and receiver housings. At the end of the 1977 program, the two rows which had over-heated had significant mechanical damage and severely damaged absorptive coatings. The rest of the rows showed varying degrees of coating degradation (powdering and flaking). To allow operation of the two damaged rows prior to delivery of new components, the receiver housings were removed from the uprights and all components were straightened in the field to the extent possible. The subsequent performance of these two rows indicated that repairs of this sort are feasible, and may be economically viable.

As described in the "Modifications" section of this report, two rows were recoated with a modified Nextel® in June, and a second pair of rows were recoated in August. To date, no visible sign of deterioration has appeared in this high-temperature version of the original coating. One collector row was modified by installing receiver tubing with a black chrome selective coating. Thus far no visible signs of deterioration have appeared in this coating.

The receiver housings installed during the 1978 program appear to be less susceptible to damage than the original design, since the polished wind screen and reflector surfaces reduce the overheating which occurred when the collector units were allowed to lead or lag in tracking the sun. However, the new housings increase the problem of protecting the sun sensor cable from focused sunlight, as they have no area which is always "safe".

Flexible Hoses. Flexible hoses are used to join the rotating components of the collector assemblies to stationary header pipes, which lead to the skid mounted power package. A significant amount of deterioration has been noted in these hoses. Cracking has occurred on several rows, primarily on the outer side of the tighter radii. This cracking may be the result of ultra-violet light exposure, since it appears to be more prevalent on the south end of the collector field and on the sides of the hoses exposed to the sun. Separation and bubbling in the outer coating of the hose has been noted on one row. This suggests damage to the load carrying layers of the hose. Leakage underneath the outer cover has also been noted on several rows.

Collector Drive Components. A broken master link was discovered on the drive chain of one collector row. Although the drive chain had not failed, the prospect of a broken chain is of serious concern. The current design of the collector drive is not fail-safe in this regard. A broken drive chain would result in the collector row being free to rotate, without restraint. Although approximately balanced, most rows would orient with the parabolic reflector pointing directly upward, until wind driven to mechanical stops. Such an occurrence would result in costly damage.

One of the collector drive motors installed during 1978 (24 volt DC), developed evidence of overheating. Performance of this motor is still satisfactory, but the sympton indicates a potential problem.

Normal Maintenance. Normal maintenance of the collector field includes the following items:

- Check flexible hose clamp connections; interval approximately 1 week. This maintenance interval depends on the condition of the hoses (see comments above).
- Check chain tension; interval approximately 3 months.
- Check motor gear box oil level; interval approximately 3 months
- Lubricate torque tube pillow blocks; interval approximately 3 months.
- An appropriate cleaning interval for the reflectors is highly dependent on the economic circumstances of the installation, and the local climate.

Tracking System and Controls

A number of operating and maintenance problems have been discovered during field operation of the revised tracking system. To date, the tracking system has required more maintenance time than any other single component of the solar-powered irrigation system.

Adjustment. As described above under "Tracking System Modifications", the current tracking system design requires intermittent manual adjustment for degree of cloud cover. A well designed and engineered system would not require this continual manual adjustment.

<u>Component Failures.</u> The electronic components of the tracking system have had an unacceptably high failure rate throughout the program. Some of these problems have been cured or corrected. Path transistors, which initially demonstrated an excessive failure rate, have been upgraded to an apparently adequate 50 amp capacity; these new components have not failed in the limited time they have been used. Several failures of integrated circuit operational amplifiers have been experienced. These amplifiers are incorporated in a variety of locations throughout the circuitry, and appear to be a weak point of the system. It is felt that most of the electronic failures experienced during operation were related to undersizing of components and the difficult environment experienced by the electronics hardware. The local environment imposes serious constraints on the selection of electronic components, as ambient temperatures of up to 120° F are normally experienced in the Gila Bend area, and temperatures of over 150° F have been measured on equipment in direct sunlight. Dust is a continual problem at the site especially when the fields undergo cultivation. An additional problem occurred during a severe electrical storm. Although the equipment did not sustain a direct lightning strike, all of the individual row control units were damaged and several required factory repair.

<u>Normal Maintenance.</u> Normal maintenance of a mature tracking and control system will include the following items (the current system requires considerably more maintenance; see Modifications: Improve Tracking System):

- Top off battery electrolyte; interval approximately 4 weeks
- Test all safety functions; interval approximately 4 weeks
- Check tracking accuracy; interval <u>should</u> be more than 2 weeks.

Power Package

The reliability of the skid-mounted power package has been acceptable. Two seasons of operation have resulted in no gross failures (with the exception of the oil leak in the turbine, described below). Component performance has been generally satisfactory; some problems have been encountered, however.

Turbine Seal Leakage. The one major failure experienced in the power package is a potentially catastrophic oil loss from the turbine gear box.

Operation of the skid package at output shaft speeds up to 1700 rpm causes no problem. (1700 rpm is the maximum output shaft speed obtained during solar-only operation, to date.) However, when hybrid operation is attempted, the output shaft speed rises to 1800 rpm as soon as solar power is adequate to carry the tare losses within the skid package. A rapid loss of oil from the turbine gear box is immediately experienced at 1800 rpm. Problems have been experienced with this seal in the past, and a modified seal was installed by Barber-Nichols Engineering in 1977 in an attempt to cure the leak. The oil leak occurs across the seals on the main turbine shaft, which rotates at 30,000 rpm when the output shaft speed is 1800 rpm. Although the problem could not be duplicated in the laboratory by Barber-Nichols, it is believed to result from a marginal seal design. The oil leakage may be aggravated by excitation of rotor shaft vibration through an accessory right-angle drive; although not a valid remedy for the leak, disconnecting the drive eliminated the oil loss.

Barber-Nichols was unable to test the turbine-gear box unit at full-power under representative conditions; field tests showed that the oil loss could be temporarily stopped by increasing back pressure in the turbine. This is indicative of the cause of the problem, but is not a solution.

Purge Interval. Another problem encountered during 1978 is a reduced ability to maintain a purge in the Freon loop. Once the leak tightness of the skid package plumbing was finalized, purging was required at approximately two-week intervals during 1977. By the end of 1978 operating season, purging was required at 3 to 4 day intervals to maintain satisfactory operation. The location of air leakage into the Freon system is not certain. Correcting turbine seal problems and locating any gross leakage should restore a two-week purge interval. However, it is believed that silver soldered copper tubing would provide better leak tightness than the threaded steel pipe currently used for interconnections between components. Reciprocating seals in the Freon feed pump are another potential site for leakage.

Check Valve Clogging. A significant obstacle to unattended operation of the solar-powered irrigation pumping system is clogging of the condenser cooling lines by agricultural debris in the sump water. Coarse "screening" was installed during the 1978 season to reduce the flow of debris through components in the cooling water loop. Although no significant improvement was shown, revised designs may help cure the problem. Automatic provision for flushing the cooling line check valve (now done manually) is another approach to curing this problem.

Normal Maintenance. Normal maintenance of the skid mounted power package includes the following items:

- Maintain oil level in the Freon feed pump oiler; a larger reservoir is needed at this location. Current refill interval is approximately 1 to 2 days, should be weekly.
- Check and when necessary top off turbine gear box oil level; currently, if maximum turbine output speed is maintained below 1700 rpm, topping off is infrequently required.
- Periodically purge Freon loop; see discussion of Freon purging above.
- Flush condenser cooling water check valve; see discussion above.

- Lubricate sheaves and pumps; interval approximately 2 weeks.
- Check, and if required, replace corrosion plugs on collector water heat exchangers; interval approximately 3 months.
- Change feed pump crank case and overrunning clutch oil; interval approximately 6 months.

Irrigation Pump, Gear Box, 50 HP Electric Motor

As described above, a variety of unexpected failures were experienced in the commercial equipment installed with the system. However, the failures which occured are not of basic significance in evaluating the performance and reliability of the solar-powered irrigation pumping system.

Electric Motor. The early failure of the 50 HP electric motor was apparently due to a manufacturing defect. The 50 HP motor supplied as a replacement has operated for many hours with no sign of further problems.

Gear Box. The gear box joining the 50 HP electric motor, the skid package output shaft, and the irrigation pump has operated satisfactorily with no signs of deterioration or problems.

Irrigation Pump. The primary cause of the problems experienced with the irrigation pump is believed to be the collection of debris on the pump inlet screen. Blockage of this screen resulted in cavitation, due to restriction of the inlet. No apparent damage was caused as a result of this cavitation, but in the process of removal, checkout and reassembly of the pump, a shaft key was left out, allowing the pump impeller to bind during initial operation. After this problem was corrected and the pump was reinstalled, no further difficulties were experienced, and the pump is now operating satisfactorily.

Normal Maintenance. Normal maintenance of the irrigation pump, gear box, and 50 HP electric motor includes:

- Follow manufacturers recommended maintenance schedule
- Top off irrigation pump oil reservoir; current interval approximately 1 week--could be lengthened as desired using a larger reservoir

Site

The environment of the solar-powered irrigation pumping system has not caused major problems to date. Several characteristics of the location, however, need to be considered in the design of equipment for field use.

The combination of cultivated fields and continual moderate winds results in infiltration of equipment by dust and grit. Good dust sealing is required on all equipment, including electronic and mechanical components.

Rodent nesting was observed in 1978, in equipment and electrical boxes. No damage has been found, but the potential for problems from this source is apparent.

Plant growth on the site has been minimal, but some vegetation is beginning to appear. The earthen pad on which the system is located was constructed in December 1976; weeds were not evident until early in the spring of 1978. In May 1978 the site was cleared of weeds and by the end of the 1978 operating season, a few weeds had reappeared (6 - 24-inch height).

The fence surrounding the site proved to be useful in protecting equipment from wind-blown debris, animals and intruders; in other areas with different local conditions it would probably be required to an even greater degreee.

Some erosion has occurred around the concrete pump pad, on the side closest to the irrigation sump.

Experimental operations at the site during 1978 were conducted from a 10' x 46' trailer, outfitted to house instrumentation and workshop facilities. This arrangement proved to be a major improvement over the 1977 program, when no shelter was available for field personnel. The efficiency gained from adequate working facilities proved to be significant.

Instrumentation, Data Collection, and Data Transmission.

A variety of problems have been experienced with components of the instrumentation system.

Sensor Failures. The pressure transducer used to monitor turbine exhaust pressure failed early in the 1978 program. The transducer was returned to the manufacturer whose diagnosis indicated an electrical overload of the bridge circuitry. No acceptable explanation of the failure has been found.

The portable differential pressure gage was temporarily disabled when O-rings in the quick disconnects (used to attach the gage to venturi taps) failed. Although the composition of the O-rings supplied with the gage is not known, use of neoprene O-rings is recommended.

The pressure transducers installed to automatically measure pressure drop across the venturi meters for Freon flow and total collector-water flow were found to introduce significant problems. Their extremely high frequency response required low pass filtering to provide a signal acceptable to digital data sampling equipment. In addition, the unexplained failure of one of the differential pressure transducers resulted in extensive delays in automating the data collection system.

Accuracy and Calibration. Adequate calibration of wind speed measuring devices is yet to be achieved. Also, problems with ripple and offset in the signal from the skid package output shaft speed transducer continue, as the revised tachometer hardware has not been installed.

Data Transmission. Transmission of data from the field site to Columbus computing facilities was disrupted on a number of occasions due to telephone line noise.

OBSERVATIONS AND RECOMMENDATIONS

The observations and recommendations summarized in this report are based upon (a) actual field experience and/or (b) extrapolations which can be made using reasonable engineering judgment. Certain of the recommendations involve modifications to improve the operation of the solar-powered irrigation pump, as it now exists. If construction of an entirely new system were undertaken, experience gained in this and other projects might lead to approaches which would not necessarily (or logically) incorporate these specific recommendations. Some of the observations and recommendations, however, are general in that they may have significance for a variety of specific designs.

General Comments

The functional goals for the design of the solar-powered irrigation pumping system were to develop a system capable of

(1) Collecting solar energy and utilizing it to drive an irrigation pump
(2) Being incorporated into a working irrigation system
(3) Being operated and maintained in a manner comparable to other agricultural equipment.

The system was demonstrated to fulfill criterion (1) during the 1977 program; evaluating components with the aim of improving performance was the goal of Task 2. Criterion (2) was addressed by the conversion to hybrid operation, as discussed under "Modifications: Task 4". Criterion (3) was addressed, in part, by Task 3, which involved improving the tracking system to achieve "unattended operation".

Criterion (3) implies that although the system must be capable of functioning without the constant attention of an operator, brief inspections at regular intervals may reasonably be required (for example, the standard electrically-powered pumping stations used on Paloma Ranch are inspected twice each operating day.) Thus, the capability for "unattended operation" may, for this application, be defined as the ability to start-up and shut down in response to available sunlight, to operate properly throughout the day without operator intervention, and to shut down in a safe manner if any failures occur. Operating personnel may reasonably be asked to inspect each morning to verify start-up, proper tracking and correct fluid levels, and to confirm shut-down each evening.

Certain characteristics of the current system preclude operation in this unattended mode. During the two seasons of operation, the greatest number of problems have been associated with the electronic equipment used to track the sun and protect the system from catastrophic failure. It is felt that the erratic behavior of these devices is related to the specific electronic design and the components used, and that a well-conceived, well-engineered, mature system could provide performance and reliability satisfying the requirements of the application. The electronic systems currently in place, however, provide neither the performance nor the reliability required. Another significant problem involves maintaining an adequate flow of cooling water to the condenser. As discussed, the present system requires that an operator monitor the inlet and outlet temperatures of the cooling water at frequent intervals, and flush a check valve when necessary. Although a safe failure would occur if the cooling water flow were severely reduced, this failure currently would result in the loss of a large quantity of Freon (approximately $400 in value) and is therefore undesirable. Experience with the problems in these two areas (electronics and coolant flow) leads to the conclusion that the current system should not be operated in the unattended mode; recommendations for addressing these problems are discussed below.

Subsystems and Components

Specific recommendations and observations are detailed below for each subsystem of the solar-powered irrigation system.

Collector Field

Recommendations regarding the collectors and associated components lie primarily in five areas.

Flexible Hoses. The present degraded condition of the flexible hoses represents a serious safety hazard; replacement is necessary. The condition of the hoses also increases the effort required to maintain a leak-tight system. Alternate materials and designs and the effect of fluid composition should be evaluated prior to the specification of new hoses. If this evaluation is not performed, hoses should be replaced at the beginning of each operating year.

Collector-Water Additive Package. The large capital investment in heat exchange equipment makes long-term corrosion protection imperative. An additive package for the collector-water was developed and utilized when the system was installed in 1977; antifreeze and anti-corrosive agents were included. Sacrificial corrosion plugs were also installed in each heat exchange unit. After two seasons of operation, however, black sludge is forming in some portions of the collector-water loop. The relationship between additive package composition, heat exchanger material, flexible hose material, and sludge formation should be thoroughly investigated.

Absorber Assemblies. The performance of the collector units is critical to the economic evaluation of any solar-powered irrigation system. Several absorber variations are in place, and instrumentation has been installed to allow evaluation of performance. Future work should make use of these existing facilities to obtain a volume of data which will permit meaningful comparisons to be made, in terms of both efficiency and operating life.

Collector Drive Mechanism. Possible alternatives to the present collector drive system need to be evaluated. The backlash inherent in the current system degrades the stability of the tracking system and contributes to control problems. In addition, the possiblity of chain breakage and resultant loss of control of a collector row needs to be addressed.

Bleed Valves. Minor improvements are needed in the provisions for bleeding air from the collector water loop. Larger bleed valves with attached discharge tubes are needed to improve the efficiency and safety of bleeding operations.

Tracking System and Controls

Recommendations for future work on the tracking system and operating controls are based on the need for reliable unattended operation.

Sensitivity to Cloud Cover. The major improvement required in the current tracking system is to achieve control system accuracy and stability sufficient for unattended operation under variable cloud conditions. Several courses of action are possible to achieve this result.

- Redesign or modify the current sun sensor to achieve an improved range of modulation, and/or reduce present collector speeds to prevent overshoot and allow adequate pulse width modulation to occur with the current equipment
- Investigate alternative tracking systems
- Incorporate automated variation of the dead band width into the present system

Reliability. Since protection of system components depends upon reliably monitoring fault indications, the poor reliability experienced is a serious concern. Further development of control functions should focus on obtaining or developing hardware which is appropriately sized and designed for service loads and environmental conditions.

One factor which may contribute to electronics failures is the high peak temperatures which occur within the enclosures. This possibility should be evaluated and potential solutions investigated.

Oil Pressure Verification. An additional modification required for a mature system is incorporation of improved logic for monitoring oil pressure in the turbine gear box. The current system's "failsafe" characteristics are in part achieved by manual verification of proper operation each time the system is started.

Failure Mode of Controls. In the design of future tracking and control systems, it will be important to consider overall failure modes of the system. The current logic monitors the mechanical and thermal operation of the collector field and the skid mounted power package for failures, and initiates storage of the collector field in the event of a fault indication.

However, failure of certain components results in loss of self-protective capabilities. For example, this year there have been several failures of electronic components which could allow the system to continue to track although collector water circulation had ceased. This could have resulted in very costly damage to the system. While realizing that nothing can be totally failsafe, improvement is definitely required (at least to regain the level of reliability of the 1977 system).

Skid-Mounted Power Package

Several problems within the power package must be corrected to allow operation in the hybrid mode and to permit unattended operation in any mode.

Hybrid Conversion. Design work for conversion to the hybrid configuration is complete, and all components have been purchased. The installation of these components on the skid mounted power package remains to be completed. However a major obstacle to operation in the hybrid mode is the oil leakage which occurs across the turbine shaft seal during operation at full design speed. As this leakage represents a catastrophic failure mode, it is imperative that the problem be corrected. It is felt that the best approach to curing this problem is to perform an experimental analysis of the cause of the seal leakage, and then to correct the design of the seal or seal environment to prevent further oil loss. It may also be necessary to modify the power package to remove offending vibrations which may be contributing to the seal leakage problem. It is more desirable to fix the seal directly than to eliminate or reduce the vibration, since future installations may well encounter similar vibration levels.

Check Valve Clogging. In order to make unattended operation of the solar-powered irrigation pumping system feasible, a solution needs to be developed for the problem of check valve clogging. Two approaches to this problem are possible. One is to improve screening of the condenser inlet water, thereby preventing agricultural debris from reaching the check valve. Another is to flush the check valve automatically instead of manually. Regardless of the approach used, the frequency with which clogging has occurred in the past and the cost of replacing the Freon indicates that high condenser pressure should be added to the conditions which are monitored by the control logic.

Purging Interval. The intervals between Freon loop purges must be increased. Economical operation will not allow frequent manual purging of the system or the efficiency loss of a poor purge. Fixing the turbine seal and rechecking joints should restore the system to its initial leakage rate (approximately 1 psi/week). The source of air infiltration into the system has not yet been identified. Future systems should use silver soldered copper tubing rather than the threaded steel pipe used on the current system. This change in design should improve the integrity of the Freon system as well as ease assembly.

Freon Contamination. Two minor additions to the Freon system are needed to improve long-term performance. A filter needs to be added, to remove contaminants in the Freon and protect the turbine and feed pump from premature wear. This filter has already been purchased and was to be installed during conversion to hybrid operation. The other addition needed is a drain in the Freon loop, to bleed off oil from leakage past the turbine gear box seal and from feed pump cylinder lubrication. This could also be used to more conveniently drain the Freon for repair of the system.

Irrigation Pump, Gear Box, and Electric Motor

The irrigation pump, gear box, and electric motor are currently operational. Although the irrigation pump is operating as designed, it should be more firmly attached to its mounting pad to meet the alignment requirements between the drive shaft, the turbine, and the gear box; this is a more stringent requirement than is conventional for agricultural installations.

Site

Further development of the site is needed in the area of lightning protection. Observations on local weather conditions may have significance for future installations of solar pumping equipment.

Lightning Protection. Operating experience has shown that the system is vulnerable to lightning. Although no direct strikes have occurred, the tracking system was seriously damaged during an electrical storm and required expensive repairs; possible methods of shielding the installation from damage of this type should be evaluated.

Weather Data. A prerequisite for future installations of solar equipment should be the continuous collection of weather data at the proposed site before installation. Weather data was not available for the Paloma Ranch site, although recorded data was available for Phoenix. While on the site, it was evident that local variations in cloud cover result in considerably different insolation received at locations only a few miles apart; for example, cloud cover over nearby foothills was considerably heavier than at the site. This was not detrimental to operation of our system, but it emphasizes the need for accurate, highly localized climate measurement, prior to and after installation of solar systems.

Instrumentation, Data Collection, Transmission and Analysis

Further development of evaluation capabilities should focus on completing the installation and calibration of present sensors, and on clarifying certain inconsistencies within the analysis of system performance.

Differential Pressure Transducers. The output of the transducers used to automatically monitor pressure drop across Freon and collector-water flow venturis must be properly filtered, calibrated, and verified. The failed transducer was replaced by the manufacturer (after the end of field operations), and must be reinstalled. Low pass filtering circuits have been fabricated; accurate flow measurements should be achieved with these components after thorough debugging and calibration.

Tachometers. The shaft encoders and digital-to-analog converters procured during the 1978 program should be installed and debugged to generate accurate and reliable output shaft and feed pump speed data.

Turbine Performance Evaluation. Analysis of recorded data yields values of power at various locations within the skid package and irrigation system. Net hydraulic horsepower is calculated from measured lift and irrigation flow rate. Shaft horsepower at the skid package output is derived from torque and speed, as described above. The ideal and actual horsepowers generated by the passage of Freon through the turbine are also calculated from the measured pressures and temperatures of the Freon at the turbine inlet and exhaust, and flow rate through the turbine nozzles.

Comparison of these calculated values throughout the data base indicates that hydraulic horsepower and shaft horsepower correlate reasonably well when the load curve of the irrigation pump and the flow restrictions in the piping are considered. However, considering turbine-wheel and gearbox losses, the calculated value of the power given up by the Freon in passing through the turbine does not agree with the shaft power value. In many cases, the calculated value of internal turbine power is less than the measured shaft power. Sensitivity analyses were conducted and instrumentation performance was reviewed to determine the cause of this inconsistency. No postulated instrumentation error appears to account for the disagreement between these values. Investigation of all parameters (including the accuracy of the available property data) should be continued so that this conflict can be resolved. The analysis program should be revised to use the measured value of shaft horsepower, after the accuracy of this value is confirmed.

STATUS OF EQUIPMENT AT SITE: DECEMBER 1978

The solar-powered irrigation system was scheduled to be shut down at the end of September 1978. There were two alternatives for accomplishing this shut down. One was to totally shut down the facility and conclude the operations by removing the trailer and disassembling all of the instrumentation/monitoring wiring and equipment. The second alternative was to temporarily shut down the facility, thus making it relatively easy to restart operations (and data gathering) if additional funding became available or if one wished to have a demonstration. The second alternative was selected as being the most expedient for the government and NML. Therefore, at no additional cost to the government, the trailer has been left in place and the instrumentation, wiring, and data recording equipment have not been removed. This will facilitate the initiation of any follow-on program or any demonstrations of the system in connection with additional work in solar-powered pumping. It is anticipated that this equipment will be maintained in place for 6-12 months.

Appendix A

Typical Data Analysis Results

The inputs and outputs of the data analysis program are printed in a standard format after each analysis run.

- The raw input data is printed using the format of the magnetic tape record
- An array of sorted values is printed, encompassing one days operation
- An array of 124 measured and calculated values is printed for each recorded data point, tabulating temperatures, pressures, flows, heat transfer rates, property values, powers and efficiencies.

Examples of each of these items are presented in Tables A-1 through A-5.

Data analysis outputs for several periods typical of different operating conditions are presented in Tables A-3 through A-16; the accompanying comments detail the significance of each set of readings. Figures A-1 through A-3 demonstrate operating characteristics as derived from the analyzed data.

Comments on Tables A-3 through A-8: Normal Operation June 23, 1978

Tables A-3 through A-8 illustrate a portion of the data analysis output for June 23, 1978. The 8-digit code at the head of each column indicates the date and time of the scan; "06230851" indicates June 23, 8:51 a.m. (Note that a six-digit time code may be used depending on the print option, but the last 4 digits always indicate time-of-day.) On this date, the data recording system was turned on at 7:51 a.m., when the operator arrived at the site; operation commenced at approximately 8:50. Automatic and manually initiated recording through 12:40 are included.

Pressure readings through 0834 reflect a recalibration operation underway.

The Freon system was purged as soon as the skid package began to come up to operating temperature; the recording at 0932 reflects this process.

Collector Row #1 was stored and shut off throughout this days operation, due to a damaged individual row controller. Collector Row #2 was shut down until 11:20, while installation of a new receiver housing was completed.

C000 ! 0086.4 MV	C001 ! 1431.1 MV	C002 0 0195.1 0F	C003 0 0160.0 0F
C004 0 0168.1 0F	C005 0 0125.4 0F	C006 0 0056.5 0F	C007 0 0085.8 0F
C008 0 0085.3 0F	C009 0 0134.7 0F	C010 0 0191.0 0F	C011 0 0208.5 0F
C012 0 0079.0 0F	C013 0 0153.5 0F	C014 0 0220.6 0F	C015 0 0206.8 0F
C016 0 0200.5 0F	C017 0 0173.9 0F	C018 0 0070.3 0F	C019 0 0075.6 0F
C020 0 0073.1 0F	C021 0 0076.5 0F	C022 07.832 MV	C023 08.466 MV
C024 08.143 MV	C025 10.703 MV	C026 10.515 MV	C027 09.813 MV
C030 00.468 MV	C031 06.497 MV	C032 0 0220.5 0F	C033 0 0223.3 0F
C034 0 0229.8 0F	C035 0 0227.6 0F	C036 0 0232.0 0F	C037 0 0224.4 0F
C038 0 0228.5 0F	C039 0 0227.2 0F	C040 0 0227.0 0F	C041 0 0194.3 0F
C042 0 0184.6 0F	C043 0 0157.8 0F	C044 0 0188.3 0F	C045 0 0189.6 0F
C046 0 0189.9 0F	C047 0 0190.1 0F	C048 0 0191.8 0F	C049 0 0191.8 0F
C050 0 0192.0 0F	C051 0 0112.3 0F	C054 001.30 MV	C055 -000.01 MV
C056 0541.8 MV	C057 -0000.1 MV	C058 * 5137.4 MV	C059 * 5136.0 MV
C062 -0000.3 MV	C063 -0000.1 MV		
C001 62 10:40:00 HR			
C000 ! 0093.4 MV	C001 ! 1582.9 MV	C002 0 0240.7 0F	C003 0 0204.2 0F
C004 0 0209.6 0F	C005 0 0115.3 0F	C006 0 0081.2 0F	C007 0 0085.7 0F
C008 0 0084.5 0F	C009 0 0158.0 0F	C010 0 0231.1 0F	C011 0 0245.4 0F
C012 0 0082.4 0F	C013 0 0191.1 0F	C014 0 0262.4 0F	C015 0 0259.5 0F
C016 0 0244.6 0F	C017 0 0221.5 0F	C018 0 0070.2 0F	C019 0 0075.0 0F
C020 0 0073.5 0F	C021 0 0080.1 0F	C022 09.305 MV	C023 10.336 MV
C024 09.756 MV	C025 10.875 MV	C026 10.903 MV	C027 11.610 MV
C030 00.458 MV	C031 06.931 MV	C032 0 0263.7 0F	C033 0 0264.0 0F
C034 0 0305.7 0F	C035 0 0267.3 0F	C036 0 0271.9 0F	C037 0 0258.6 0F
C038 0 0269.5 0F	C039 0 0264.3 0F	C040 0 0269.1 0F	C041 0 0239.8 0F
C042 0 0227.7 0F	C043 0 0230.9 0F	C044 0 0231.2 0F	C045 0 0232.2 0F
C046 0 0233.5 0F	C047 0 0233.1 0F	C048 0 0218.1 0F	C049 0 0235.0 0F
C050 0 0227.6 0F	C051 0 0144.3 0F	C054 000.38 MV	C055 000.01 MV
C056 0695.4 MV	C057 -0000.1 MV	C058 * 5125.9 MV	C059 * 5124.4 MV
C062 -0000.3 MV	C063 -0000.1 MV		
0001 62 11:00:00 HR			
C000 ! 0098.3 MV	C001 ! 1957.2 MV	C002 0 0257.2 0F	C003 0 0227.1 0F
C004 0 0232.2 0F	C005 0 0120.9 0F	C006 0 0052.7 0F	C007 0 0084.8 0F
C008 0 0081.9 0F	C009 0 0155.4 0F	C010 0 0279.3 0F	C011 0 0271.2 0F
C012 0 0085.4 0F	C013 0 0203.9 0F	C014 0 0291.0 0F	C015 0 0289.5 0F
C016 0 0277.3 0F	C017 0 0242.0 0F	C018 0 0068.5 0F	C019 0 0072.7 0F
C020 0 0075.2 0F	C021 0 0081.9 0F	C022 11.010 MV	C023 13.364 MV
C024 11.738 MV	C025 10.960 MV	C026 10.875 MV	C027 13.502 MV
C030 00.491 MV	C031 07.342 MV	C032 0 0290.0 0F	C033 0 0289.7 0F
C034 0 0294.3 0F	C035 0 0292.0 0F	C036 0 0294.6 0F	C037 0 0288.4 0F
C038 0 0290.4 0F	C039 0 0289.5 0F	C040 0 0292.2 0F	C041 0 0270.5 0F
C042 0 0261.0 0F	C043 0 0252.3 0F	C044 0 0260.2 0F	C045 0 0261.6 0F
C046 0 0262.8 0F	C047 0 0252.4 0F	C048 0 0263.6 0F	C049 0 0254.1 0F
C050 0 0264.0 0F	C051 0 0153.4 0F	C054 -000.58 MV	C055 000.01 MV
C056 0753.1 MV	C057 -0000.1 MV	C058 * 5122.1 MV	C059 2216.4 MV
C062 -0000.1 MV	C063 -0000.1 MV		
0001 62 11:04:00 HR			
C000 ! 0098.6 MV	C001 ! 1594.7 MV	C002 0 0272.2 0F	C003 0 0235.2 0F
C004 0 0242.7 0F	C005 0 0123.5 0F	C006 0 0059.4 0F	C007 0 0084.8 0F
C008 0 0081.5 0F	C009 0 0172.6 0F	C010 0 0231.5 0F	C011 0 0273.0 0F

TABLE A-1. TYPICAL RAW INPUT DATA

	62/09/25/36	62/09/40/00	62/10/00/00	62/10/20/00	62/10/40/00	62/11/00/00	62/11/04/00	62/11/06/00	62/11/08/00	62/11/10/00
CH	1	2	3	4	5	6	7	8	9	10
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	17.3	25.3	350.0	1431.1	1582.9	1957.2	1584.7	1284.8	1362.8	2113.1
2	84.2	87.9	118.4	195.1	240.7	267.2	272.2	272.6	273.9	266.2
3	87.5	90.7	108.7	160.0	204.2	227.1	236.2	240.9	241.2	245.2
4	78.5	81.5	111.6	168.1	209.6	232.2	242.7	254.9	251.3	261.5
5	64.7	68.3	98.3	106.4	115.3	120.9	123.5	132.3	132.3	128.8
6	60.9	62.9	73.4	86.5	81.2	82.7	89.4	101.7	91.8	80.2
7	59.9	61.9	66.6	85.8	85.7	84.8	84.8	88.0	94.2	89.4
8	69.9	71.3	66.7	85.3	84.5	81.9	81.5	85.2	91.2	87.4
9	66.7	67.8	100.4	134.7	158.0	168.4	172.6	182.6	190.5	153.3
10	74.0	75.1	121.7	191.0	231.1	279.3	281.5	288.1	288.1	289.3
11	80.2	82.4	126.7	208.5	246.4	271.2	278.0	277.4	279.3	278.4
12	76.9	79.3	79.4	79.0	82.4	85.4	84.8	85.2	85.7	86.7
13	82.0	84.5	112.1	168.5	191.1	203.9	203.6	195.4	190.4	185.8
14	112.5	112.3	144.2	220.6	262.4	291.0	295.0	300.5	304.2	303.0
15	66.6	67.1	131.4	206.8	259.5	289.5	292.5	297.2	302.2	303.6
16	56.8	57.4	130.1	200.5	244.6	277.3	276.8	281.8	289.8	285.9
17	67.5	69.1	119.2	179.9	221.5	242.0	247.6	254.5	262.7	170.3
18	61.5	62.7	68.5	70.8	70.2	68.5	67.4	67.4	68.3	67.8
19	70.4	72.5	70.6	75.6	75.0	72.7	86.1	111.5	73.5	72.2
20	72.7	72.7	73.4	73.1	73.5	75.2	73.6	74.2	74.6	77.6
21	69.7	69.3	76.3	76.5	80.1	81.9	81.8	81.0	79.9	79.4
22	1.0	1.0	2.6	7.8	9.3	11.0	9.8	9.1	7.1	10.2
23	.8	.8	2.7	8.5	10.9	13.4	11.9	11.3	9.1	13.4
24	.8	.9	2.4	8.1	9.8	11.7	10.3	9.6	7.4	6.8
25	4.8	5.0	9.3	10.7	10.9	11.0	12.8	14.3	7.2	7.1
26	7.3	4.8	9.2	10.5	10.9	10.9	12.9	14.4	7.0	7.1
27	4.7	7.3	8.0	9.8	11.6	13.5	13.9	14.2	14.7	14.5
28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5
31	5.3	5.6	6.0	6.5	6.9	7.3	7.4	7.4	7.4	7.5
32	88.2	89.1	141.5	220.5	263.7	290.0	295.5	301.7	302.4	285.4
33	88.6	89.0	148.3	223.3	264.0	289.7	295.4	299.7	300.4	285.8
34	90.3	90.3	161.3	229.8	305.7	294.3	299.6	305.3	305.7	290.2
35	90.1	90.5	166.7	227.6	267.3	292.0	297.8	302.1	303.4	292.6
36	88.2	88.6	171.6	232.0	271.9	294.6	300.5	306.1	312.3	309.6
37	89.2	89.1	167.3	224.4	258.6	288.4	295.9	300.4	300.1	284.7
38	90.1	89.4	172.5	228.5	269.5	290.4	297.9	302.1	302.9	286.0
39	89.1	88.3	172.3	227.2	264.3	289.5	296.8	300.3	300.5	283.8
40	90.0	89.5	171.0	227.0	269.1	292.2	298.2	300.8	301.2	285.9
41	62.1	62.1	123.3	194.3	239.8	270.5	273.9	273.2	277.6	282.3
42	86.3	88.7	118.2	184.6	227.7	261.0	264.4	266.4	266.8	266.6
43	90.7	92.2	126.1	187.8	230.9	262.3	266.8	266.1	266.8	268.7
44	89.5	90.7	126.5	188.3	231.2	260.2	265.4	264.7	264.8	268.3
45	88.7	90.8	125.6	188.6	232.2	261.6	267.3	266.0	266.6	270.3
46	89.6	92.1	124.7	189.9	233.5	262.8	268.5	266.5	266.6	270.7
47	86.7	89.1	123.9	190.1	233.1	262.4	267.6	265.6	268.1	271.1
48	86.7	91.1	122.9	191.8	218.1	263.6	268.3	267.4	270.1	273.9
49	89.7	92.4	122.7	191.8	235.0	264.1	269.0	266.8	270.9	275.5
50	90.8	94.5	122.6	192.0	227.6	264.0	269.1	266.2	271.2	275.2

TABLE A-2. TYPICAL SORTED INPUT DATA

PAGE NO 1

DESCRIPTION /TIME	06230751	06230754	06230834	06230844	06230851	06230900	06230920	06230932	06230940	06230949
R-113 FLUID TEMPERATURES,F										
TURBINE INLET	89.0	89.6	96.4	97.5	97.7	119.2	184.4	209.1	226.5	228.3
TURBINE OUTLET (NO 1)	87.3	87.9	96.9	98.8	98.5	87.7	138.8	177.4	165.8	163.1
TURBINE OUTLET (NO 2)	86.6	87.0	92.5	93.8	92.8	87.4	146.7	184.2	166.8	164.1
REGENERATOR OUTLET (VAPOR)	79.3	79.7	85.2	86.3	87.1	87.7	97.1	128.6	109.3	105.8
CONDENSER OUTLET (LIQUID)	81.8	82.0	82.8	83.3	85.7	87.5	92.6	96.3	87.7	87.9
FEEDPUMP INLET	79.8	80.1	81.9	82.7	82.7	87.3	92.6	101.1	90.0	88.6
REGENERATOR INLET (LIQUID)	82.7	82.9	85.0	86.5	82.5	87.1	92.4	104.9	90.0	88.7
PREHEATOR INLET (LIQUID)	82.5	86.2	94.7	92.6	87.8	87.7	120.9	155.4	130.9	129.5
PREHEATOR OUTLET (LIQ+VAP)	86.1	86.2	87.8	87.8	93.9	125.5	181.0	186.5	218.0	224.0
BOILER OUTLET (VAPOR)	96.4	97.1	102.3	102.4	99.7	119.9	187.2	215.8	230.9	231.8
WATER TEMPERATURES,F										
CONDENSER INLET	79.5	79.9	81.0	81.5	85.8	82.2	84.8	85.3	78.9	78.9
CONDENSER OUTLET	82.5	82.9	83.9	84.4	85.4	84.4	86.4	88.3	83.1	84.0
WATER-ETHYLENE GLYCOL TEMPS,F										
BOILER INLET	112.3	112.5	112.8	112.8	96.9	134.2	204.6	228.0	236.5	243.6
BOILER OUTLET	83.3	83.5	84.0	84.8	93.0	130.2	188.5	216.1	223.9	229.0
PREHEATER OUTLET	82.9	82.9	82.9	83.2	92.5	127.6	184.9	209.6	218.9	223.8
EXPANSION TANK	81.2	81.5	85.2	86.2	87.4	120.9	167.5	189.3	189.7	184.9
COLLECTOR FIELD INLET	80.6	80.6	79.8	80.1	102.1	128.4	177.1	203.2	217.9	222.2
NO 1 COL ROW INLET	99.0	100.0	105.2	107.8	109.3	109.4	113.6	116.2	117.6	118.4
NO 2 COL ROW INLET	103.6	104.4	109.3	111.6	113.0	114.1	119.3	122.6	124.0	124.7
NO 3 COL ROW INLET	105.2	106.1	105.8	108.3	79.4	106.1	168.0	192.0	208.9	216.9
NO 4 COL ROW INLET	102.8	103.9	107.4	110.2	86.3	118.0	172.7	198.3	214.3	219.0
NO 5 COL ROW INLET	99.3	100.2	109.8	112.5	95.8	122.9	173.9	199.6	216.0	219.9
NO 6 COL ROW INLET	98.3	99.2	105.8	108.6	100.4	125.1	174.2	200.0	216.2	219.4
NO 7 COL ROW INLET	95.8	100.1	109.0	111.7	102.2	125.9	174.4	200.1	216.0	219.3
NO 8 COL ROW INLET	101.1	102.4	109.9	112.3	103.2	126.5	174.9	200.2	216.4	220.3
NO 9 COL ROW INLET	100.7	101.9	108.6	111.1	103.4	127.1	175.0	200.6	216.2	220.3
NO 1 COL ROW OUTLET	99.7	100.6	105.5	106.5	106.6	107.6	112.3	114.2	115.1	117.4
NO 2 COL ROW OUTLET	103.2	104.0	106.0	106.2	106.8	107.9	112.8	114.9	116.3	118.4
NO 3 COL ROW OUTLET	107.7	108.5	105.6	106.0	101.0	128.6	197.3	218.8	226.3	237.3
NO 4 COL ROW OUTLET	104.7	105.6	105.7	105.7	100.7	135.6	205.6	226.9	232.0	241.4
NO 5 COL ROW OUTLET	101.5	102.4	107.4	106.9	109.3	138.0	207.7	230.1	234.9	243.2
NO 6 COL ROW OUTLET	101.8	102.7	106.9	106.9	101.9	145.6	213.8	234.1	238.2	245.9
NO 7 COL ROW OUTLET	102.4	103.2	107.8	107.3	104.6	148.1	211.1	233.3	235.8	243.0
NO 8 COL ROW OUTLET	100.9	101.5	106.5	106.2	99.3	152.2	211.5	234.9	238.4	243.4
NO 9 COL ROW OUTLET	100.4	101.3	107.7	107.3	99.0	148.1	205.3	229.9	0.0	240.5
MISCELLANEOUS TEMPERATURES,F										
RUPTURE DISC (LOW)	88.4	88.8	92.2	92.9	93.0	93.3	96.3	101.3	102.8	103.6
RUPTURE DISC (HIGH)	96.9	97.7	103.2	101.7	100.9	116.8	175.7	193.5	208.7	215.2
INSTRUMENT AMBIENT	85.7	85.8	86.9	87.7	88.7	86.0	86.5	88.7	89.5	87.5
TURBINE GEARBOX NO 1	86.5	86.9	90.0	90.5	91.6	92.0	110.3	129.1	144.2	161.2
BLANK	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BLANK	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BLANK	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE A-3. PAGE 1 OUTPUT; JUNE 23, 1978, 0751-0949

PAGE NO 2

DESCRIPTION /TIME	06230751	06230754	06230834	06230844	06230851	06230900	06230920	06230932	06230940	06230949
PRESSURES										
PREHEATER INLET, PSIA	15.7	15.7	14.0	6.7	11.1	16.8	41.3	45.7	70.3	73.8
BOILER OUTLET , PSIA	14.8	14.9	14.1	6.6	7.3	14.6	42.6	42.5	69.5	73.1
TURBINE INLET , PSIA	14.5	14.5	14.1	6.6	7.4	14.7	43.2	43.3	70.4	74.3
TURBINE EXHAUST, PSIA	0.0	17.0	14.1	7.2	7.9	8.1	9.1	3.6	8.5	8.7
CONDENSER , PSIA	14.6	14.6	14.1	7.0	7.6	7.9	9.1	10.0	6.5	6.6
EXPANSION TANK , PSIA	15.2	15.2	14.0	52.2	52.3	55.2	63.1	63.1	70.5	71.9
LIQUID LEVEL,FT										
TAILPOND SUMP	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
R-113 FLOWS										
FLOW-VENTURI ,LB/MIN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	109.8
TURBINE-NOZZLE ,LB/MIN	22.5	22.5	21.6	10.2	11.3	22.2	61.8	60.7	97.5	102.8
FP FLOW/TUR NOZ FLOW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	106.9
FEEDPUMP (ACTUAL) ,GPM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.5
FEEDPUMP(100 PCT V.EFF),GPM	.1	.1	.1	.1	1.3	1.2	5.9	4.8	10.5	10.8
FEEDPUMP VOL EFFCY,PCT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	102.8
COLLECTOR FLOW,GPM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.5	34.6	45.7
WATER FLOWS ,GPM										
IRRIGATION-PUMP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2300.0
CONDENSER-COOLING	*******	-.5	.1	.1	-.3	-5.8	-12.5	87.7	117.5	149.5
WEATHER DATA										
AMBIENT TEMP, F	87.3	86.0	91.6	89.6	92.1	93.8	95.0	96.8	98.1	100.7
WIND VELOCITY,MPH	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
SOLAR RADIATION,BTU/(HR-FT2)										
H TOTAL (HORIZ)	125.3	128.0	170.3	178.2	184.9	191.6	209.8	222.9	226.4	232.4
H DIFFUSE (HORIZ)	25.6	25.6	28.6	29.7	31.9	32.0	38.7	43.3	36.2	34.3
P-C SOLAR POWER SYSTEM										
OUTPUT SHAFT SPEED, RPM	8.8	8.8	12.8	12.8	141.8	136.1	651.0	528.1	1163.7	1200.0
OUTPUT TORQUE, LB-FT	-.1	-.1	-.1	-.0	.2	3.7	44.7	47.5	79.0	81.1
OUTPUT POWER, HP	-.0	-.0	-.0	-.0	.0	.1	5.5	4.8	17.5	18.5
ELECT AUX POWER INPUT,KW										
50-HP MOTOR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IRRIG PUMP HYDRAULIC POWER,HP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.7
TEMPERATURE DIFFERENTIALS,F										
BOILER (E.G.-WATER)	29.0	29.0	28.8	25.0	3.9	4.0	16.1	11.9	12.6	14.6
PREHEATER (E.G.-WATER)	.4	.6	1.1	1.6	.5	2.4	3.6	6.5	5.0	5.2
BOILER + PREHEATER	29.4	29.6	29.9	29.6	4.4	6.4	19.7	18.4	17.6	19.6
CONDENSER (WATER)	3.8	3.0	2.9	2.9	-.4	2.2	3.6	3.0	4.2	5.1
IDEAL CONDENSER PRESS,PSIA	7.2	7.2	7.4	7.4	7.9	8.1	9.0	9.7	8.2	8.2
EXCESS CONDENSER PRESS,PSI	7.4	7.4	6.7	-.5	-.1	-.2	.1	.2	.3	.4
HEAT TO BOILER,BTU/SEC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	43.4	81.1	120.1
HEAT REJECTED IN COND,BTU/SEC	*******	-.2	.0	.0	.0	-1.8	-6.2	36.4	68.4	105.7
TURBINE POWER(INTERNAL),HP	*******	.3	-.0	-.0	-.0	2.5	8.9	5.7	17.9	20.4
TURBINE EFFICIENCY,PCT	7.8	0.0	0.0	0.0	0.0	136.1	63.4	40.6	56.1	62.0
POWER SYSTEM EFFCY,PCT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.9	15.6	12.0
POWER SYS+IRRIG PUMP EFFCY,PCT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0
DT COND(R113 O-WATER O),F	-.7	-.9	-1.1	-1.1	.3	3.1	4.2	8.0	4.6	3.9
CH SEPARATOR(PCT OF DHACT)	.0	9.4	-37.9	13.1	27.1	-.1	-.0	-1.2	-.2	-.1
BLANK	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BLANK	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE A-4. PAGE 2 OUTPUT; JUNE 23,1978, 0751-0949

PAGE NO 3

DESCRIPTION	/TIME	06230751	06230754	06230834	06230844	06230851	06230900	06230920	06230932	06230940	06230949
NUMBER OF ACTIVE COL ROWS		7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
COLLECTOR-FIELD FLOW,LB/MIN		0.0	0.0	0.0	0.0	0.0	0.0	0.0	134.3	280.9	369.6
HB NORM TO SUN,BTU/(HR-FT2)		211.2	212.8	234.7	235.1	234.9	236.2	235.1	237.2	242.5	248.8
HBN NORM TO APER		208.3	210.0	233.9	234.6	234.6	236.1	235.1	237.2	242.4	248.6
HEAT INC ON COL ROW,BTU/SEC		38.3	38.0	43.0	43.2	43.2	43.4	43.2	43.6	44.6	45.7
(TOUT-TIN),F	ROW										
DELTA T	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DELTA T	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DELTA T	3	2.5	2.4	-.2	-2.3	21.6	22.5	29.3	26.8	19.4	20.4
DELTA T	4	1.9	1.7	-1.7	-4.5	14.4	17.6	32.9	25.6	17.7	22.4
DELTA T	5	2.2	2.2	-2.4	-5.6	13.5	15.1	33.8	30.5	16.9	23.3
DELTA T	6	3.5	3.5	1.1	-1.7	1.5	20.5	39.6	34.1	22.0	26.5
DELTA T	7	3.6	3.1	-1.2	-4.4	2.6	22.2	36.7	33.2	19.8	23.7
DELTA T	8	-.2	-.9	-3.4	-6.1	-3.9	25.7	36.6	34.7	22.0	23.1
DELTA T	9	-.3	-.6	-.9	-3.8	-4.4	21.0	30.3	23.3	-216.2	20.2
DELTA T	AVG	1.9	1.6	-1.2	-4.1	6.5	20.7	34.2	31.0	-13.3	22.8
DELTA T	FIELD	31.7	31.9	33.0	32.7	-5.2	5.8	27.5	24.8	18.6	21.4
COL ROW FLOW	,LB/MIN										
FLOW	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FLOW	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FLOW	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.2	40.1	52.8
FLOW	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.2	40.1	52.8
FLOW	5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.2	40.1	52.8
FLOW	6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.2	40.1	52.8
FLOW	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.2	40.1	52.8
FLOW	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.2	40.1	52.8
FLOW	9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.2	40.1	52.8
COL ROW EFFCY ,PCT	ROW										
EFFCY	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EFFCY	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EFFCY	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.3	28.6	38.7
EFFCY	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.6	26.1	42.5
EFFCY	5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.9	27.9	44.2
EFFCY	6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.5	32.5	50.2
EFFCY	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.9	29.2	44.9
EFFCY	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.0	32.5	43.6
EFFCY	9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.1	-319.0	36.3
EFFCY	AVG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.3	-20.3	46.9
EFFCY	FIELD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.2	27.9	41.2
AVG VALUES											
COL OUT TEMP,F (AVG)		102.8	103.6	106.3	106.6	102.3	142.3	207.5	229.7	201.1	242.1
COL IN TEMP,F (AVG)		100.9	102.0	108.0	110.7	95.8	121.7	173.3	198.7	214.9	219.3
FIELD VALUES											
COL OUT TEMP,F (FIELD)		112.3	112.5	112.6	112.8	96.9	134.2	204.6	228.0	236.5	243.6
COL IN TEMP,F (FIELD)		80.6	80.6	79.8	80.1	102.1	128.4	177.1	203.2	217.9	222.2
DT OUT(AVG-FIELD),F		-9.5	-8.9	-6.0	-6.2	5.4	8.1	2.9	1.7	-35.4	-1.5
DT IN(FIELD-AVG),F		-20.[illegible]	-21.4	-28.2	-30.6	6.3	6.7	3.8	4.5	3.0	2.9

TABLE A-5. PAGE 3 OUTPUT; JUNE 23, 1978, 0751-0949

NOTE: Pages A-8 through A-20 were computer printouts of poor reproducible quality for a report.

Readers interested in further information about these data should contact one of the authors at Battelle, Columbus Laboratories, 505 King Avenue, Columbus, OH 43201.

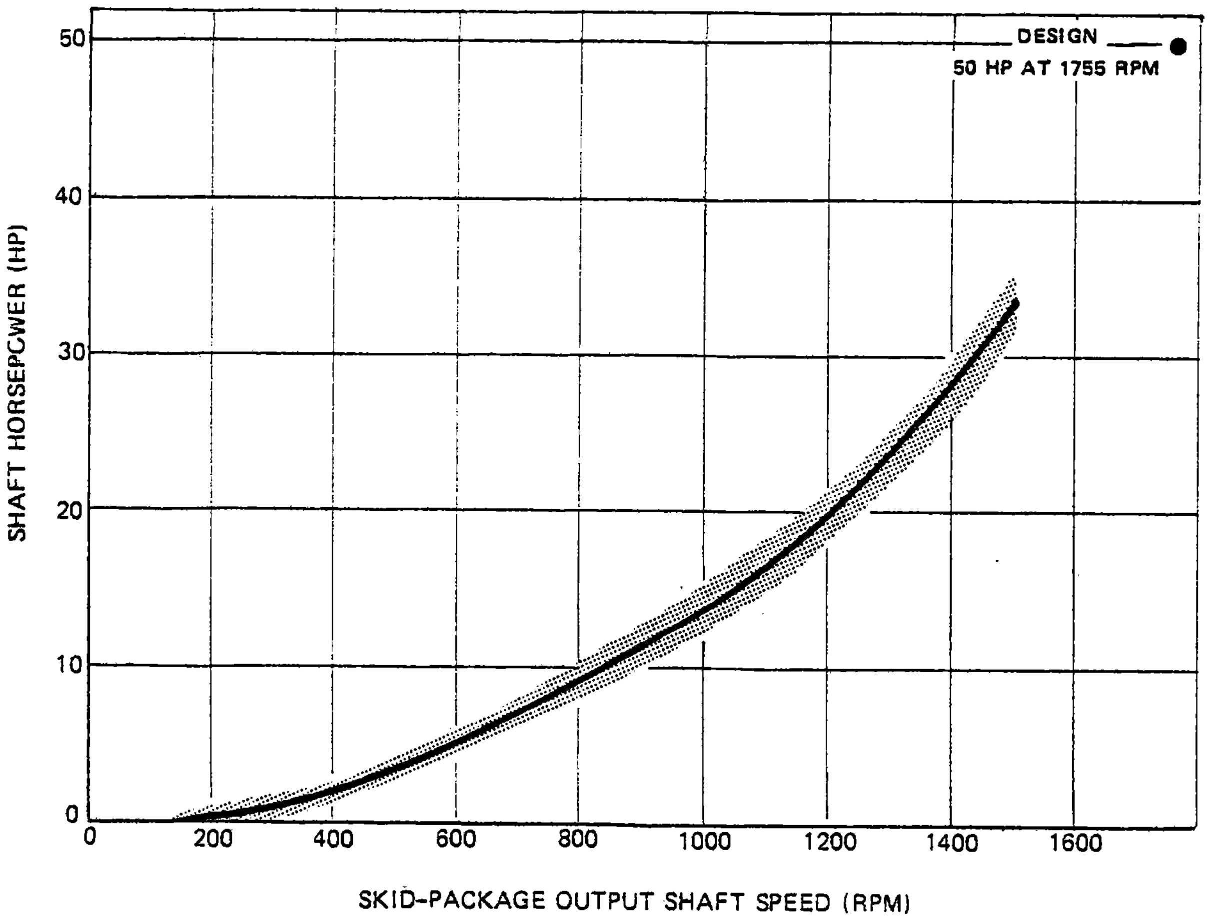


FIGURE A-1. OUTPUT SHAFT HORSEPOWER AS A FUNCTION OF SKID-PACKAGE OUTPUT SHAFT SPEED

[redacted]

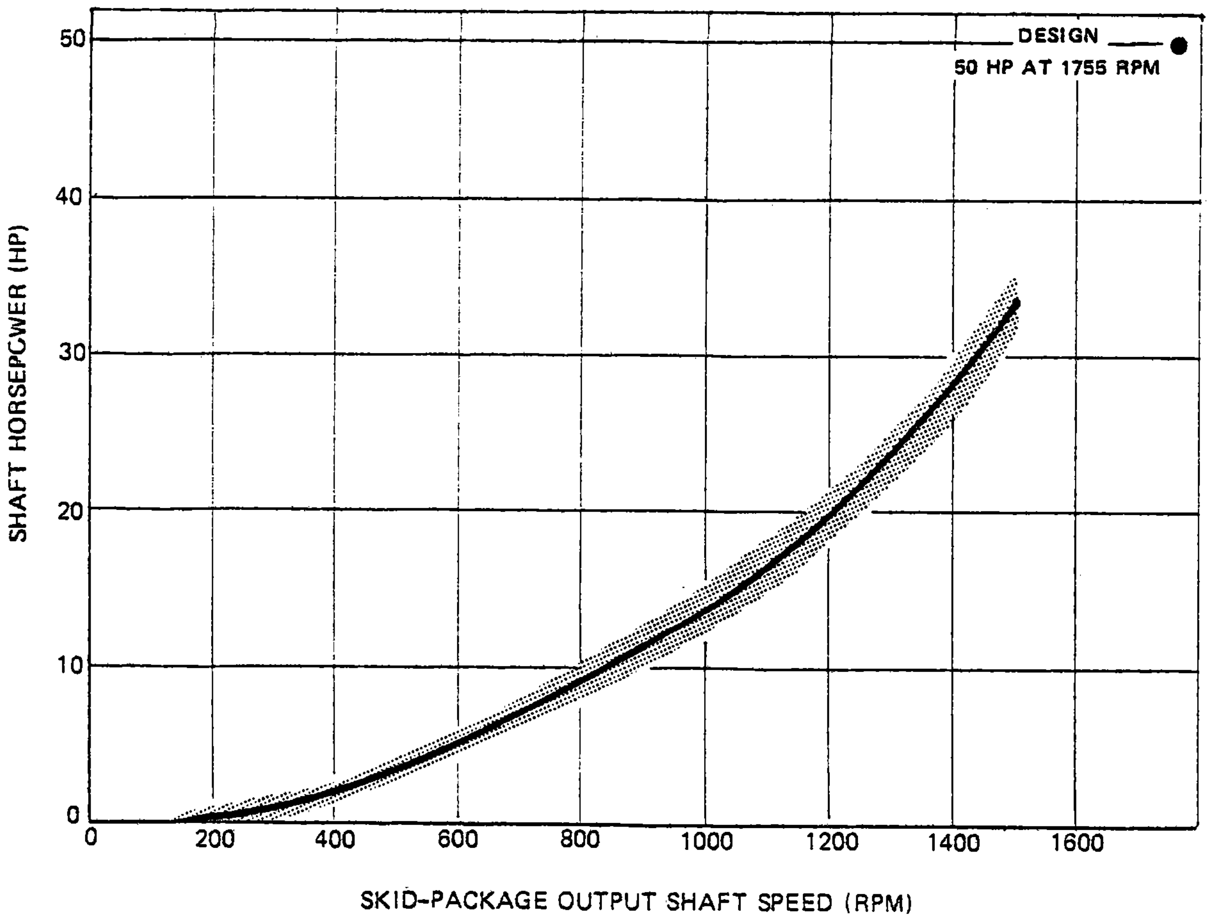
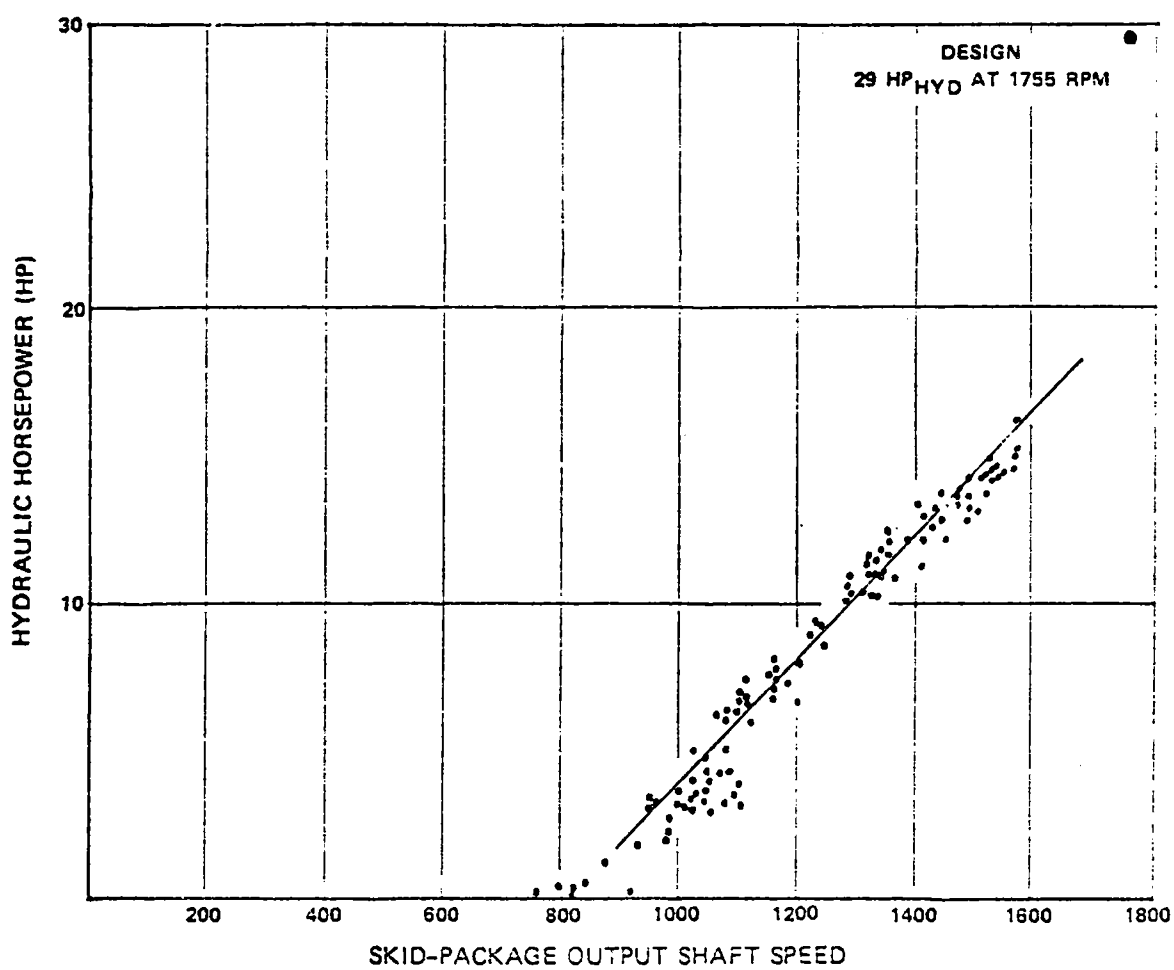


FIGURE A-1. OUTPUT SHAFT HORSEPOWER AS A FUNCTION OF SKID-PACKAGE OUTPUT SHAFT SPEED



Note: Higher flow losses in the pump discharge line (resulting from addition of a flow meter) yield lower net hydraulic horsepower than specified in the original design.

FIGURE A-2. HYDRAULIC HORSEPOWER AS A FUNCTION OF SKID-PACKAGE OUTPUT SHAFT SPEED

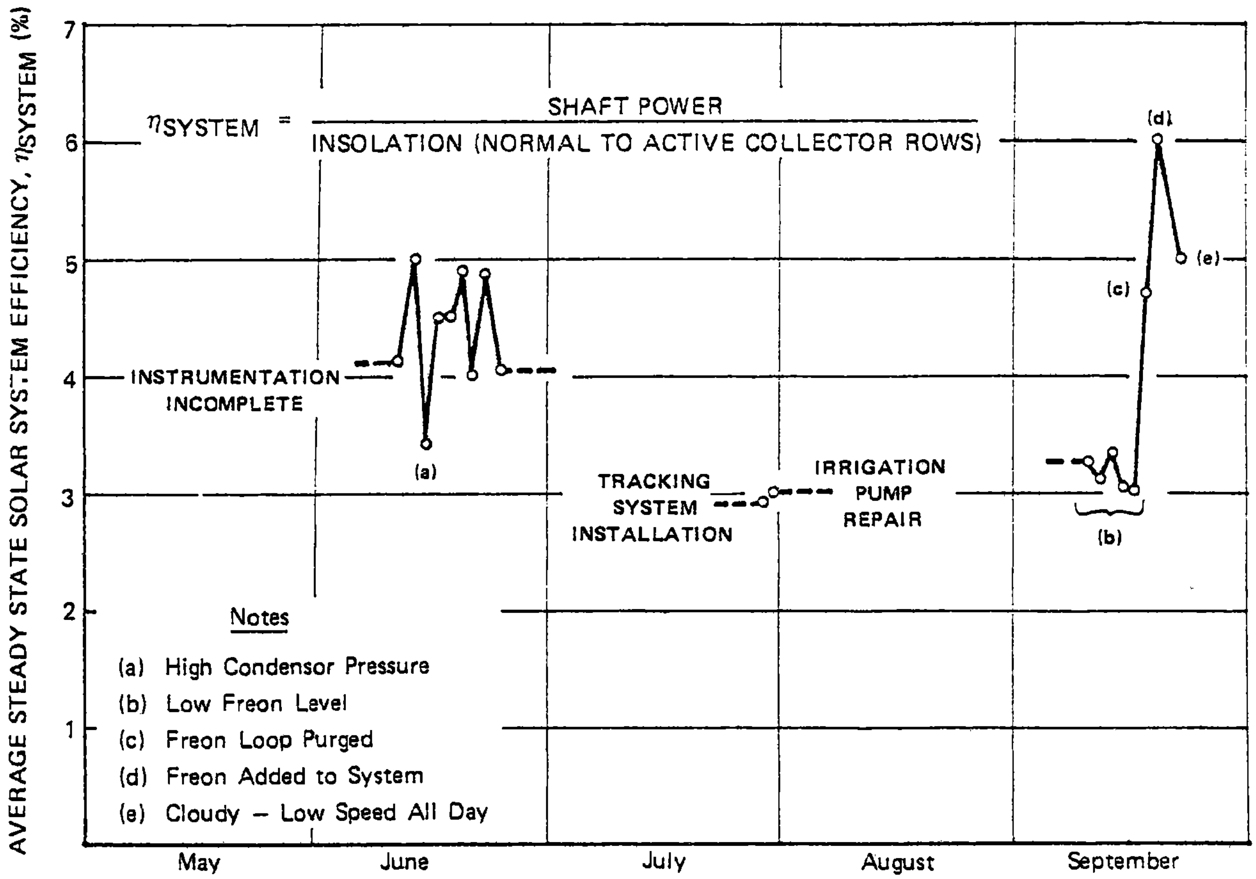


FIGURE A-3. AVERAGE STEADY STATE SOLAR SYSTEM EFFICIENCY VERSUS MONTH OF 1978 IRRIGATION SEASON

APPENDIX B

DETAILED DESCRIPTION OF DATA ANALYSIS PROGRAM

APPENDIX B

DETAILED DESCRIPTION OF DATA ANALYSIS PROGRAM

Raw Input Data

Raw input data is obtained from the magnetic tape written by the data logger and from manually recorded data entered through the terminal keyboard. The capacity of the Esterline-Angus data logger is 64 channels of information (labeled 0-63). Not all channels are used and there may be gaps in channel numbers. For example, Channels 52 and 53 are inactive but other active channels follow. Manual input data can be entered as 64 through 99.

Sorted Input Data

During sorting of input data, all inactive channels are filled with zeros and all input data are entered into an equivalent array labled 1 through 100. The array numbers are a value of 1 greater than the Esterline-Angus channel numbers because an array number of 0 is not permitted as an accessible storage-location indicator.

Page 1 Output Data

Page 1 Output Data lists and identifies pertinent temperatures. The values are unchanged from the input data recorded by the Esterline-Angus logger.

Page 2 Output Data

General system performance data are provided in the Page 2 Output Data. Output values are calculated as described in this section.

Assumption: Measured sump water level (SWELEV) is obtained in one of two ways:

(1) From data base for most recent previous entry

(2) From manual input data for this day

(a) If only one manually input value for the day, the value will be used for all data.

(b) If more than one manually input value available, the appropriate values for the time of the data points will be selected.

Output values are calculated as follows:

- $P_{preheater}$ = $6.2189\ V_{(23)}^{*}$, psia
- $P_{boiler\ outlet}$ = $6.4103\ V_{(22)}$, psia
- $P_{turbine\ inlet}$ = $6.1125\ V_{(25)}$, psia
- $P_{turbine\ exhaust}$ = $1.2019\ V_{(25)}$, psia
- $P_{condenser}$ = $1.2195\ V_{(26)}$, psia
- $P_{expansion\ tank}$ = $6.4103\ V_{(27)}$, psia
- Water Lift = SWELEV (or V_{68}) + 3.0417, ft
- $\rho_{R113_{feed\ pump}}$ = $f\ (V_{(7)})^{**}$, lbm/ft^3
- FA_{R113} = $f\ (V_{(7)})$; thermal expansion factor for R113 venturi flow meter
- CF_R = $FA_{R113}\ \sqrt{\rho_{R113}/\rho_{R113\ @\ 85\ F}}$
- CF_{R1} = $7.481\ CF_R/\rho_{R113}$
- ΔP_{R113} = $27.68\ (0.001\ V_{(58)} + 0.012)/1.0014$, in H_2O; pressure drop across venturi flowmeter
- If $V_{(67)} > 0.0$: $\Delta P_{R113} = V_{(67)}$
- $\omega_{R113,v}$ = $CF_R 10^{(0.4841\ \log_{10}\ (\Delta P_{R113}) + 1.4336)}$, lb/min; venturi flow, where $\omega_{R113,v} = 0$, if $\Delta P_{R113} = 0$.

---

* $V_{(23)}$ indicates value logged or entered in Channel 23, etc.

** f (   ) indicates value obtained from a polynomial curve fit of property data.

- $\omega_{R113,t}$ = $36.28\ P_{turbine\ inlet} / \sqrt{T_{turbine\ inlet} + 459.7}$, lb/min; turbine flow.
- $GPM_{fp\ actual}$ = $7.481\ \omega_{R113,v}/\rho_{R113}$
- RPM_{shaft} = $V_{(1)}/1.94$
- If $V_{(85)} > 0.0$: $RPM_{shaft} = V_{(85)}$

Assumption: Belt Ratio (BR) (feed pump to gear box output) = 3.46

- $GPM_{fp,\ 100\ pct\ vol\ eff} = 0.4008\ (7.4805)\ RPM_{shaft} / (BR \cdot \rho_{R113})$
- If ethylene-glycol ratio (ETHGLY) = 0: $\rho_{col} = f\ (V_{(16)})$ for water
- If ethylene-glycol ratio > 0: $\rho_{col} = f\ (V_{(16)}, ETHGLY)$ for E.G./H_2O mixture
- $FA_{col} = f\ (V_{(16)})$; thermal expansion factor for collector field venturi flowmeter (Barco 2-1/2-480)
- $CF_{col} = FA_{col} \sqrt{\rho_{H_2O\ @\ 70\ F}/\rho_{col}}$
- $CF_{col\ 1} = CF_{col}\ \rho_{col}/7.481$
- $\Delta P_{col} = 27.68\ (0.001\ V_{(59)} + 0.009)/1.0042$
- If $V_{(28)} > 0.0$: $\Delta P_{col} = V_{(20)}$, in H_2O; pressure drop across collector-field venturi flow meter
- $GPM_{col} = CF_{col} 10^{(0.489\ \log_{10}\ (\Delta P_{col}) = 0.891)}$, gal/min; where

  $GPM_{col} = 0$, if $\Delta P_{col} = 0$.
- $\omega_{col} = GPM_{col}\ \rho_{col}/7.481$, lb/min
- $V_{wind} = 0.075\ V_{(55)}$, mph
- $H_{total\ horiz} = 35.01 \left| V_{(31)} \right|^*$, Btu/hr-ft^2
- $H_{diffuse\ horiz} = 35.69 \left| V_{(30)} \right| CF_{shadow}$, Btu/hr-ft^2, where CF_{shadow} = f (time of year); seasonal correction factor for shading of ring on pyronameter

---

* | | denotes absolute value.

- TORQ $= V_{(56)}/(2.665(12))$, lb-ft
- $HP_{shaft} = TORQ \cdot RPM_{shaft}/5252$, hp
- $\rho_{cond\ H_2O} = f(V_{(18)})$, lb/ft^3
- $HP_{irrig\ pump\ (hydraulic)} = 4.051\ (10^{-6}) \cdot (\rho_{cond\ H_2O}) \cdot (GPM_{irrig\ pump}) \cdot$

  (water lift), hp; where $GPM_{irrig\ pump} = V_{(65)}$
- $P_{cond\ ideal} = f\ (V_{(6)})$, psia
- If limiting ΔP_{R113} is not available ($V_{(66)} \leq 0.$); set

  Volumetric $Efficiency_{feed\ pump} = 0$ (V.E. fp = 0)
- If $V_{(66)} > 0.0$: $GPM_{R113\ limiting} = CF_{R1}\ 10^{(0.481\ \log_{10} V_{(66)}\ +\ 1.4336)}$

  V.E. fp $= 100\ GPM_{R113\ limiting}/GPM_{fp}$ 100 pct vol eff
- $Q_{boiler\ inlet} = (CP_{col})\ (\omega_{col})\ (DT_{boiler})/60$, Btu/sec, where

  $CP_{col} = f\ (V_{(16)})$ for water in collector circuit, or

  $CP_{col} = f\ (V_{(16)}$, ETHGLY) for ethylene-glycol/water in collector circuit

  $DT_{boiler} = V_{(14)} - V_{(16)}$, °F
- $h_{turb\ inlet} = f\ (T_{turb\ inlet}, P_{turb\ inlet})$, Btu/lb, where

  $P_{turbine\ inlet}$ is set to 1. (10^{-8}), if logged values if $\leq$ 0.
- $s_{turb\ inlet} = f\ (h_{turb\ inlet}, P_{turb\ inlet})$, if $P_{turb\ inlet} \leq 50$ psia, Btu/lb-°F

  $= f\ (P_{turb\ inlet}, T_{turb\ inlet})$, if $P_{turb\ inlet} > 50$ psia

- $h_{boiler\ outlet}$ = $f\ (P_{boiler\ outlet})^*$, Btu/lb
- $\Delta h_{separator}$ = $h_{boiler\ outlet} - h_{turb\ inlet}$, Btu/lb
- Δh_{actual} = $h_{turb\ inlet} - h_{turbine\ exhaust}$, Btu/lb
- $PCT_{\Delta h\ loss\ at\ separator}$ = $100.\ \Delta h_{separator}/\Delta h_{actual}$, pct, or

  $0.$, if $\Delta h_{actual} \leq 0.$
- $\Delta h_{\Delta s=o}$ = $h_{turb\ inlet} - h_{turb\ exhaust,\ \Delta s=o}$, Btu/lb
- $Q_{hp\ equiv.}$ = $\Delta h_{actual}\ \ \omega_{R113,t}$, Btu/min
- $HP_{turb,\ internal}$ = $Q_{hp\ equiv}/42.4167$, hp
- η_{turb} = $100.\ \Delta h_{actual}/\Delta h_{\Delta s=o}$, pct, or

  $0.$, if $\Delta h_{\Delta s=o} \leq 0.$
- $Q_{reject\ to\ cond}$ = $(60\ Q_{boiler\ inlet} - Q_{hp\ equiv})/60.$, Btu/sec
- GPM_{cond} = $60.\ (7.481)\ Q_{reject\ to\ cond}/((V_{(19)} - V_{(18)})\cdot\rho_{cond\ H_2O})$,

  gal/min, or = 0., if $(V_{(19)} - V_{(18)}) < 0.$
- $\eta_{pwr\ sys\ effcy}$ = $Q_{hp\ equiv}/Q_{boiler\ inlet}$
- $\eta_{(pwr\ sys\ +\ irrig\ pump)\ effcy}$ = $100.\ (42.4167)\ HP_{irrig\ pump\ (hydraulic)}/$

  $Q_{Boiler\ inlet}$, pct, or = 0., if $Q_{boiler\ inlet}$

  $\leq 0.$

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* Calculation of $h_{boiler\ outlet}$ was based on the assumption of saturated vapor at the boiler outlet; this assumption proved to be invalid at some operating conditions.

Page 3 Output Data

Collector performance data are provided in Page 3 Output Data. Output values are calculated as described in this section.

- Assumption: Number of active collector rows (XN_{rows}) is set as follows:
  - (1) Default is 9 active rows
  - (2) Manual input data of number of active rows and row number of active collector rows.
- Active collector rows are indicated by a 0. or 1. in the data base at storage array locations 247 to 255 for Rows 1 to 9, respectively. Call this parameter ϕ_{Ni}.
- Collector row flows are obtained as follows:
  - (1) - If manual input data on ΔP for the 9 collector-row flow meters are available for this day:
    - (a) If only one set of manually input data, these values will be used for all data (see Item 1.C below).
    - (b) If more than one set of manual input data are available, the appropriate values for the time of the data points will be selected.
    - (c) $\omega_{col\ row\ i} = CF_{col\ 1}\ 10^{(0.4891\ \log_{10}\ \Delta P_{col\ row\ i}\ +\ 0.1)}$, lb/min

      $= 0.,\ \text{if}\ \Delta P_{col\ row\ i} = 0.$

      Then, if $\omega_{col} > 0.$, the collector row flows will be normalized so that the total collector flow by rows agrees with ω_{col}. This is necessary because coefficients in the equation for collector-row flow ($\omega_{col\ row\ i}$) are not accurately known.

If $\left(\sum_{i=1}^{9} \omega_{col\ row\ i}\right) < 0$; no correction needed

If $\left(\sum_{i=1}^{9} \omega_{col\ row\ i}\right) > \omega_{col}$: $RAT_f = \omega_{col} / \left(\sum_{i=1}^{9} \omega_{col\ row\ i}\right)$

If $\left(\sum_{i=1}^{9} \omega_{col\ row\ i}\right) \leq \omega_{col}$: $RAT_f = \left(\sum_{i=1}^{9} \omega_{col\ row\ i}\right) / \omega_{col}$

Then, $\omega_{col\ row\ i} = RAT_f\ \ \omega_{col\ row\ i}$.

(2) If manual input data on ΔP for the 9 collector-row flow meters are not available for this day, get 9 collector-row flows from the data base for the most recent data in which the collector flow for the fifth collector row is positive. Look up values in the data base only once for this day and use the values for all data points for this day. If any collector row flows retrieved from the data base are zero, normalize the relative ratio of flows ($RAT_{f,i}$) to give values for 9 rows by filling in average flow for zero data before calculating the relative ratios of flows.

- Get $\omega_{col\ row\ i\ sv}$ from data base, where $\omega_{col\ row\ i\ sv}$ = saved value of flow in collector row i.
- $RAT_{f,i} = \omega_{col\ row\ i\ sv} / \left(\sum_{i=1}^{9} \omega_{col\ row\ i\ sv}\right)$

Then calculate the collector-row flows for this and subsequent data points for this day as follows:

- $\omega_{col\ row\ i} = \omega_{col} \cdot RAT_{f,i}\ \ 9\ \phi_{Ni} / XN_{rows}$.

Other collector performance parameters are calculated as follows:

- $TIM_{solar} = TIM_{Gila\ Bend} + ET/60. - 0.5293.$ where ET is equation of time = f ($TIM_{Gila\ Bend}$).

Assumption: Latitude (Lat) = 33. deg.

Assumption: Aperture area per collector row ($A_{col\ row}$) = 5960./9.*

- $H_{beam\ horiz} = H_{total\ horiz} - H_{diffuse\ horiz}$
- Day_{yr} = 1. + Integer value of (TIME/24.)
- $\delta = 23.45 \sin\ [\frac{2\pi}{365}\ (284 + DAY_{yr})]$, deg; declination
- TC = time of day
- HR = 15. (12. - TC) $\pi/180$, days; hour angle
- $\cos\theta_z = \cos(Lat)\cos\delta\cos(HR) + \sin(Lat)\sin\delta$, where

  θ_z is angle of beam radiation incident on a horizontal surface
- $\beta = 90. - \theta_z$, where β is solar altitude angle in deg above the horizon
- $H_{bn} = H_{beam\ horiz}/\sin\beta$, where H_{bn} is normal to sun
- $\sin\alpha = \cos\delta\ \sin(HR)/\cos\beta$, where α is azimuth angle
- $\tan\Omega = \tan\beta/\sin\alpha$
- $\Omega = \tan^{-1}(\tan\Omega)$
- $\Omega = |\Omega|$, where Ω is projected solar altitude in east-west plane
- $H_{bna} = H_{beam\ horiz}/\sin\Omega$, where H_{bna} is normal to aperture
- $Q_{inc\ col\ row} = H_{bna}\ A_{col\ row}/3600$, Btu/sec
- $\eta_{col\ row} = 100.\ \omega_{col\ row\ i}\ CP_{col}\ (\Delta T_{col\ row\ i})/(Q_{inc\ col\ row})(60.)$
- $\eta_{col\ field} = 100.\ (V_{(14)} - V_{(41)})\ \omega_{col}/(Q_{inc\ col\ row} \cdot XN_{rows})$

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* Total collector area of 5960 sq. ft. was measured in accordance with ASHRAE Standard 93-77, based on edge to edge projected area of a nominal twenty foot module, excluding edging.

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