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SOLAR TOTAL ENERGY PROJECT FINAL TEST REPORT

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ABSTRACT

The Solar Total Energy Project (STEP), a cooperative effort between the United States Department of Energy (DOE) and Georgia Power Company (GPC) located at Shenandoah, Georgia, has undergone several design modifications based on experience from previous operations and test programs. The experiences encountered were discussed in detail in the "Solar Total Energy Project Summary Report" completed in 1987 for DOE. Most of the proposed changes discussed in this report were installed and tested in 1987 as part of two 15-day test programs (SNL Contract No. 06-3049). However, several of the suggested changes were not completed before 1988. These plant modifications include a new distributed control system for the balance of plant (BOP), a fiber optical communications ring for the field control system, and a new control configuration reflecting the new operational procedures caused by the plant modifications. These modifications were tested during a non-consecutive day test, and a 60-day field test conducted during the autumn of 1989. These test were partially funded by SNL under Contract No. 42-4859, dated June 22, 1989. Results of these tests and preliminary analysis are presented in this test summary report.

FOREWORD

The research and development described in this document was conducted within the U.S. Department of Energy's (DOE) Solar Thermal Technology Program. The goal of the Solar Thermal Technology Program is to advance the engineering and scientific understanding of solar thermal technology, and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates solar flux by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Parabolic dishes up to 17 m in diameter track the sun in two axes and use mirrors or Fresnel lenses to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multimodule system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100°C in low-temperature troughs to over 1500°C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve each system concept through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of DOE and its network of national laboratories that work with private industry. Together they have established a comprehensive, goal-directed program to improve performance and provide technically proven options for eventual incorporation into the nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Components and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning R&D activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to ensure a successful program.

The systems experiments of this study were conducted at the Solar Total Energy Project (STEP) at Shenandoah, Georgia, by the Georgia Power Company, in cooperation with the DOE and under the technical direction of Sandia National Laboratories. The STEP plant utilizes solar energy to generate a large part of the electricity and to displace part of the fossil fuels normally required to operate a commercial knitwear factory owned by Bleyle of America. The purpose of the experiments was to provide a better understanding of the relationships between the solar resource and demands placed on the system by the electrical power, process steam, and air conditioning requirements of the factory.

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1 Introduction.

The Solar Total Energy Project (STEP) is a 400-kilowatt co-generation steam power plant that uses both solar and fossil energy inputs and is the world's largest industrial application of the solar total energy concept. The STEP facility was completed by the United States Department of Energy (DOE) in 1982 for the purpose of testing the distributed collector concept in a co-generation application. The co-generation concept produced electricity with by-product waste heat being used for process steam and chilled water for air conditioning.

The STEP facility is located in Shenandoah, Georgia, 25 miles southwest of Atlanta International Airport, at Exit 9 of Interstate 85. The site consists of 5.72 acres in the Shenandoah Industrial Park adjacent to the Bleyle Knitwear Plant. The site also hosts other research programs to further the development of solar energy. STEP is owned and operated by Georgia Power Company with direct funding and technical support from Sandia National Laboratories. The United States Department of Energy monitors the continuing technical program.

During 1989, Sandia National Laboratories contracted with Georgia Power Company to perform a test program at the STEP facility to determine the effectiveness of the 1988 plant modifications. These plant modifications were partially funded by the Department of Energy and partially by Georgia Power Company. They were a continuation of modifications that were installed during 1986 and 1987. The original modifications consisted of a pressure surge tank, a larger area boiler tube bundle, a gas-fired steam superheater, new computer field control units, and silvered film to replace aluminized film on five solar concentrators. The later plant modifications (made during 1988) consisted of the installation of a new fiber optical communication ring to the collector field, a new distributed control system to the balance-of-plant (BOP), and various improvements to the collector field to improve reliability. A series of non-consecutive, sunrise-to-sunset, one-day experiments were run to test these plant modifications that emphasized the solar/fossil hybrid mode of operation. The solar collector field testing was performed in parallel with full-plant operational testing.

The focus of the 1989 test program at the Shenandoah STEP facility was monitoring the solar field performance and the reliability of the new fiber optical control system installed during 1988. A goal of the fiber optic installation was the elimination of spurious electrical signals, both internally and externally generated. The overall STEP plant performance was also monitored. The goal of this portion of the test was to integrate the new Foxboro BOP control system to optimize performance of the entire system. A measure of the performance of the new control system was developed by an analysis of data comparing electrical energy production with energy inputs produced by solar and fossil fuel sources in the plant. Other items of particular interest included a better definition of the relationship between energy added to the superheater, fossil-fuel powered heater, and the solar field; increases in over-pressure required to prevent two-phase flow of the Syltherm heat transfer fluid, and weathering properties of the silver film on the modified solar concentrators.

The principal deliverable of the 1989 testing was performance data for the operating solar thermal system resulting from the modified components or subsystems. This report presents a discussion of the test objectives and the results achieved, along with supporting input data, graphs and tables. The major 1988 and 1989 plant modifications, not documented elsewhere, are also included.

2 Experimental Program.

A series of modifications was recently completed to the control system for the BOP, and the collector field of STEP. These modifications included a new state-of-the-art BOP control system from Foxboro and a new fiber optical communications ring for the collector field control system. These improvements together with prior modifications completed the upgrade modifications to the original design of the STEP plant. Final testing of the complete package was conducted during the 1989 series of tests. This test series completed the evaluation of the STEP concept as a commercial product.

Two sets of experiments were performed at STEP during 1989. The first experiment consisted of non-consecutive day test runs of the plant during the fall of 1989. The second series of experiments consisted of continuous operation of the solar collector field concurrently with plant operations, as well as off-set track operation when non-consecutive day tests were not run. The solar collector field tests were performed with the goal of obtaining a high number of operating hours of the field components. During and following these tests, data analysis was performed, and the results are presented in this report.

The purpose of the non-consecutive day plant tests was three-fold. First, hybrid tests similar to those run in 1987 were repeated under more stable conditions with the new BOP and field control system. This yielded better analysis and confirmation of the previous 1987 results. Second, the results from this series of tests allowed the plant to be optimized by tuning the various control loops, and to be operated as an integrated system to define an optimum strategy of operation. Third, the tests of this sequence conducted in the solar-fossil hybrid modes allowed the development of data to determine the solar fraction of energy input to the plant.

During both test sequences, special emphasis was placed on the new collector field control system with its newly installed fiber optical communications ring. Tests were performed to measure the increased performance of the solar collector field that resulted from the fiber optical installation. In the 1987 tests, the collector field control system communicated with the collectors using electrically transmitted data. Although the system performed well and operator manpower requirements were much reduced, some problems persisted that precluded complete unattended operation. Among these problems were Collector Control Unit (CCU) boards damaged from lightning strikes and collector defocusing due to power spikes. Fiber optics helped to alleviate these problems by supplying a degree of electrical isolation. Field tests were performed to determine grounding, lightning and spurious power effects on the field control system. In addition, power down effects on field availability were also determined.

The BOP control system, with the new Foxboro Intelligent Automation (I/A) series of controllers, was studied in the non-consecutive day tests. This new system has many state-of-the-art features that provide for complete automatic control of the steam side of the plant. Lack of control stability due to manual operation of the plant hindered earlier tests. This problem was nearly eliminated with the new control system, which has easily configured software and many advanced features. Self-tuning control loops are among these features. Also, Foxboro is currently working with Georgia Power Company and Auburn University to develop an expert system that will optimize the steam turbine's heat rate. The control configuration developed for the expert was used during the non-consecutive day tests.

This final report covers the results of both sequences of tests. The non-consecutive day test results focus on plant performance and optimum strategies for various solar conditions. The consecutive field tests focus on operating experience for the collector field that may affect the plant as a commercial operation. Also, lessons learned from the

operation and installation of the collector field modules are included. Finally, conclusions and recommendations are developed for future scaled-up versions of a STEP-type facility.

The 1989 STEP Testing Project proceeded in three stages. During the first stage, the test site was prepared by making numerous repairs, calibrations, and plant modifications prior to testing. The plant was run in a non-test mode in order to determine potential problems and to prevent deterioration of the equipment. In the second stage, the plant operated during a series of non-consecutive one-day tests to determine the optimal operating strategies and to collect data. During the third stage of the test program the STEP field was run on a continuous basis. Specific tests focused on the collector field, the BOP, and the new Foxboro System.

2.1 Plant Modifications.

A number of plant modifications have been made since completion of the STEP facility in 1982. These modifications include a major redesign of the field control system for the 113 dish collector field, a new steam generator boiler tube sheet with 42% greater surface area, and a fossil-fuel powered steam superheater. An expansion buffer tank was added to the piping of the Dow Corning Syltherm 800 heat transfer fluid (HTF) to enable elevation of its operating pressure. In addition, five collectors were resurfaced with 3M Corporation's silvered film, ECP-300, having greater reflectivity than its aluminized reflective film, FEK-244, currently installed on the STEP collectors.

Several problem areas remained in the STEP process after all these plant modifications. These problem areas centered around the control system for the BOP and the communication system to the field. There were also several miscellaneous reliability problems remaining in the solar field components.

As designed, the STEP control system centered around a DEC 11/44 for field control, data collection, and some BOP control functions. The rest of the BOP process was controlled by a mixture of pneumatic and analog electronic devices. With the development of the new field control system, the DEC 11/44 lost most of its control function and became an over-powered data acquisition system (DAS). The BOP controls were partially upgraded in a piecemeal fashion with no integration of components. To make matters worse, the control philosophy behind the plant was based on the original design. The new plant modifications, e.g., the fossil-fuel steam superheater, required a new control configuration to match the new control philosophy that went along with it. As a result of these factors, the plant became a manually operated collection of individual processes.

The remaining problems in the collector field control system were less severe than those of the BOP. These problems were mostly component environmental reliability problems involving the communications link, and some other miscellaneous components such as Hall effect sensors, magnets, thermocouples, motors, and ejectors.

2.1.1 Balance-of-Plant Controls.

In the eight years since STEP was built, a technical revolution occurred in the area of digital distributed control systems. To take advantage of these developments, a new digital distributed control system was installed in the STEP facility. The new STEP control system is a fully distributed, modern control system by The Foxboro Company. The system is Foxboro's Intelligent Automation (I/A) series control

system. The I/A system employs the Intel 80286 microprocessor with a Unix-type operating system. The hardware installation at STEP consists of a work station with a CRT, a keyboard, a mouse, and touch screen capability. The work station has its own independent processor that communicates over a bus line to other processors. The other processors control an 80 megabyte hard disk drive, two communications ports, and the main process itself. The process control module communicates with field bus modules over a lower level bus, and they in turn terminate to instruments and devices in the field.

The control configuration resides in the I/A software. STEP as presently configured has 10 control loops, 25 analog input signals, and 25 output signals (10 analog outputs and 15 contact closures). The major control elements consist of a three-element loop controlling drum level, loops to control the heat transfer fluid (HTF) temperature from the collector field, and the HTF heater, and steam temperature from the steam superheater. There are two loops to control steam pressure and flow. The remaining loops control auxiliary equipment throughout the plant.

The control upgrade required some installations of new equipment. These new installations consisted for the most part of current-to-pressure (I/P) and pressure-to-current (P/I) devices to replace pneumatic controllers, a Fisher level instrument for the hotwell, an electronic retrofit for the Fisher level instrument on the deaerator, and a variable speed drive for one of the Field HTF pumps. All existing instruments were terminated on Foxboro field busses, although fewer were actually programmed into the control configuration. Thus, the addition of devices and instruments only required software changes at the work station.

2.1.2 Control Configuration.

Operating Doctrine. The original design of the plant required that steam superheat be supplied by the steam generator. This in turn required HTF temperature control by the field and the HTF heater. Subsequent operation and analysis determined that the field was better operated at lower temperatures, and that superheat added by fossil fuel energy represented a better utilization of fossil fuel input. As a result of these studies, a fossil-fuel superheater and a new steam generator tube bundle with more heat transfer surface was added to the system. The operating philosophy of STEP thus became: Operate the field to maximize heat transfer out of the field regardless of output temperature. The remaining thermal requirement will be supplied by the HTF heater and a fossil-fuel steam superheater. Practically speaking, this operating doctrine amounts to maintaining maximum mass flow rate of HTF in the field.

During the 1987 STEP tests this operating doctrine was further elaborated. It was discovered that drum pressure in the steam generator typically exceeded turbine requirements (first stage pressure) by as much as several hundred psig. Stable control of the drum pressure was difficult to achieve. However, with the use of the steam superheater, independent control of pressure and temperature became possible. Control problems ceased when drum pressure was matched to first-stage turbine pressure, plus a 40 psig. to 90 psig. throttle pressure loss through the admission valve. Furthermore, it was found that HTF temperatures out of the HTF heater were minimized for a given turbine output. The steam generator became a mass flow supplier for the turbine with minimum fossil fuel input.

The balance between fossil fuel inputs of the HTF heater and the steam superheater is optimized by recognizing that turbine power output is directly proportional to mass flow through the turbine, and proportional to the square root of the steam temperature. Thus the impact of an increase in mass flow is greater than that of steam temperature. Furthermore, the optimum velocity of the steam is twice that of the velocity of the turbine blade. Since steam velocity increases with temperature there is a point at which increased steam temperature results in increased exhaust temperature with less conversion to mechanical power. Final plant optimization is achieved when steam temperature out of the superheater is increased until exhaust temperature starts to rise. At that point optimum steam velocity has been exceeded.

In summary, the operating doctrine of STEP is as follows:

1. Maintain maximum HTF flow in the field regardless of solar conditions.
2. Determine desired electrical power output level of the plant.
3. Increase HTF heater temperature until steady state drum pressure reaches 60 psig. to 90 psig. more than the first-stage inlet turbine pressure.
4. Increase fossil-fuel superheater output temperature until exhaust temperature starts to increase above the saturation temperature for the given load and exhaust pressure.

Control Configuration. To implement the new operating doctrine, a new control configuration was developed for STEP in software for the Foxboro system. Functional block diagrams of this new control configuration are shown in Figures 1 through 7. Figure 1 shows the compound FIELD (a compound is a directory containing a collection of control blocks, or elements of control code). FIELD contains a proportional integral differential (PID) block that controls field flow, and blocks that control the positioning of FCV6030 and FCV6040. In addition, a computational block (FY6000) computes a heat balance from the field. This last function is the only important function in the compound since the flow is usually maintained at maximum. The control elements were added only to keep field temperature control an option. Heat balance from the field is important for control of the HTF heater. In all cases the input and output control blocks reside in compound PIO.

Compound HTFTMP in Figure 2 controls the firing rate of the HTF heater. PID8335 compares the drum pressure to first-stage turbine pressure differential with the desired setpoint differential and calls for increased or decreased drum pressure accordingly. The desired drum pressure is used as a set point in PID201. This controls drum pressure by increasing or decreasing HTF heater firing rate. Control block FY7070 computes heat balance for the HTF heater. This heat balance is summed with heat balances from the field and the fossil-fuel superheater. The energy balance from the turbine is subtracted out of the total and the result is used to bias the output of PID201. Thus, if energy balances in the plant change, the firing rate of the HTF heater immediately changes to offset the plant disturbance.

Compound SHSTMTMP in Figure 3 controls the firing rate of the fossil-fuel fired steam superheater. PID8101 controls steam outlet temperature by increasing or decreasing the firing rate of the unit. Control block FY212 computes heat balance for the superheater needed for control of the HTF heater.

Figure 1. STEP Collector Field HTF Flow Control Configuration

Figure 3. STEP Steam Generator Drum Level Control Configuration

Figure 4. STEP Steam Superheater Temperature Control Configuration

Figure 6. STEP Steam Bypass Flow Control Configuration

Figure 7. STEP Miscellaneous Control Functions Configuration

Compound FDWTRCONT in Figure 4 contains a three-element drum level control scheme that closely matches the original design configuration of the plant. Three-element control was abandoned for a simpler control scheme in the previous retrofit, using a programmable process controller by Yokogawa, YEW80 Series. Compounds CONCONTR, STEAM, and ODDSNENDS in Figures 5 through 7 contain various PID loops previously controlled by pneumatic controllers.

2.1.3 Field Modifications.

Modifications were made to the STEP field equipment in order to improve its operational reliability and to address several problems that were found during field operation. Lightning damage to the network and collector control units (CCU), actuator motor repair and replacement, and tracking errors were addressed by refitting the network with fiber optics, replacing actuator motors with new models on row one, and modifying the CCUs on row one.

Normal procedures were used to prevent problems with electrical surges in the collector field. These procedures included individual grounding of each collector, checking electrical contact resistance between the collector frames with the ground, using sacrificial chips on the collector control units and electrical surge protectors on the cables to the control room. Although these protection methods are normally effective for an individual collector, the aggregate of 113 serially linked collectors gave serious control problems due to spurious signals on the line, causing not just one, but often a whole row of concentrators to drop off the network. Therefore, the optical fiber network was chosen to improve the isolation between collectors.

Modifications of the Communications Network. The STEP field communications network and several of the CCUs were severely damaged by lightning. The lightning was determined to have traveled over the twisted pair wiring of the communications network into the CCU computers. In order to electrically isolate the CCUs, the network was refitted with fiber optic cables and fiber optic interface boards. There has not been a single incidence of lightning damage since the refitting.

The communications network also suffered from poor reliability during normal operation and especially during start-up. Network failure often sent most or all of the solar collectors to their stow position and induced additional problems with actuator motors. Each failure required a time-consuming procedure to restore the network operation. Communications reliability was improved by replacing two damaged fiber optic cables and by modifying several of the fiber optic circuit boards to improve the network's ability to isolate malfunctioning CCU processors from the network.

TABLE 1. Lock Rotor Test Results		
Motor Type	Run Windings Only	Run & Start Windings
1/10 HP Motor	2.5 Amps	2.75 Amps
1/15 HP Motor	2.0 Amps	5.0 Amps

The STEP design routes the communications signal through each of the 113 CCU processors forming a large loop network configuration. The original design tightly couples the CCU processors to the network. If any of the CCU processors malfunctioned, it would normally shut down part or all of the communications on the network. To help isolate the network from failed computers and damaged fiber optic cables, two modifications were designed and incorporated into the system.

The first fiber optic interface modification helps isolate a failed computer from the network. When a computer would fail to reset properly on power-up, it could cause the serial communications chip to energize the fiber optic transmitter and thus block the network. The circuit shown in Figure 8 detects when the transmitter is energized for more than 0.1 seconds and then reroutes the network around the failed computer.

The second modification isolates a failed network section. In addition to computer failure, fiber optic cable damage and unplugged fiber optic connectors cause failures by allowing sunlight to enter the network and block communications. The circuit in Figure 9 detects when the network signal is energized due to any of these failure modes for more than 0.1 seconds and shuts off the signal from the fiber optic receiver to stop further communications blockage.

Fiber optic interface boards were modified and installed at the north and south ends of collector rows one, three, and five. The proper functioning of these modifications was proven several times during collector field operations. Use of these modifications reduced the time it took to return the network to service after a failure. Modification of the entire field would greatly increase the network reliability. A new fiber optic interface board was designed that incorporates both modifications.

Automatic Field Monitoring and Control. One aspect of the test program was the automatic monitoring of field operation and the automatic control of tracking mode. To achieve this goal, software was written, and an interface between the fiber optic network and a microcomputer was designed to allow monitoring of the tracking mode. Neither the software nor the interface were completed, although some preliminary testing of a prototype interface was begun. The software and interface were intended to be used to tap into and not affect the communications on the network. This setup would log the start and end times of tracking periods, any collector that failed to track properly, the fault status of failed collectors, and the time of collector failures. Automatic monitoring and measurement of tracking time would have a far greater accuracy than that available from manual observation of the solar field.

TABLE 2. Actuator Relay Assignment	
Actuator	Associated Relays
Polar 1	K1, K2
Polar 2	K3, K4
Declination	K5, K6

Automatic Field Control. Preliminary design efforts toward monitoring and controlling the field from a microcomputer indicate that software can be written for a personal computer, which can then issue tracking commands and log collector status automatically. The timing of the communications is critical to the proper operation of the solar field, which must receive one command for each of the 113 collectors every 20 seconds. When a collector does not receive its regular command, it will go to the stow position. This timing requirement can be met using the task scheduler of the microcomputer or a similar timing mechanism on a PC. Sufficient components for the fiber optic to serial port interface are available on site using spare parts from the fiber optic interface boards.

Motor Replacement. Several of the motors used in the collector positioning actuators had failed and needed repair or replacement. The supplier of the original motors was no longer in business, so exact replacements were unavailable. Although many of the 1/10 HP motors were rewound, they tended to perform more poorly than the new ones did. The motors on the Polar 1, Polar 2, and Declination actuators on each of the nine Row 1 collectors were replaced with 1/15 HP motors available from a local distributor.

Several of the 1/15 HP motors seemed to suffer coil burn-out damage during normal operation. The stall and run currents of both the 1/10 HP and 1/15 HP motors were measured and are given in Table 1. The fuses used on the 1/15 HP motor were found to be too large at 5 amps and were reduced to 3 amps, Slo-blow type. While this prevented the motors from burning out, it resulted in excessive numbers of blown fuses. As a temporary measure, the fuses were replaced with 3-amp circuit breakers to reduce the time required to restore the collector to operation.

The rate of 1/10 HP motor failure from coil damage seemed to be increasing. It was found that the motor repair contractor was omitting the thermal protection device from the new coils installed in rewound motors. The lack of thermal protection led to the early failure of many 1/10 HP motors. One of the failed motors was disassembled, the coil opened and the thermal protection device located. The contractor was informed of our findings.

TABLE 3. Actuator Relay States		
Actuator Motion	Relay States	
	K1,K2,K3	K4,K5,K6
IN	Off	Off
OUT	Energized	Energized
STOP	Energized	Off
UNDEFINED	Off	Energized

The row-one actuators were found to jam when they were run to the fully retracted position. The 1/15 HP motors would then stall and trip the 3 A breakers. The actuators that regularly jam are assumed to have been over stressed during their operational life. It was found that the actuators would not jam if they were prevented from going to the fully retracted position. Limit switches were added to collectors 108 and 109 of row "one" to address this problem.

In order to limit the travel of the actuators, the motor drive relays circuit had to be modified and a source of the limit signal generated. The motor drive relay circuits associated with actuator travel [found in the Control and Instrumentation Subsystem (CAIS) Manual, Figure 3-6, CCU Functional Block Diagram, page 3-23], and the relay states associated with travel direction are given in Tables 2 and 3. The CCU circuit of Figure 10 shows where the limit switch signals could be injected.

On Collector 109, a microswitch was mounted on the collector support frame to detect full south travel of the declination actuator. The limit signal shown in Circuit A of Figure 11 energizes relay K5 stopping further south travel while still permitting north travel of the actuator.

On collector 108, a Hall Effect Sensor (HES) and a magnet were mounted on the collector support frame to detect full east travel of the Polar 1 Actuator. The limit signal shown in Circuit B of Figure 11 energizes relay K1 stopping the Polar 1 Actuator motion while still permitting west travel.

The rate of motor failures has been greatly reduced since the addition of correctly sized breakers, and the rate of tripped breakers due to jammed actuators has been reduced since the addition of limit switches on the offending actuators.

Modification of the Collector Control Units. Several problems with the CCUs have been noted since their installation by Prime Manufacturing in 1986. The nine CCUs on Row 1 were modified in February 1989 to address these problems. The following descriptions of the problems and modifications are taken from a letter by Tommy Hicks, an engineer with Prime Manufacturing, Inc.

1. Regions of the circuit traces on the printed circuit board of some of the CCUs were found to be corroded. This problem resulted from electrolysis of the traces due to the operation of the CCUs while under power and with water on the board. Water could reach the boards if an enclosure had to be opened during wet weather. This problem was addressed by the application of a waterproof coating to the nine CCUs on row one.
2. The new 1/15 HP motors did not always reverse direction properly if the motor was already rotating and the CCU gave it a command to rotate in the reverse direction. This problem was due to the difference in characteristics of the new 1/15 HP motor and the old 1/10 HP motor. The old motor used a "capacitor start and run" design, which allowed reversing direction simply by reversing the power polarity. The new motor used a "relay start" design, which requires the motor to come to a complete halt before reversing power polarity. This problem was addressed in the software of the CCU by inserting a three-second delay to allow the motor to come to a complete halt before the motor direction was reversed.

3. Due to errors in the original design, some of the units would intermittently fail to execute their programs correctly. This was caused by memory errors due to electrical noise and occurred most often during initial power up of the field. Once the failed CCU was located, it could be brought back to normal operation by turning its power off for a few seconds and then back on. A "watch dog" timer circuit was added to detect the problem and to reset the CCU. Unless the watch dog timer is reset by a periodic signal provided by the proper execution of the CCU programs it will wait for one second and then reset the CCU.
4. A manufacturing problem was traced to a batch of mislabeled capacitors used in the A/D clock generator. The improperly sized capacitors caused the A/D convertor to run at a sampling period of 20 seconds instead of a faster rate. The speed was increased by using the baud rate clock from the communications chip in place of the capacitor-controlled A/D clock.
5. Some of the collectors would sometimes add or lose rotation counts, resulting in tracking errors and an increased incidence of motor problems. This problem was attributed to coasting of the motors after the halt command was given by the CCU. The CCU hardware and software were modified to properly decode the direction and count signals from the two Hall Effect Sensors used to sense rotation. In the modified CCU, when the hardware detects that the count signal has gone high, it records the state of the direction sensor. If the direction sensor is still in the same state when the count signal goes low, then the count is considered invalid and is not used. Otherwise the count signal is considered valid and is used to update the position status of the collector.

Figure 8. Modification A to the Fiber Optic Interface

Figure 9. Modification B to the Fiber Optic Interface

Shenandoah Solar Center	
Title	
Relay Driver Circuit	
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A	
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Figure 10. Relay Drive Circuit

Figure 11. STEP Field Limit Switches

2.2 Description of Experiments.

To meet the requirements of the test program two different test specifications were prepared for SNL approval. The first test specification required non-consecutive day operation of the entire STEP plant. The second test specification called for operation of the collector field either in focus in conjunction with plant operation or alone in off-set track. The number of tests of each type was determined by the available solar resource. Each test type is described in the sections that follow.

2.2.1 Non-Consecutive Day Plant Test.

Objectives. In this test the objectives were threefold. The first was to determine the energy contribution of the fossil-fuel steam superheater and its relation to the solar collector field and the fossil-fuel HTF heater energy contributions. The second was to determine the impact on overall plant performance of the new BOP controls system. Finally, the objective was to evaluate the control configuration developed for the BOP control system and assess its impact on optimizing the performance of the plant.

Activities. In order to determine the impact of the various fossil-fuel and solar energy sources on the system, data were collected on magnetic disk using the Foxboro I/A series control system. The Foxboro system has a data acquisition feature integrated into its software. These data were used to compute complete energy balances for the various plant subsystems. The components monitored included the collector field, the fossil-fuel HTF heater, the steam generator, the fossil-fuel steam superheater, and the turbine generator. Process steam, and A/C from the absorption chiller were not generated in this test. All data were collected on a once-a-minute basis.

Throughout the day the overall condition of the collector field was noted in the daily operating log book and start-up anomalies were noted. In addition, the status of the collectors was noted and any failures were logged and categorized. The field status was noted in the log each time a stable operating point of the plant had been reached, and these records were used to determine the percentage of collectors available and in focus.

The solar/fossil-fuel hybrid mode of operation allowed operation during periods of variable solar resources. The FFH was operated at variable temperatures determined by the control system to maintain drum pressure at a fixed set-point level. The drum pressure was set to maintain a differential of 60 to 90 psig. between the drum and the first stage of the turbine. This pressure differential was determined for each of several generator output levels, which were held fixed for a period of stable operation. The SSH was initially set at 720 degrees F and varied downward by increments of 20 degrees F until the turbine exhaust reached 230 degrees F. This was considered the optimum operating point for the plant.

The HTF loop operating pressure was maintained at 40 psig. throughout the tests. A sample of HTF was taken at the end of the final test day. The samples were shipped to the manufacturer, Dow Corning, for chemical and physical analysis, discussed in section 3.1.3 of this report.

2.2.2 Collector Field Test.

Objectives. The Sandia/STEP collector field test was conducted with three major objectives: evaluation of the impact of field modifications on field operation, measurement and analysis of the failure rates and failure modes of the major collector subsystems, and measurement of the collector field operation time. While the original test specification called for the operation of only Rows 1, 2, 3, and 5 for a total of 20,000 hours, the entire field was operated to ensure maximum collector availability during full plant testing. The test was conducted with four technical goals: to log the collector operation time, to log all collector failures and modes, to determine the mean time between failures for the major collector field components, and to log the performance of the fiber optic network and collector control system both during full plant operation and during field only operation.

Activities. The day's activities began with the application of power to the collector field from the electrical breaker enclosures located between Row 6 and Row 7. HTF fluid flow through the collectors was maintained in the field whenever it was possible that a collector might go into focus due to a mechanical or controller failure. Typically upon power-up one or more of the CCUs would fail in a way that blocked communications over the fiber optic network. The failed CCUs were located by shutting off power at the breaker enclosure in a pattern that progressively isolated the failed CCUs into smaller and smaller portions of the network. A failed CCU could then be brought back to normal operation by turning its power off for a few seconds and then back on. Once communication to the entire field was established the field could be commanded to go into offset-track mode from the touch screen control panel in the control room. The field operation was monitored by personnel in the field, and any non-operating collector, its failure mode, and the time of the failure was recorded in the log sheets. At the end of the day the field was commanded to stop tracking and to go to the stow position. Once all the collectors were in the stow position, the power to the field was removed at the breaker's enclosure and HTF fluid flow was discontinued.

Both the solar field operation and reliability data were recorded on the collector field reliability status log sheets. The data for the modified collectors in Row 1 could then be compared with the data for the modified collectors to evaluate their relative performance.

While the test specification called for separate operation and reliability log sheets, the reliability log sheets also contained all the required information on the hours of field operation. The collector-field reliability-status log sheets contain information on which collectors were not operational, when they failed, how they failed, and when they were returned to service.

2.3 Experimental Methods.

Balance-of-Plant Testing Method. A greater degree of stability became available with the installation of the new control system. In the 1987 test, stability was difficult so that one-hour averaged data were used for analysis purposes. In the current test, stable operating points were established and times noted. Data collection was accomplished by the Foxboro control system, which has its own data acquisition system (DAS), or data Historian. The data Historian resides in the software of the control system. Once the data are collected, they are stored on hard disk in report formats by the Informix report writer software package. Data used for analysis were representative one-minute average points chosen during stable operating periods rather than

longer period averages of data. The one exception to this involved the insolation data. Because the level of thermal output of the field lagged a change in the insolation level by about seven minutes, a seven-minute average of the insolation data was used in the computation.

The experimental procedure used throughout the tests was to operate the plant at one of several electrical output levels chosen in order to obtain variability of the data set to be derived from the tests. This was done after the plant was warmed up and on-line. Operation would continue at that power output level until a sufficient number of stable operating points had been collected. Stable points were deemed to be those at which process variables were close to their set-points and when effects of plant upsets from the field and other sources were not present. A census of field collectors was taken at or around these times to correct insolation values for variations in efficiency due to loss of collectors.

Two factors complicated the analysis. First, the deaerator has had a long history of control problems that are introduced by a periodic upset in the form of increased and decreased steam demand. This sawtooth upset, with an approximate period of three minutes, added noise to the steam flow measurements. To correct this problem, data points at or near median flow rates were favored heavily during data selection.

The second complicating factor actually turned out to be a benefit. It was difficult to obtain variable operating ranges of the plant due to the unusually good solar conditions throughout the test. We needed to operate at several power production levels and solar insolation levels. It was impossible to measure characteristics of plant performance at lower insolation levels since most days logged insolation levels in excess of 900 watts per square meter. However, the number of collectors on line varied greatly over the test. This allowed discounting of the field efficiency to obtain variability in solar input. The procedure used involved normalizing insolation inputs to an average field performance of 105 collectors on line.

Reliability Testing Method. The intent of the reliability experiment conducted on the solar field was to determine the mean time between failures for the major collector components and to determine the effect of modifications to the collector field by comparing reliability between rows. The data collected for reliability analysis were recorded manually on log sheets and were derived from control panel messages, control panel printer output, and from visual inspection. Collector status was recorded from the time at which the field was commanded into the track mode until commanded into the stow mode. All of the known collector failures were recorded along with the time of loss of collector service and the time of return to service.

Reliability Experiment. The operation and failure data were entered into log sheets. The operational hours for each row of collectors were determined and the failure data were grouped by both row and failure type. Then the mean time between failure (MTBF) per collector for each of the major collector components was determined. The reliability of the Row 1 collectors was then compared with that of the control Rows 2, 3, and 5. In addition the overall field reliability was determined.

3 Experimental Results.

In the following section the results of the 1989 STEP test program are summarized.

3.1 Non-Consecutive Day Plant Test.

In order to improve the conversion of thermal energy into electricity there are two main areas of interest in testing the BOP portion of the plant. The first is the performance of the individual components to convert thermal energy to electrical energy. The second area is in the management of the operation by a new control system through its control of the individual components and through the operating doctrine imposed on the system by the overall philosophy imbedded in the control configuration.

3.1.1 Plant Performance.

The performance of the STEP plant was measured by operating the plant over a range of generator output levels and insolation levels. Since there is no control over solar input to the collector field, generator output was held fixed at one of several levels until stable plant conditions prevailed. Changes in solar input and number of collectors available supplied the variability necessary to develop a model of solar fraction as a function of generator output and insolation shown in

Figure 12.

the graph above. The curves shown in Figure 12 are developed from two different equations, one for below 650-watt insolation, and the other above 650 watts. Each of the curves shown above has constant insolation values. The curve for 530 watts of insolation fell off rapidly because the field had barely enough energy to keep the plant operating even at minimum levels of output. The data points shown on Figure 12, along with the curves, were those with insulations within 5% of the constant values of their respective curves. Data outside these ranges were excluded from the figure for purposes of fair representation. Both equations, below and above 650 watts, were developed using an exponential form with regression analysis. The equations used are shown below:

$$\ln y = a + bx + cz,$$

where y = the solar fraction,
 x = kW generator output, and
 z = solar isolation in watts.

This expression may be used to predict solar fraction, or fraction of the plant's input energy that was supplied by the solar field, from a desired generator output and available solar input. A more convenient way of representing the same information is shown in Figure 13 below. Here each curve represents a constant value of solar fraction and the ordinate and abscissa are solar isolation and generator output, respectively. The generator output may be varied given the solar isolation input to the field to maintain a desired solar fraction, which is set by policy. The curves in Figure 13 were derived directly from the curves shown in Figure 12 without the use of curve fitting. A plant operator is able to choose the best level of electrical output, given the amount of solar insolation, by referring to Figure 13.

Figure 13.

One feature of the data should be noted in Figure 12. When examining the entire set of data plotted, one notices that scatter of the data was more pronounced at the lower generator output levels than at higher levels. This lessening of scatter was caused by the tendency of personnel to operate the plant at higher output levels when solar resources were abundant and the field reliability was high. The tighter data scatter indicated a tighter range of operating conditions rather than more inherent stability of the plant at higher output levels.

Field efficiency as a function of field differential temperature, i.e., field outlet temperature minus field inlet temperature, was examined as part of the plant tests. The results are shown below in Figure 14. Here are shown actual data points along with a curve fitted to the data. The relative flatness of the curve seems to agree with earlier results found by Stine and Heckes [9], which suggested flatness due to a trade-off between First-law and Second-law efficiencies.

The curve form chosen to fit the data was an exponential form that rose rapidly near zero, then more slowly as the ordinate increased. This is the sort of behavior one expects from efficiency as temperature differential increases in the field. Temperature differential should correlate directly with field efficiency. However, as the overall temperature in the field rises, conductive losses in the field will increase in proportion to difference between field temperature and ambient temperature. Convection and radiant losses increase more rapidly at higher temperatures than do conductive losses. Thus, the efficiency curve levels off at higher differential temperatures.

Figure 14.

Although an exponential curve best fits the data, its curvature was not very pronounced. Derating the field to compensate for missing collectors tended to "linearize" the data more than it should, although larger than normal losses are expected due to downed collectors. The noise, or scatter, of the data seen in Figure 14 is large in some cases. Although all the data collected from the experiment are shown, 14 of the points were excluded from the estimation of the curve as outliers.

3.1.2 Balance-of-Plant Controls.

A major problem encountered in the control of the BOP was a periodic upset in steam flow caused by action of the deaerator unit. The problem is exemplified in Figure 15 below showing steam flow from the steam generator for sampled periods from two different operating days. The sample periods are from October 12, 1989, and October 27, 1989, which compares steam flows before and after corrective actions were made to the deaerator. On October 12 the problem was pronounced, with a 1200 lbs/hr steam flow oscillation with a period of about three minutes. On October 27, the steam flow fluctuations were more random with less excursion.

The cause of the problem goes back to the construction of the plant when the level control on the deaerator was mounted nine inches too low. This resulted in the deaerator unit being controlled in on/off fashion by the limit switches on the unit. This problem persisted until recent action isolated and fixed the problems. During the installation of the Foxboro control system the level instrument was mounted to its correct height; however, during installation of Foxboro software a mistake was made in reversing the sense of the PID block controlling condensate level in the

Figure 15.

de-aerator. The problem was difficult to diagnose because the limit switches were still activated in hard-wired fashion and masked action by the Foxboro control system.

Finally after the software errors were eliminated, the loop proved impossible to tune because the flow control valve acted over a 30-second period and the process acted in less than 10 seconds. The I/P converter controlling the flow control valve was found to have limited air handling capability. The problem was eliminated when the I/P converter was exchanged for a larger unit as seen in the October 27 data in Figure 15. Tuning of the control loop and repair to the valve may improve performance further.

The performance of the new control configuration can be seen in Figure 16. Here the data were taken from a test run on October 23, 1989. The solar input to the collector field was excellent throughout the day, except around solar noon when a cloud bank came through. The operation level of the plant was established and stabilized prior to this period. As insolation to the field fell HTF return temperature started to drop. As the total heat balance in the plant began to change, the biased output from the HTF heater control PID block adjusted to increase the firing rate of the HTF heater. Thus, heat balance in the plant was preserved with the additional energy from the HTF heater making up the difference. The PID controller to the HTF heater controlled drum pressure as an input, in addition to the biased output from the heat balances. The drum pressure input to the PID block allowed finer and slower response time adjustments to the HTF heater firing rate.

Figure 16 shows another upset to the plant around 1430 hours when the output from the generator were changed to a higher level. Again the heat balances throughout the plant was disturbed. The control system again responded to the disturbance by an immediate change upward to the HTF heater firing rate followed by slower control action to maintain a set drum pressure. It should be noted that during the first plant upset when insolation fell, no intervention by the operator was necessary for the plant to recover equilibrium. However, during the second upset when the output level of the plant was changed, set points for drum pressure and the fossil fueled superheater temperature were also changed to levels known to establish a new equilibrium.

Figure 17 is from a plant test run on October 27, 1989. This set of data shows nearly ideal operating conditions for both solar conditions and the plant in general. Here the plant was warmed up and operated at about 200 kW for nearly an hour before being set up to 265 kW for the rest of the day. Initially, the drum built up pressure as the system warmed up. Steam flow was increased to maintain above minimum flow while the steam superheater heated up under fire. After the turbine came on line, conditions stabilized until the generator output was increased and the plant stabilized again. The output of the plant remained constant throughout the rest of the day.

Several features of Figure 17 are notable. First, a modulation in output temperature from the fossil-fuel steam superheater is present. A smaller modulation is also present in the drum pressure. In both cases the problem is probably due to slightly out-of-tune control PID blocks. Judging by their responses to upsets, both controllers may be slightly under-damped. Also, the bias parameter in the HTF heater controller may need fine adjustment, as it seems to over-compensate for changes to plant heat balances. Finally, the de-aerator still has some problems in stabilizing steam flow. This problem, while not as great as before, may be due to PID control block tuning and valve wear.

All Scales (except Steam Flow)

10/23/69

Figure 16.

All Scales (except Steam Flow)

10/27/89

Figure 17.

Near the end of the day the plant was shut down because the turbine developed bearing noises. The noise was intermittent and lasted less than 30 seconds in each case. The noise prompted the plant operators to bring down load in several steps. The noise occurred each time the turbine load was reduced. Finally, before the turbine could be shut down it tripped due to high vibration. Later when the turbine was disassembled for inspection it was found that the thrust bearing on the low pressure side had worn down to bare steel and that the turbine bound up due to lack of clearance. No wear was apparent in the other bearings. The timing of bearing noise indicates an out-of-balance condition during load reduction. It may be that constant extraction steam flow oscillation caused by the deaerator brought about the wear to the low-pressure thrust bearing.

3.1.3 Heat Transfer Fluid Performance.

In earlier system tests it was determined that the heat transfer fluid (HTF), Syltherm 800 (tm), was being used outside of its optimum pressure and temperature point. The original vendor data indicated a greater operational range than was evident from STEP experience. The STEP plant suffered from pump cavitation and clogging of the fluid transfer components due to the HTF phase change and degradation. The problem was addressed by adding an expansion tank, which allowed the HTF system to be operated at a higher pressure. The HTF chemistry analysis results in Table 4 show the differences in HTF quality after the addition of the expansion tank immediately before the 1987 testing.

The viscosity went down to acceptable values in 3/9/87, and an increase in the percentage of the lighter molecular weight components, the cyclics and linears, indicated that less degradation of the HTF was occurring. The Dow Corning analysis of 1/12/90 states that the HTF contains reasonable levels of contaminants. This analysis is supported by the performance of the HTF observed during the plant testing. No problems with pump cavitation or clogging of the fluid transfer system were encountered. Although the HTF was found to perform quite satisfactorily, its high cost remains its primary disadvantage.

TABLE 4. Dow Corning Chemical Analysis of the Syltherm 800(tm)					
Property	3/31/86	3/89/87	8/27/87	3/11/88	1/12/90
Viscosity (cs):	16.4	10.79	10.37	10.75	10.47
Acid Number:	0.165	0.224	0.102	0.140	0.044
Flash Point (F):	200	175	150	160	180
Total -OH (ppm):	421	866	240	161	155
Free Water (ppm):	209	196	438	114	56
Cyclics (%):	2.56	5.58	10.85	8.3	4.93
Linears (%):	3.16	8.01	11.40	10.4	10.43

3.2 Collector Field Test.

After the modification of the field communications network and the replacement of Row 1 motor breakers the solar field performed quite well. Some solar field modifications discussed in the recommendations section would allow further improvement in the field reliability and monitoring.

3.2.1 Field Controls.

Collector Hours Summary. The hours of collector operation are summarized in Table 5. The hours of collector operation for thirty days are given and are broken down into the hours for each row. Since there are nine collectors per row on all odd numbered rows and there are ten collectors per row on even numbered rows, except for row 12 with only nine collectors, the even numbered rows will produce more possible collector hours per day.

Rational for Operating Entire Field in Off-Set Track. While the original test specification required only the operation of rows 1, 2, 3, and 5 the entire field was run during the test execution. The entire field was operated to help ensure that any problems with the collectors would be found and the maximum number of collectors would be operational during plant testing.

Demonstration of the Fiber Optic Interface Modification. Several instances of network fault isolation were recorded in the field operation log sheets. In each instance of network failure the rows protected by the fiber optic interface modifications continued to function while communications on unprotected rows stopped. Modifications were added on the far north and south collectors on Rows 1, 3, and 5. Network failures were observed in which Rows 1 through 5 continued operating while Rows 6 through 12 lost communication, causing the collectors automatically to go to the stow position.

3.2.2 New Field Components.

Field Reliability Summary. The collector field reliability and the mean time between failure information is summarized in Table 6, which is a summary of collector reliability. One area of low reliability both on Row 1 and in the entire field is in the mechanical components. In large part this is due to the aging of the field components, such as flexible fluid lines that would leak and actuators that would jam. Another area of low reliability was in field communications. This problem was due primarily to the sensitivity of the network to the failure of any

TABLE 5. Collector Operations Summary												
Row	1	2	3	4	5	6	7	8	9	10	11	12
Hours	1549	1720	1645	1647	1596	1738	1520	1506	1426	1558	1460	1619
Collect./Row	9	10	9	10	9	10	9	10	9	10	9	9
Hrs/Collect.	172	172	183	165	177	174	169	151	158	156	162	180

of the 113 collector control units. The reliability of both mechanical and communications systems could be improved, and recommendations for improvements are given in the recommendations section.

Row 1 Mechanical Failures. While Row 1 apparently had the most mechanical failures of any of the twelve rows, almost all of the Row 1 mechanical failures were due to temporary jamming of worn and deteriorated collector positioning actuators. This seemed to be aggravated by the reduction in size of the actuator motors from 1/10 HP to 1/15 HP. Excess wear was due to the fact that the actuators had been stressed often during their lifetime by being driven to their extreme limit of travel. The jamming problem was eliminated on collectors 108 and 109, which had regularly jammed because of the installation of two prototype limit switches. These limit switches were installed in late November near the end of testing and had little effect on the reliability statistics.

Hall Effect Sensors. The old connections between the Hall Effect Sensors (HES) and the CCUs retained rain water, which caused corrosion and shorting. Crimp-on style connectors were used to replace the old connections. New connectors were installed on every collector that failed to track properly due to inaccurate position information. Many of the collectors had to have the sensors reworked before field testing began. The sensors are used to monitor the actuator position by counting rotations of the actuator motors. The position reading was inaccurate due to lost rotation count signals by low-quality connections between the sensors and the CCU.

Thermocouple Failure. Thermocouple failures were located using a statistical analysis of field temperatures in addition to normal field operation monitoring. This was only done twice during testing. Computer printouts of the thermocouple readings for the entire field were taken and anomalous readings were used as indicators of thermocouple failure. Thermocouple failures were also observed during normal operation when a collector would stay in offset track and fail to reach focus, although conditions would have allowed focused tracking.

TABLE 6.							
MTBF by Subsystem (HOURS)							
Row	Hours per Collec.	Row MTBF:	Mechan- ical	CCUs	Commun- ication	HES	Thermo- couples
1	172.1	15	22	82	194	258	1549
2	172.0	61	172	287	215	1720	573
3	182.7	48	206	183	206	822	235
4	164.7	61	183	549	206	329	823
5	177.3	53	133	319	199	798	532
6	173.8	97	1738	----	174	869	348
7	168.9	76	380	507	152	1521	760
8	150.6	60	167	502	151	1506	753
9	158.4	42	130	238	143	475	357
10	155.8	74	390	779	156	779	519
11	162.2	91	487	730	146	----	1460
12	179.8	67	540	202	147	----	809
Overall MTBF(hours):		50	132	288	171	759	542

3.2.3 Reflectivity Tests.

A separate study was requested by Sandia National Laboratories and was included in the contract to gather reflectometer reading on reflective film installed on various collectors in the collector field. The data gathered were compared to previous data on the performances of aluminized versus silverized mylar film. The film was installed as part of an earlier contract from Sandia. In earlier tests the film was allowed to get dirty, then washed for comparison on both types. The aging process was never addressed in the earlier study. The data gathered as part of this contract adds the dimension of reflective film aging to previous studies.

Reflectance of ten of the parabolic dishes was measured on three separate occasions using a portable specular reflectometer manufactured by Devices and Services Company (See Table 7). The reflectometer measures the percentage of a photon beam being reflected by a surface into an aperture. Of the ten solar collectors being tested, five have an aluminum surface (3M Brand ECP-244), and five have a more advanced silver-backed surface (3M Brand ECP-300). The advantage of the silver-backed surface is readily seen by comparing the reflectometer readings of the respective collectors.

Also, the degradation of reflectance due to a build-up of dust and other debris on the collector surface can be observed in the data collected. The first set of readings was taken on May 15, 1989. The collectors were then washed, and a new set of readings was taken on May 31. The final set of readings taken November 19, 1989, without cleaning clearly shows the degradation over time when compared with the May 15 readings.

TABLE 7. Average Percent Reflectance			
Dish No.	May 15	May 31 (after washing)	Nov. 19
406	90.8	94.9	89.2
407	89.1	94.4	86.8
408	88.8	93.9	86.9
409	90.7	95.8	85.8
410	88.0	94.6	85.1
606	78.0	81.8	78.3
607	77.3	81.3	78.7
608	77.6	81.5	79.7
609	77.8	81.4	78.7
610	79.4	81.4	77.9

Figure 18.

Figure 19.

4 Conclusions and Recommendations.

Some specific conclusions mentioned throughout this report are summarized as follows:

1. The proper sizing of circuit breakers to polar and declination motors in the collector field is critically important to reducing motor failures, and hence increasing collector reliability. This conclusion applies only to the present aging equipment. New installations would focus more attention on proper motor sizing.
2. The use of limit switches was found to be useful in reducing collector actuator jamming in worn actuators, and in reducing wear due to over-extension.
3. Control problems were discovered in CCUs during motor reversals due to the "relay start" design of newly installed motors. The originally installed motors used a "capacitor start" design. Software modifications were able to solve the problem.
4. Problems with electrical transients and isolation of CCU boards are very serious in large distributed systems. However, electrical isolation by means of fiber optical communication is both inexpensive and reliable for distributed solar collector fields.
5. Data collected during the test showed greater variability in solar fraction during period of low power generation than at periods of higher power generation. The scatter of the data is due more to operator bias in selection of operating points than to factors inherent to the plant.
6. The sources of periodic plant disturbances originating in the deaerator were isolated and determined to result from several independent errors in installation and equipment malfunction. The periodic plant disturbance, which had been a persistent long term problem, was eliminated with corrective action.
7. Turbine failure resulted from thrust bearing wear. The bearing wear, almost exclusively to the low pressure side of the turbine, may have resulted from uneven loading due to less than design demand for extraction steam and the periodic demand for extraction steam from the deaerator.
8. The Dow Corning analysis of 1/12/90 confirms that the HTF continued to perform with little sign of deterioration and reasonable levels of contamination. This would indicate that the elevation of pressure in the HTF system was a successful design modification to the plant.

Based on the above conclusions and others throughout this report the following recommendations are offered:

Recommendation for Fiber Optic Interface Modification. A major problem at the start of testing was the reliability of the field communications network. While the network hardware was repaired and made functional the original communications network design allowed a failed collector control unit (CCU) to block communications on part or all of the network. Almost every time the field was powered up, one or more CCUs would fail and block communications which could then only be restored after a time-consuming search for the failed CCUs. A modification to the fiber optic interface was designed and installed on a few collectors to help isolate failed CCUs from the network and prevent blockage of the network. The modified interfaces functioned well and were observed to isolate network failures in several instances. Plans were completed for the modification

of all the fiber optic interfaces in the field to insure the isolation of all CCU failures from the network at a cost of about four thousand dollars. To ensure the reliability of future solar fields these plans should be included in future designs.

Recommendation for Limit Switch Addition. Limit switches should be added to any future collector design to prevent regular jamming of their positioning actuators. The limit switches are inexpensive, under \$10 per actuator, and few of the actuators on Row 1 jam regularly. Two prototype limit switch designs have been installed on collectors 108 and 109. The prototype limit switches seem to eliminate actuator jamming and thus save the manpower required to reset breakers and free the actuators.

Recommendation for CCU Motor Drive Algorithm. A common mechanical failure observed in the field was a stalled motor due to thermal protection shutdown. These motors have to be allowed to cool for half an hour or more before the collector can be repositioned. The motors are apparently being run until the actuators reach their limit of travel and then are being left turned on, resulting in overheating and thermal protection shut-down. This problem is due to a motor drive algorithm contained in the CCU software, which in some cases continued to drive a motor after it stalled. This software should be modified to detect all cases of stalled motors, to cut the motor power, and then to indicate the failure at the control panel.

Recommendations for Balance of Plant. In future operation of a STEP-type facility, HTF flow should be maintained at its maximum rate regardless of solar conditions. This will require two pumps operating in series, e.g., pumps P-6001 or P-6002 with the assistance of P-7001 or P-7110. The operating doctrine should be followed as outlined in section 2.1.2 of this report. The preferred operating mode should be the fossil/solar hybrid mode with electric output determined by minimum solar fraction requirements set by policy.

Recommendations for Control System. The controls upgrade to the STEP Facility significantly improved operation of the plant. The new operating doctrine, based on solar/hybrid operation, was implemented into the control system's software with relative ease. The control computer has the capability of maintaining several selectable control configurations at once. Thus, multiple operating doctrines and modes can be tested and compared. Also, an expert system was built and tested in open-loop at the STEP facility. Preliminary test indicate that successful operation of the plant by a closed-loop supervisory expert control system is feasible.

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