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Solar Total Energy Project Summary Report

Georgia Power Company
7 Solar Circle
Shenandoah, Georgia 30265

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Summary Report

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ABSTRACT

The purpose of this summary is to present the Key Operational Experiences of the Georgia Power Company (GPC) team during its participation in the Solar Total Energy Project (STEP) from May, 1977, to the termination of the Department of Energy (DOE) Cooperative Agreement in September 1985. The original program between DOE and the GPC, and under the technical direction of Sandia National Laboratories (SNLA), was conceived to further the search for new sources of energy. STEP is continuing to supply valuable research data through support contracts from SNLA and funding from Electric Power Research Institute (EPRI) along with technical coordination with Solar Energy Research Institute (SERI) and other electric utilities and solar energy industries. The STEP is viewed as an absolute success as a concept demonstration and experimental facility. Although portions of the system were derated and the expected loads never developed, the overall systems worked well and continues to operate. Most of the problems encountered were solved. The technical achievement and lessons learned at STEP should be considered for use by other solar technologies in the national and international communities.

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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ACKNOWLEDGEMENT

This report was produced by the combined efforts of several people as follows :

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EXECUTIVE SUMMARY

Georgia Power Company/Solar Operations is pleased to present this "Solar Total Energy Project (STEP) - Summary Report" for solar test activities at Shenandoah, Georgia. The purpose of this report is to present the key operational experiences of the Georgia Power Company (GPC) operating team during its participation in STEP from May 1977 to the end of the Department of Energy (DOE) Cooperative Agreement (DE-FC04-77ET20216) in September 1985. Technical information has been developed subsequently under a SNLA cooperative modification and test program, and these data are included for a more complete evaluation of each issue. An appendix provides a summary of all activities and participants.

The original cooperative program between DOE and the GPC was conceived to support the search for new sources of energy. STEP is continuing to supply valuable research data through support contracts from SNLA and funding from Electric Power Research Institute (EPRI), along with technical coordination with Solar Energy Research Institute (SERI) and other electric utilities and solar energy industries. The present joint program with SNLA is conducting experiments in critical system areas to improve future designs for solar commercial applications.

BACKGROUND

The Shenandoah Project is the world's largest industrial application of the solar total energy concept. It is a part of the National Solar Thermal Energy Program initially funded by DOE, under the technical direction of SNLA. The objective of the project is to evaluate a solar total energy system that provides electrical power, process steam, and air conditioning for a knitwear factory operated by Bleyle of America. Solar energy generates a large part of the electricity and displaces part of the fossil fuels normally required to operate the factory. Construction was completed in 1982, and operations were initiated under the management of the Georgia Power Company staff.

When the STEP program was initiated at SNLA in 1977, DOE specified the following program objectives:

- Produce engineering and development experience on large-scale total-energy systems as preparation for later commercial sized applications.
- Assess the interaction of solar energy technology with the application environment.
- Narrow the prediction uncertainty of the cost and performance of the Solar Total Energy System.
- Expand solar engineering capability and experience with large-scale hardware systems.
- Disseminate information and results.

It is perceived that each of these objectives has now been met. Solution of electrical, mechanical, and system problems has produced significant information for later system designs, and progress has been discussed and reported in many forms. Weekly meetings have been held at STEP since Georgia Power became responsible for operations, and the minutes are on file at the STEP library along with all procedures, drawings, specifications, design, and construction reports. Many technical papers (by SNLA, Georgia Power, and others), public relations speeches, advanced degree theses, and papers by university students have also reported technical results. Monthly and annual Reports pertaining to Georgia Power STEP activities have been prepared and distributed since the program began in 1977.

In 1986, DOE and SNLA recognized the merit of collecting, quantifying, assessing, and reporting on the key problems or issues encountered during the start-up, operational, and testing phases of STEP. Therefore, the goal of this report is to describe key experiences associated with specific technical areas during these phases. Each discussion includes information that provides or suggests an engineering solution. The specific cause of each problem is not discussed because it is believed that the examination of solutions to the operational issues will contribute more to a data base for future designs and operation of large-scale solar energy systems.

The material is oriented to objective four, which calls for the "expansion of solar engineering capability and experience with large-scale hardware systems." Reports that address the other objectives will be produced when the SNLA/Georgia Power modification and test programs are completed.

KEY EXPERIENCES

The technical issues are listed below along with a summary of the experience encountered for each system.

Significant Start-up Anomalies

During the start-up phase, several mechanical operational problems were encountered. Although most were related to supplier and design areas, at least one resulted from operator error -- water contamination of the heat transfer fluid (HTF). These problems were not surprising in their magnitude, frequency, or difficulty of solution, and experience suggests that they can never be eliminated. The primary recommendation is that strict formality and adherence to designer approved quality control procedures, start-up specifications, and acceptance procedures be a key part of solar demonstration projects. Planning for and providing well-trained and adequate numbers of operating personnel can reduce the impact of these startup problems.

Another major issue during start up was associated with the collector field flow controls. Although solutions are suggested, the issue remains unresolved. Other design-related problems during startup, including HTF system operational issues and collector field control performance, are significant enough to justify a separate section for each in this report.

System Hardware and Software Controls

Centralized control was the accepted system strategy applied during the STEP design phase, and a centralized control system was selected and installed to manage the various subsystems making up the STEP plant. Centralization of the control system greatly complicated the software, which was never made completely operational. A high failure rate of sensor hardware in the collector field, coupled with complex software, made operation of STEP difficult and seriously degraded performance. Poor documentation made software improvements difficult.

Redesign of the collector field control system with a distributed system has eliminated most collector field control problems. Planned changes in the balance of plant (BOP) control system will improve operational efficiency. Full testing of control subsystems hardware and software should be planned for an acceptance testing period before plant start up. Complete control system hardware and software documentation should be provided for the start-up phase of the program.

Environmental Experiences

Water-related problems caused many equipment failures and excessive repair and maintenance. Prototype testing for some of the equipment that failed was performed in the dry Southwestern climate, which did not expose components to troublesome environmental elements.

Field changes by the operations staff, with design assistance from SNLA, corrected most problems.

The durability of the collectors' reflective film was less than desirable. Reflective film technology has improved considerably since construction of STEP, but experience re-emphasizes the need for a low cost, durable, highly reflective surface. A strong environmental issues design effort should be applied to each site for future solar system designs.

Heat Transfer Fluid System Performance

Evaluation of a heat transfer fluid (HTF) manufactured by Dow Corning, called SYLTHERM 800 (TM), was an important evaluation aspect of the STEP program. A significant amount of this HTF was lost during operation. Performance was seriously impaired by improper use of the HTF, and excessive manpower was required to operate STEP because of many HTF system anomalies. It is known that initial HTF operating pressure data supplied by Dow Corning were incorrect, resulting in design and operating pressures below the current recommended HTF operating pressure. The HTF operating pressure has been increased by SNLA/GPC modifications.

Later operations suggest that the major fluid problems have been resolved. The Dow Corning SYLTHERM HTF is currently operating in an excellent manner and will be maintained for the STEP for continued experimental evaluation of other concept designs. However, for future designs, care should be taken to ensure that the properties of new or significantly advanced systems, components, materials, and designs are well defined by the suppliers; understood thoroughly by the users; and monitored carefully by plant designers, suppliers, and operators.

System Thermodynamic Considerations

The efficiency of the collector field was measured to be 42.6 percent for instantaneous steady state; 31 percent for day-long efficiency; and 23 percent for a 30-day test. These values are lower than anticipated. Availability studies show that the greatest loss of potential for power production occurs in the collection process because of the optical losses in the collector system. Seventeen percent of the energy collected on a typical day was needed for collector field warm-up to normal operating conditions. For design conditions and for a receiver elevation angle of 45 degrees, the heat losses per unit collector aperture area were 130 W/m^2, representing the results of a concentrated design effort to minimize heat losses.

The orientation of the receiver was found to affect its heat losses significantly. This suggests an operating strategy that varies the set point temperature dependent on insolation and receiver elevation angle, which would optimize the efficiency and power production capability of the collector field. A fossil-fuel superheater has been added to STEP because the steam temperature requirements of the steam turbine did not match the HTF temperatures attainable from the collector field. The causes were poor performance by the HTF system, collector control and flow distribution problems, and excessive steam system pressure drops. Steam turbine inlet pressure has not been increased, but HTF system-pressure increases have dramatically improved maintainability and performance.

Electric Power Parasitics and Operational Manpower

Excessive electric consumption is not considered a problem. Electrical parasitics will always be high at projects like STEP because of the scaled down plant capability and experimental nature of the project. At full design performance, the percentage of parasitics as installed is 10 percent. With new energy conservation techniques and a reasonable commercial-sized plant, it is believed that a solar total energy system can operate at a parasitic energy consumption percentage competitive with conventional power plants. These values are 1 percent for gas turbines, 4 percent for coal generation, and 5 percent for nuclear systems.

Excessive operational manpower was a problem at STEP, due to poor performance of components (particularly the HTF system), a complex control system, and moisture-induced and other equipment failures. These manpower problems have been resolved by SNLA and GPC procedures and modifications. For future commercial plant designs, operational manpower requirements and electric energy parasitics should continue to be a key consideration in the design process.

Coincidence of Solar Energy Source and Its Application Demand

The Bleyle knitwear factory demand schedule did not match the availability of the STEP solar energy supply, thereby reducing the annual performance of STEP. The cause is the hourly, daily, and seasonal variation of the sun and the fixed and rigid manufacturing schedule for factory operation. The concept and testing of STEP have provided some of the answers, but have not solved the problem. Because STEP is a cogeneration system with two fossil-fuel sources, it is flexible enough to supply any combination of the outputs. The STEP plant can provide a useful output even when solar conditions are less than desirable. Oversizing of the solar plant, provision of supplementary fossil energy, and energy storage may correct the time-dependent problems, but economic parity with conventional energy sources would be extended due to the additional cost of these systems. The originally planned multi-day thermal storage system, which was eliminated late in the design phase, could have prevented the time mismatch problem.

CONCLUSIONS

STEP has achieved all the original program objectives. The performance of STEP was severely limited by the decision to reduce the collector field from 192 to 114 collectors, to eliminate multi-day thermal storage, and Bleyle's business decision not to expand manufacturing capacity (and the resultant total energy load). This performance does not affect the expected solar total energy concept performance for a commercial-sized system.

An important lesson learned from STEP is that operational costs were increased, and performance was decreased, by failures of systems, software and hardware associated with control of flow, temperature and position for the solar collector field. Anomalies with the high-temperature heat transfer fluid also contributed to excessive manpower and poor performance, as did a larger-than-expected loss of availability in the optical portion of the collector system. Some of these problems have been resolved; others are in the process of resolution.

Operational manpower utilization and electric energy parasitics, although high for STEP, are not considered problems for a commercial-sized solar total energy system. Environmental, mechanical, and electrical problems (and operator errors) were irritating and costly, and delayed acquisition of experimental data. However, they are not expected to be problems in a second generation system since they are amenable to procedural solutions.

STEP is viewed as a successful concept demonstration and experimental facility. Although portions of the system were derated, and the expected loads never developed, the system worked well; provided considerable engineering data; and continues to operate. The technical achievement and lessons learned at STEP should be considered for use by other solar projects worldwide.

1.0 INTRODUCTION

This report was prepared in response to work statements of (SNLA) RFQ No. 53-8034 by Georgia Power Company/Solar Operations. Supporting data were collected over a 10-year operating period for the Solar Total Energy Project (STEP) at Shenandoah, Georgia. STEP was initiated and funded primarily by the United States Department of Energy (DOE) through a Cooperative Agreement (DE-FC04-77ET20216) with Georgia Power Company.

Section 2.0, Program and Objectives, describes the total energy concept and its general mode of operation. The commercial application to which STEP is connected and a total site description are also presented, followed by a discussion of original STEP participants and their roles, and current active parties.

This report is oriented toward STEP program objectives pertaining to development of solar engineering capability and experience. The goal is to describe the issues encountered within specific technical areas, and to provide information that suggests an engineering solution. The cause of each problem is not discussed because it is believed that solutions for the operational issues will contribute more to future designs and operation of solar energy systems.

The technical areas presented in Section 3.0, Key Operational Experiences, are:

1. Significant start-up anomalies

2. System hardware and software controls

3. Environmental experiences

4. Heat transfer fluid system performance

5. System thermodynamic performance

6. Electric power parasitics and operational manpower

7. Coincidence of solar energy source/application demand

Although all seven issues are discussed, their impacts on STEP operations were significantly different, and some issues are interdependent. The most important experiences are associated with the control system and the heat transfer fluid, which seriously influenced the cost of operation through manpower and materials expense and dramatically reduced achievement of performance goals. Therefore, these two issues are given the most attention in this report.

Detailed analysis is provided in separate documentation for overall system performance from a formal test program consisting of 29 special test specifications, a 30-day test, a 14-day test, a heat-loss test, and a planned 15-day test on current modifications. However, summary information on thermodynamic considerations is given since it is so closely associated with the anomalies experienced with the HTF system, the collector field control system, and collector field flow control.

In this report, coverage of key operational experiences with STEP is followed by an appendix that contains a description of the project. This appendix concludes with a summary of activities from initiation of the DOE Cooperative Agreement to the present. Analysis of system performance and a description of system modeling are being reported by SNLA. Reports and technical papers on system performance, collector field heat loss, and turbine evaluation are referenced in Appendix C.

2.0 PROGRAM AND OBJECTIVES

In 1977, the United State Department of Energy (DOE) declared Georgia Power Company the winner among 16 competitors from 14 states for the location and application of the Solar Total Energy Project. The Georgia Power Company site most nearly met all project requirements regarding weather, accessibility, energy requirements, and other important considerations.

Design work for the solar energy system was completed between 1978 and 1980. Georgia Power Company provided cost-sharing support and coordination throughout the design and construction stages, and assumed responsibility for operation of STEP in July 1982. Ownership was transferred to the Georgia Power Company at the end of DOE operational funding in September 1985. Cost-sharing programs with SNLA continued after this period to conduct modifications and tests on components and systems. This support led to the correction of system deficiencies, along with other improvements that have increased performance significantly and reduced manpower and maintenance problems drastically. Although this report emphasizes the activities through the DOE contract period, some activities after that date influenced some of the key experiences and are discussed where necessary.

The period comprising site selection, design, construction, operation, dissemination of cost and performance data and system, subsystem, and component testing will culminate with a period of commercial operation. That will complete the experimental system development program originally planned by DOE, SNLA and Georgia Power Company in May 1977. At that time, Georgia Power Company will prepare a conceptual design on a scaled-up STEP-type system, and a 20-year cost-of-energy projection study will be compared with those of other energy systems.

At present, Georgia Power Company operates the facility as part of its Shenandoah Solar Center, which includes offices, visitor space, exhibits, and test facilities for research and development. Besides STEP, an accelerated effort has been applied to experimentation with photovoltaics and point-focus concentrator electric-engine design concepts.

2.1 TOTAL ENERGY CONCEPT

The total energy concept - also called cogeneration - makes use of waste heat from electrical power generation to meet other energy requirements. Combined with a solar energy system, the total energy concept offers these benefits:

- It provides energy from a renewable source.
- It makes maximum use of the collected energy.
- Its closed-loop system releases no pollution.
- It is compatible with existing utility services.

In 1977 cogeneration was being used sparsely throughout the United States, and STEP was the first known application of a solar cogeneration system to industry. However, major efforts by both industry and utilities are now being undertaken to reduce energy costs by utilization of inexpensive natural gas and oil for cogeneration and parallel on-site industrial electric generating applications. This increased trend toward distributed energy systems is synergistic with the commercialization of solar energy.

2.2 STEP OPERATION

Operation of the STEP system begins with circulation of a heat transfer fluid (HTF) through the receiver tubes of the parabolic dish solar collectors. The HTF referred to throughout this report is a polydimethylsiloxane produced by Dow Corning under the name SYLTHERM 800. Solar energy is focused on the receivers by concentrators to heat the HTF to 750° F. The HTF is then pumped to a heat exchanger, where it boils water and produces superheated steam. The superheated steam drives a turbine generator, producing electricity. Medium-pressure steam is extracted from the turbine for knitwear pressing, and low-pressure steam exhausted from the turbine is used to produce chilled water for air conditioning. (A more detailed description of the system is given in Appendix A.)

2.3 COMMERCIAL APPLICATION

The 25,000 ft^2 Bleyle Knitwear Factory was initially operated with conventional energy sources. The solar energy system was designed to generate 11 billion Btu/yr and 11 million Btu/hr peak thermal energy. The thermal energy is used to produce 400 kWe of electricity, 1,380 lbs/hr of process steam at 350° F and 120 psig, and 257 tons of air conditioning. Energy needs beyond the solar-derived portion required by the Bleyle Plant are supplied by conventional sources.

The Bleyle Plant building was designed to include DOE and Georgia Power recommendations for energy efficiency. Energy conserving features alone, exclusive of the solar equipment, reduced the factory's energy needs by 46 percent, thus saving more than $25,000 per year (at 1982 utility rates). Energy data gathered by Georgia Power in the factory were used to determine the building's energy requirements, and this information was used to design the solar energy system.

2.4 SITE DESCRIPTION

The Project site is dominated by a field of 114 parabolic dish solar collectors, each 23 feet in diameter, that track the sun and concentrate the rays to heat a circulating fluid. An easement obtained from adjacent landowners guarantees unobstructed sunlight for the collectors.

The Shenandoah Solar Center also contains four trailers used for offices, visitor center, library, and maintenance. A separate concrete block mechanical building houses the operations and control equipment. It is adjacent to an outside concrete pad that contains the steam generator, fossil-fuel heater, high-temperature storage tank, and other equipment, such as the recently added fossil-fuel steam superheater and the heat transfer fluid pressurizing system.

A meteorological station at the site, operated by the Georgia Institute of Technology since 1977, continues to collect solar energy data. Its insolation and surface weather instruments make it one of the most sophisticated stations in America for gathering data about the sun. Information collected by the station was used in designing the solar total energy system and will continue to be used to support the national weather network and to document the solar resource for the Southern Company service area.

A Georgia Power Company electrical substation designed for STEP is providing new technology and engineering experience for integrating the electrical output of the cogeneration solar system with the company's 15,000 MW system. A major mechanical repair building is located between the mechanical equipment area and the substation.

The Bleyle Knitwear Plant is adjacent to the STEP site on land owned by the Company. It consists of the original 25,000 ft^2 building, a recently acquired 48,000 ft^2 building, an employee lounge, and parking for 200 cars.

The Shenandoah Solar Center contains two other significant and current activities. A 1,000 ft^2 glass-surfaced concentrator (McDonnell Douglas Corporation) is providing solar energy at 28 percent optical- to-electric efficiency to produce 25 kW(e) at peak sun condition (the power unit is a United Stirling Model 4-95 engine design). Another program is an Electric Power Research Institute/Georgia Power cooperative program to test and develop a 28 percent efficient photovoltaic system, involving performance testing of commercially available photovoltaic modules.

Multiple, stand-alone, small photovoltaic systems are being tested at Shenandoah. Program management and experimentation on other photovoltaic and energy end use research is in process for SNLA and other organizations.

2.5 STEP Participants

The organizations shown in Table 2-1 participated in the development of the Solar Total Energy Project over the first 5 years of planning, designing, construction, initial operation, and testing. The table illustrates the relationships among the participants during the earlier phases of the program. Of the original participants, only Sandia National Laboratories, Bleyle Corporation of America, Georgia Institute of Technology, and Georgia Power Company are involved in the day-to-day research program. The Electric Power Research Institute continues a keen interest in the program and has funded various phases of operations, including technical and funding support for preparation of this report.

TABLE 2-1

PROGRAM MANAGEMENT:	**United States Department of Energy**
TECHNICAL MANAGEMENT:	**Sandia National Laboratories, Albuquerque**
DESIGN TEAM:	**General Electric Company** **Lockwood-Greene Architects and Engineers** **Scientific Atlanta** **Owens-Corning Fiberglas, Inc.** **Mechanical Technology, Inc.**
CONSTRUCTION TEAM:	**Dow Corning Corporation** **L. B. Samford, Inc.** **B & W Mechanical Contractors** **Joe North, Inc.** **General Electric (Daytona Beach)** **Solar Kinetics, Inc.**
SITE TEAM:	**Georgia Power Company** **Bleyle Corporation of America** **Georgia Institute of Technology** **Heery & Heery, Architects & Engineers** **Shenandoah Development** **Owens-Corning Fiberglas Corp.** **Westinghouse Electric Corp.**

2.6 Program Objectives

The DOE objectives for the national Solar Total Energy Project at Shenandoah, Georgia were to:

1. Produce engineering and development experience on large scale total energy systems as preparation for later commercial sized applications.

2. Assess the interaction of solar energy technology with the application environment.

3. Narrow the prediction uncertainty of the cost and performance of the Solar Total Energy System.

4. Expand solar engineering capability and experience with large-scale hardware systems.

5. Disseminate information and results.

Achievement of the objectives relating to solar engineering experiences is significantly enhanced by the material provided in the following sections of this report. Detailed chapters discuss seven major areas that should benefit the solar design and operation industry for industrial applications of distributed solar systems. The knowledge and subsequent benefits are of use not only to STEP designs, but are also supportive and complementary to other solar projects. The combined data base from this program will be useful in future solar programs and designs.

It is expected that all primary objectives will be met after the current program of steam plant and HTF system modification and testing. This program will evaluate redesigned collector controls, modified HTF utilization, efficiency enhancements for collector surfaces, evaluation of thermal losses, and collector field flow and temperature control. The results of these test activities will be reported when available.

3.0 KEY OPERATIONAL EXPERIENCES

The goal of this report is to present the key operational experiences encountered over a 10-year solar technology program for the Solar Total Energy Project (STEP). These experiences are directly applicable to one of the major objectives identified for STEP during its conception: to "expand solar engineering capability and experience with large-scale hardware systems."

As with the other four objectives of the program (Section 2.0), it is believed that this objective has been met completely. In considering which key operational experiences should be reported, it was concluded that the experience gained was not limited to engineering details. Design philosophy during times of rapidly changing technology, company policies, public attitudes, and national and international funding and programs are equally pertinent and important. Specifically, the reduction in federal funding during the design and construction phases, and the falling cost of oil and gas during the operational phase, had a strong influence on the federal and utility participants and played a part in the key experiences. These experiences are presented primarily from the viewpoint of Georgia Power Company's Solar Operations Staff and its supporting contractors, with contributions from the Electric Power Research Institute and from university and private consultants.

To support the expansion of solar engineering capability and experience, this section addresses the following key operational experience areas and presents detailed technical discussions for each:

- Significant Start-up Anomalies
- System Hardware and Software Controls
- Environmental Issues
- Heat Transfer Fluid System Performance
- System Thermodynamic Performance
- Operational Electric Consumption and Manpower
- Coincidence of Solar Energy Source/Application Demand

Each experience includes an overview, a system description (if appropriate), a summary, and a solution (if available). Following the introduction are expanded sections that provide examples of the experience, cause, and solution in detail.

Each experience is followed by a discussion pertaining to how the information gathered can be applied to future designs in areas of policy, cost reduction, and improvements in performance, operation and maintenance.

3.1 SIGNIFICANT START-UP ANOMALIES

Check-out of the mechanical system for initial operation began before completion of construction and covered the period from August 1981 to the spring of 1983. This overlap in phases, called inspection and acceptance testing, is not unusual in the start up of such a plant. A few mechanical systems did present difficulty and are included here for completeness of documentation, and to amplify the need for continued close attention to these dynamic and overlapping phases. The STEP control system startup which produced a more significant problem not subject to an immediate and routine solution by the operational staff, is discussed in Section 3.2.

Because of the number of contractors used during the construction phase, an engineering team closely monitored installation of the system. This quality control activity was beneficial and contributed to the confidence that the specifications were met, that installation followed design drawings, and that necessary changes were approved and documented.

During acceptance testing, the operations staff, supported by the designer and program management team, prepared an extensive specification and procedural document to ensure that all operating systems were tested or accepted including parts, components, and sub-systems. Inspection and acceptance tests are listed in Table 3-1.

Although the start-up activities did not follow a regimented procedural program, all the items identified in the plan were accomplished and approved by a team made up of DOE, SNLA, and GPC personnel. In July 1982, all inspections were complete and most acceptance testing accomplished. Continued difficulty with the collector control system, the collector field flow control, and the HTF system prevented completion of the acceptance test of the total system. Although these three problems were encountered during start up, only recently have solutions been proposed or implemented.

During acceptance testing, certain anomalies associated primarily with pumps, valves and HTF were encountered. Each encounter was evaluated by the operating engineers, changes were made to the components, and the drawings were upgraded. Although each issue was resolved by engineering and operations personnel, it is suggested that these problems could be reduced by more formal planning procedures, monitoring, review, and documentation of a tightly controlled program for the parts suppliers, operators, and system designer.

The cost of these anomalies in terms of materials or manpower is difficult to quantify. Information is not available to determine whether construction of conventional power plants has a lower percentage of occurrence of start-up anomalies than encountered at STEP, but these items could not be completely eliminated at any cost for any power plant. Since STEP is an experimental plant, perhaps a more forgiving attitude is required to accommodate the required flexibility for most favorable engineering investigation. These start-up anomalies are consistent with a pioneering plant that combined demonstration scale with pilot plant novelty.

TABLE 3-1
SOLAR TOTAL ENERGY PROJECT
INSPECTION AND ACCEPTANCE TESTING LIST

1.0 COLLECTOR FIELD CONTRACT INSPECTIONS
2.0 COLLECTOR INSPECTIONS
3.0 BUILDING AND MECHANICAL AREA INSPECTIONS
4.0 INSULATION INSPECTIONS
5.0 CONTROLS INSPECTIONS
6.0 ACCEPTANCE TESTING
    6.1 Operational Validation of Air Operated Field Valves
    6.2 Operational Validation of Heat Transfer Fluid (HTF) Air Operated Valves
    6.3 Alignment and Operational Validation of Pumps P6001, P6002,P7001, P7110, P6433
    6.4 HTF System Integrity Test
    6.5 Fossil-fuel Fired Heater Maintenance Testing
    6.6 HTF Thermal Conditioning
    6.7 Mechanical Area Component Startup Testing
    6.8 Operational Validation of Steam Side Valves
    6.9 Proportional Valve Linearity Flow Tests
    6.10 Power Conversion System (PCS) Water Analysis
    6.11 PCS Steam Side Integrity Test
    6.12 Steam and Condensate Component Checks
    6.13 Local Control of PCS Steam Side Components
    6.14 PCS Steam Operations
    6.15 PCS Components and Subsystems Control by Control and Instrumentation-System
    6.16 Initial Turbine-Alternator Operation
    6.17 PCS Performance Testing
    6.18 Turbine Maintenance Testing
    6.19 Collector Control Unit (CCU) Control Function Check with CCU Tester
    6.20 Operation of Collectors with CCU
    6.21 Collector Receiver HTF Integrity
    6.22 Individual Collector Optical and Thermal Performance Testing with CCU
    6.23 Individual Collector Maintenance Testing
    6.24 Individual Collector Control from Serial Control
    6.25 Components and Collector Subsystem Control by CAIS
    6.26 Instrumentation Source to Data Accuracy Verification
    6.27 Electrical Subsystem Performance and Maintenance Testing
7.0 TOTAL SYSTEM ACCEPTANCE

The following paragraphs provide detailed accounts of each technical area for which problems were encountered, or for which additional re-design, test operation, and component replacement were required. Following the description and the solution, remarks are presented pertaining to how these solutions apply to future designs.

Pumping Systems

As a part of the acceptance testing program, all pumps and electric motors were mechanically aligned within the specifications of the manufacturer. Each of the electric motors was momentarily started to determine rotational direction relative to the marked rotation arrow of the housing. After verification of rotation, the mechanical coupling between the electric motor and the pump was installed. When the fluid was available in the suction line, air was vented until fluid was present on the down stream side of the pump. Each pump was started with partial flow by throttling the downstream valves, and the pump flow was momentarily blocked to determine the no-flow pressure. The pump was then loaded to full flow, and the pressure monitored. If a flowmeter was available in the line, measured full flow was compared with the design value. During each of the start-up tests, proper current flow in each phase of the electric motors was checked.

Condensate Pump (P-8740) did not operate properly during the check procedure. (See Figure A-1 in Appendix A.) Pressure at full flow was well below the specified value. Once the turbine-generator was started in January 1982, it was determined that the boiler feed water flow was not adequate to maintain water levels in the steam generator except levels below 100 kW. Several tests were made, including one that used the deaerator as a catch basin to determine the actual flow through the condensate pump under full flow conditions, which ascertained that the condensate pump was not producing proper flows.

A documentation check for correct pump rotation was made and proper rotation speed of the electric motor was verified. Then, suction and downstream gauge accuracy were verified, and a search was conducted for obstruction in lines to and from the pump and gauges. Since these verifications did not resolve the problem, the pump was removed and sent to the supplier and then to the manufacturer, but when it was returned it continued to be a problem. A pump manufacturer visited the site and reviewed verifications of the tests that had been done, but he could not suggest any other tests.

Finally, the factory that had rebuilt and tested the pump reported that the pump should rotate in the direction opposite to that indicated by the arrow on the housing. By reversing the direction, the system operated as designed. Poor quality control and resultant excessive cost of correction of this defect should be attributed to the supplier and manufacturer. More than 5 months of time and effort were lost because of this problem. A strong, technically competent start-up team, with an adequate number of members, must be trained to resolve these problems. However, it would take an unusual insight to detect that the manufacturer was in error in indicating the rotational direction of a pump. Although they can never be eliminated, these problems can be minimized by design specifications and quality control and by use of experienced operating engineers.

During the start up of the steam generator system, another pump produced inadequate feed flow due to the lack of net pump suction head (NPSH) for the linear stroke boiler feed pump (P-8470). During design, the deaerator was properly placed on the roof of the control building to provide more than 25 feet of NPSH, which normally would have been adequate for a centrifugal pump. But the small linear stroke boiler feed pump, because of its oscillating flow, had a NPSH of minus 3 ft with a design-specified 1.5-in line between the deaerator and the boiler feed pump. This caused the heated pressurized water to flash to steam on the suction stroke of the boiler feed pump and compress back to liquid on the compression stroke with zero resultant flow.

A reassessment of the design and replacement of the 1.5-in line with a 3-in line increased the NPSH to the positive value required, and no more problems were encountered. The design process erred in this area since feed pump design has been routine for years. Competent start-up personnel can solve this type of problem as it occurs.

The linear stroke boiler feed pump caused a pulsating flow in the boiler feed water line to the steam generator. Even with a very good compensator in the line, the flow pulsed to such an extent that accurate flow meter measurement of the boiler feed water was difficult. The boiler feed water flowmeter was implemented in the STEP system design as a check on the steam flowmeter.

In steady state conditions, these two measurements should have been the same. However, the pulsating feed flow through the flowmeter resulted in a measurement that could not be compared with the steam flow. Even on an analog measurement, the recording chart pin would oscillate between 40 percent and 100 percent of full flow at a frequency of 2 to 3 hz. Digital recording of the flowmeter readings was no better than the analog readings.

Steam Generator System

During the final stages of the start-up testing of the steam generator, before formal testing, an operation was conducted to cool the HTF in the mechanical equipment area. The cool HTF in the solar collector field was pumped through a hot steam generator, which caused a thermal shock in the steam generator and pulled five of the steam generator tubes away from the hot tube sheet of the superheater, resulting in a water leak into the HTF. The existence of these leaks was not discovered at that time.

The water contamination of the heat transfer system led to significantly accelerated generation of cyclic oligomers. Operational activities continued after the incident, because the effect on the system was not immediately apparent. However, anomalous system operation suggested water contamination, and a search for the source was conducted. When the steam generator was identified it was disassembled and the leaking tubes were rewelded to the tube sheet. However, the stress induced by the welding opened additional tube sheet seal weld leaks on other tubes, and all the tubes on that tube sheet had to be welded and leak tested.

The HTF supplier (Dow Corning) later stated that the inhibitor in the SYLTHERM 800 was "used up" by combining with the leaking water, so additional inhibitor was added and the fluid reconditioned. (More detail on the HTF is presented in Section 3.4.)

The potential for thermal shock and major equipment damage (and even personnel hazards) is always present in any high-temperature system. Many industrial systems are cycled from cool-down to hot operating conditions on a daily basis, so the requirement for daily cycling of the solar system is not the main issue. It is true, however, that power generation systems, once heated, maintain operations on a continuous basis and thermal shock exposure is not as prevalent.

This experience, directly attributable to operator error, could be termed a very costly accident, which involved almost 6 months of resolution time and lost operating time. This type of error can be minimized by a more formal operating program of start-up and operating specifications and procedures, qualification of operating personnel, and early integration of an adequate number of operating personnel into the design process.

Fossil-Fuel Heater

The original intent of the fossil fuel heater (FFH) for STEP was to provide only enough thermal energy to the turbine-generator to allow electric generation at a rate sufficient to meet the needs of the Bleyle Plant and STEP. The FFH was found to be capable of approaching that goal, but the efficiency and durability has been poor. The nameplate rating of the FFH is 12 MBtu/hr input and 8 MBtu/hr output, giving an efficiency of 67 percent at full load. The heater has been tested for efficiency and found to be somewhat below that value, particularly at partial load. This poor performance and excessive mechanical and control failures have caused excessive manpower and repair costs, and severely reduced performance.

The internal refractory and firebrick have been the major cause of failure several times for the FFH. The refractory firebrick was repaired by the manufacturer twice in 1982, twice in 1983, and again in 1985. There was a second failure in 1985, during a 30-day DOE test, but the repair was done by the STEP personnel following the recommendations of the manufacturer.

In December 1984, a thermodynamic analysis of the FFH conducted by Auburn University showed that the combustion efficiency of the FFH was 62 percent, and the general efficiency was 60.3 percent. The largest energy loss was due to an excessively high exhaust gas temperature of approximately 1,100° F. The recommendation was to install a boiler feedwater preheater and a combustion air preheater in the exhaust stack, which could theoretically raise the total efficiency to about 80 percent. To date, several designers have been contacted, including the original suppliers, but quotations for neither resolution could be obtained.

Another thermodynamic problem with the FFH was the declining efficiency, under partial load, to 25 percent at low fire. For STEP to produce any appreciable electrical generation, except under the absolute best solar conditions, the system had to be operated in the hybrid mode, where the FFH firing rate is inversely proportional to the solar contribution. Therefore, with a good solar input, FFH efficiency was poor.

For many solar projects, the variable nature of the solar resource usually requires back-up or supplemental energy inputs. As long as solar projects require supplemental energy and are struggling to be economically competitive, the efficiency of the supplemental supply system must have a high priority during the design phase. In future designs, the part load efficiencies of supplemental systems should be evaluated closely. The recent installation of a fossil-fuel steam superheater has proved a superior choice of a supplemental system with the added advantage of less stress on the heat transfer fluid from the elevated temperatures of the FFH.

The solar system idea of a solar/fossil fuel hybrid using a steam superheater is of particular advantage to the Southeast where the summer peak power demand on the utility occurs after sunset. This feature may be economically competitive with energy storage concepts to meet the time-dependent functional requirements for energy delivery.

Pneumatic System

The STEP pneumatic and water treatment systems presented continuing difficulty with operation and reliability. Most of the problems were due to compressor failures and water in the instrument air lines. These problems have not yet been corrected because of redesign, installation, and testing of systems that have a much stronger influence on total system performance and manpower utilization.

The original air compressor at the STEP was an Ingersoll-Rand 15-hp unit that required daily lubrication and had to be overhauled in December, 1982. It was decided that the compressor was undersized for the STEP air requirements, so a larger compressor (an Ingersoll-Rand 40 hp unit) was purchased and installed in March, 1983. It was never determined if the smaller compressor was overloaded by system requirements, or if its performance was due to air leaks resulting from poor installation and maintenance.

In July, 1983, the more serious problem of water in the instrument lines was discovered. Many of the pneumatic controllers, especially the collector field branch flow controllers, had to be rebuilt because they had been flooded. The source of the water was not determined, the air supply system was suspected. It was speculated that the air dryer was overloaded, so an automatic water vent was installed on the air compressor to reduce the amount of moisture going into the dryer. Later it was discovered that if the supply air pressure to the demineralizer control system was allowed to fall below the water supply pressure, water would backfeed into the instrument air system. These types of interface problems can be avoided by design changes and improved supplier models.

The air dryer also has been a constant maintenance problem. It is a heat regenerated desiccant type dryer consisting of two columns -- one is used to dry the air while the other is being regenerated. The problems occurred when the system was switching columns, and one or more of the control valves stuck open. The valves could not seat properly because the desiccant had cracked or broken down to a powder that was blown into the valves. This problem was caused by the air dryer being undersized or overpressured. When specifying equipment such as this, the equipment should be only slightly oversized. If it is too large it will add unnecessary electric energy parasitics.

The air dryer was rated at 55 CFM for the original configuration, but the new compressor is rated at 130 CFM, which is an overload for the original air dryer. With an automatic moisture drain, as long as water does not get to the desiccant column, the system works normally. However, when the air dryer is overloaded and the humidity is high, problems arise from water-contaminated desiccant, improper solenoid valve operation, and shuttle valve failures.

Water Treatment System

In 1983, problems with the water treatment system developed, primarily in regard to the absence of a diagnostic system to alert an operator when a valve or solenoid is faulty. Many unnecessary regenerations and many man-hours of excessive maintenance resulted from this deficiency.

The 26 pneumatic valves can only be checked by a time-consuming process of elimination to find a problem. Broken stems in the valves did not show up until the valves were disassembled for repair. Pressure problems with bad valves were corrected by installing a pressure gauge on the caustic pump.

It was also found that the unit was not functioning properly on some regeneration cycles. Resin was sometimes blown onto the floor or into the chemical holding tank on the patio. When the air pressure droped below the water pressure, water was introduced into the air lines. This could only be corrected by replacing the check valve on the air line to the demineralizer. A faulty check valve allowed water and chemicals to get into air lines, which created many other problems with solenoid valves and instrumentation throughout the plant. Other problems included contamination of the resin beds because of improper operation of the demineralizer, water softener and charcoal filter.

The pneumatic system and the water treatment system have demanded considerable attention by operation and maintenance personnel. Expert consultants have been used along with service people provided by the suppliers and the manufacturers, but problems persist and solutions are not apparent. Reliable and maintenance-free air and water systems should be available, since they are conventional and standard equipment. Compared with the turbine generator and the absorption chiller, which are more complex, the maintenance on the air and water systems has been much greater. It is suggested that future system designs stress the requirement for reliable auxiliary systems that will require less maintenance.

Collector Field Flow Control

Control of the collector field outlet temperature has been a continuing and unresolved problem at the STEP. Because the design collector fluid outlet temperature is at the limit of the HTF, there is little room for deviation of collector temperature.

Two reasons for this lack of control have been identified: mechanical and measurement accuracy problems with the receiver fluid outlet temperature sensors, and an inability to balance the fluid flows through the collectors.

The receiver fluid temperature sensing problems have been solved by replacement of the RTD sensors with thermocouples. Flow control of the collector field has been a more difficult problem, and, as a result, the field has been operated at a reduced temperature to account for the range of flows through the individual receivers. Attempts at collector flow control have stopped since early in the startup phase. Design solutions are available and future experiments will investigate the performance enhancements of some of these solutions.

The 114 receivers in the STEP field are connected in parallel to the HTF supply and return lines by main supply and return manifolds running down the center of the collector field, and 12 perpendicular branch manifolds supplying 9 or 10 receivers each. The main supply and return manifolds consist of Schedule 40 piping tapering in nominal pipe size from 4-in to 2-in to maintain a constant flow velocity of 8 ft/s throughout the collector field. The branch manifolds are also tapered from 1-in to 3/4-in to maintain constant flow velocity. Each receiver is connected to a branch manifold with up-and-down piping, with the inlet being 3/4-in diameter tubing, and the return, 1/2-in tubing. In the receivers, the HTF flows through a beehive-shaped coil of 210 ft. of 1/2-in diameter stainless steel tubing. The nominal flow of HTF through each receiver at full design conditions is 1 to 2 gpm.

The 12 flow control valves (one in each branch manifold) increase or decrease the flow through all the receivers on each branch manifold, until a return temperature (set by the system operator) is met. Therefore, a single automatic control valve adjusts the flow to the nine or ten collectors on the branch manifold to maintain the specified temperature.

Individual temperature control is not incorporated for each collector except for the six front-row collectors that are not seasonally shaded by another collector in front of them. These collectors have "shadowing valves" that control the flow to maintain a pre-set outlet temperature. These valves increase flow to the unshadowed collectors when the remaining collectors on the branch are shaded and require less flow to maintain outlet temperature.

Hand-operated balancing valves are provided at each collector. Each collector incorporates an overtemperature control function that senses the maximum HTF temperature in the receiver and defocuses the collector when that temperature exceeds the 765° F HTF limit. This defocus function keeps the HTF from overheating when flow through the receiver is inadequate to carry away the heat concentrated on the receiver.

During start-up testing at the STEP it was found that when the collector field operating temperature was adjusted close to the HTF temperature limit, many of the collectors in the field would automatically defocus because of a sensed over-temperature. Many attempts were made to balance the flow to each collector by adjusting the automatic branch control valves and the manual valves at each collector until the HTF outlet temperatures from all collectors on a branch manifold were equal. It was found that this balance was unstable and could not be maintained for extended periods when insolation levels changed the collector field flow changed.

It was concluded that there were three reasons balanced flow for all collectors on a branch manifold could not be attained: the small throttling pressure drop available, changes in pressure drop across the balancing valves because of large changes in viscosity with temperature of the heat transfer fluid, and inaccurate fluid temperature sensing at the receivers.

After many attempts to attain balanced flow on each manifold, the balancing valves were all opened for full flow, and the branch flow control valve temperature settings were reduced so that none of the collectors sensed an over-temperature condition. This resulted in a collector field outlet temperature significantly below the design temperature.

The result of lowering the solar collection temperature is a reduction in the thermodynamic efficiency of the power conversion system. Some compensation was provided by operating the STEP in the hybrid mode, using the fossil fuel HTF heater to raise the temperature of the HTF after it came from the solar field. As long as natural gas or other fossil fuels are inexpensive, this is a practical alternative for maximizing the performance of a solar system that incorporates electrical power generation. This, besides the undersized collector field (because of reduced initial construction funding), is why most of the operational testing of this system has been in the hybrid mode.

Several guidelines for future solar energy system design come from these experiences. In terms of collector field piping, if the average fluid outlet temperature from the collector field is to be at or near the heat transfer fluid's temperature limits, all collectors must heat the fluid to this temperature (within narrow limits). One way to ensure that each collector is operating at a specified fluid outlet temperature is to have individual flow control valves that accurately sense the fluid temperature. Although this may be expensive for large point-focus fields, the gain in system performance may outweigh the expense. Placing two or more collectors in series would reduce the number of valves required.

An alternate possibility would be to connect the branch manifolds in a "reverse return" flow configuration. This is a technique for connecting parallel flow restrictions (the receivers) so that each has the same pressure differential between supply and return manifolds. Without reverse return manifolding, receivers at the supply end of a manifold have the highest pressure differential across them, and those at the far end of the manifold have the smallest pressure differential and therefore the lowest flow. This difference in pressure drop makes balancing receiver flows considerably more difficult than with reverse return flow.

This latter technique (reverse return) for flow balancing will soon be executed at the STEP for a single branch. If it does not produce the desired balanced, flow and temperature control for individual collectors it may be necessary to install individual valves on each collector. For either solution, the cost of additional piping or valves and the additional thermal loss due to conductive heat transfer must be compared against the gain in performance.

Summary of Significant Start-Up Anomalies

Experience suggests that during the design phases and construction, careful attention must be given to ensure that components and subsystems supplied by vendors meet design specifications and are installed properly by the contractors. Rigorous attention must be paid to subsystem startup, with formal documentation made of the startup tests and careful consideration given to providing drawings for changes. Design documentation must be continually compared with test results. Good reports by the startup team and detailed analysis by the design team will help ensure that program objectives are met.

In the case of the steam generator tube sheet failure, it is imperative that operators on new systems ensure that operating procedures are prepared and reviewed with the design engineers. System thermal shock exposure on solar systems is enhanced by the nature of the daily heat-up and cool-down cycle. Operating procedures must be reviewed in detail with specific attention to the potential for thermally shocking system components. Operator training programs should be written using designer criteria for the degree of shock capability that each system can handle.

For HTF flow control, experienced operating personnel must be able to encounter deviations from normal design specifications and be prepared to make field modifications to achieve design performance. Distributed solar designers need to reevaluate collector field performance as a function of cost of individual collector flow control.

3.2 SYSTEM HARDWARE AND SOFTWARE CONTROLS

The control and instrumentation system (CAIS) for STEP was designed by General Electric of Daytona Beach under the direction of SNLA. The system was designed to provide an operator interface for control of the plant, provide the necessary inputs and outputs for control purposes, and perform data acquisition, archiving, and retrieval for analysis and reporting.

Significant operational difficulties have been encountered with the CAIS, and, as expected, the system would be designed differently today. The primary difference involves the architecture of the system. The CAIS was designed as a centralized control system with a single central computer making nearly all decisions. This arrangement made the software on the central computer complex and difficult to understand and modify. The approach today would be more distributed, including a network of microprocessor-based controllers with their own areas of control.

The distributed control concept has been extensively implemented at STEP with the replacement of the central collector field control system, and may be further realized if a proposed replacement of the balance-of-plant control system is achieved. Operational results for the collector field show a dramatic reduction of operating and maintenance manpower. Significant improvement in performance is shown from this and other nominal changes.

The major problems encountered with the CAIS and the corrective measures taken on some of the problems are discussed in the following sections.

Overview

To adequately discuss the problems and solutions for the CAIS, a description of the scope of the tasks expected of the STEP control system is necessary, and a brief review of the overall STEP design is in order. Because of the complex nature of STEP, it is beneficial to divide the total design into smaller functional blocks:

1. Solar Energy Collector Field Subsystem (114 parabolic collectors)

2. High Temperature Energy Transport Subsystem

3. Steam Generation Subsystem.

4. Electric Power Generation Subsystem.

5. Chilled Water Subsystem.

6. Control and Instrumentation Subsystem.

Solar energy is first collected by the collector field subsystem. Using the HTF as a medium, the energy transport subsystem receives and then transfers energy to the energy conversion plant, where it is either stored or directed to the steam generation subsystem. As an option, the energy transport subsystem may provide additional energy by routing the HTF through a fossil-fuel heater. Superheated steam is routed to the electric power generation subsystem, which was designed to produce up to 400 kW of electric power. Medium pressure extraction steam from this subsystem can be routed to the adjacent Bleyle knitwear factory for process steam, and exhaust steam can be routed to the chilled water subsystem for air conditioning.

Considering the varying load demands for electric power, chilled water, and process steam under unpredictable solar conditions, it is easy to conclude that system control is complicated. The purpose of the CAIS, then, is to safely manage the other subsystems under varying conditions to produce reliable, economical and optimized power to the knitwear factory.

Architecture of the Control & Instrumentation System

The centralized CAIS architecture placed the responsibility of data gathering, computations, executive decisions, direct control activations, and provision of an operator interface on a central computer system [originally designed around a Digital Equipment Corporation PDP 11/34]. These responsibilities required the original designers to provide a means of communication between the central computer and three types of peripheral components. One component was duplicated to provide operator flexibility. These peripherals and their functions are listed in Table 3-2.

Table 3-2
Peripherals

Peripheral System	Function
Energy Utilization Processor (custom design)	**Analog and digital input signal conditioning, A/D conversion, D/A conversion, analog and digital control output signal conditioning and buffering**
Intecolor Model 8001 Color Computer System (2 units)	**STEP system status display and operator's console**
PDP 11/03 Micro-Computer	**Field communication processor**

To provide for possible power failure, the CAIS also included an uninterruptable power supply (UPS) to maintain the computer/peripheral system. A natural gas powered generator was designed into the system to supply power to the collector field subsystem so that the concentrators could be moved to a safe position in the event of power failure.

Control System Elements

The following subsections discuss particulars of each major element of the control system, problems encountered, and corrective measures (as applicable).

Central Control Computer: The original CAIS design specified a PDP 11/34 minicomputer, with an RSX-11M operating system, as the central control computer or central processing unit (CPU). Although the choice of computers was excellent, the selection of the RSX-11 operating system for use in process control caused problems even before the control system was completely assembled. Matters were further complicated by the decision to program control system functions in FORTRAN.

For collecting data from (and controlling) the collector field, the PDP 11/34 communicated with a PDP 11/03 micro computer through a DR-11C general purpose parallel interface. This configuration was to provide high-speed data exchange between the computers. A problem arose immediately, however, because the version of RSX-11M supplied did not support the DR-11C as a system device leaving the FORTRAN control programs without a means of establishing a software communication link. Specialists were called in and a considerable delay was necessary while special software modifications were developed, tested and installed.

Control of the remainder of the plant subsystems (referred to as balance-of-plant or BOP) was carried out by communicating with the energy utilization processor by way of a DR-11B high-speed direct memory access interface. Once again, the same problem was encountered as was encountered with the DR-11C. As before, testing of the control system was delayed while special drivers for the DR-11B were developed.

Communication between the PDP 11/34 and two operators' consoles (Intecolor 8001) was through a more straightforward RS-232C serial interface, requiring one serial port for each console. Since the serial ports were standard devices supported by the RSX-11M operating system, development of special communication drivers was not required.

Once all I/O drivers were developed, the FORTRAN control programs could communicate with the PDP 11/03, the EUP, and the operator consoles. However, the programing philosophy used in developing these control programs introduced new and significant problems in regard to system performance.

The RSX-11M operating system is a multi-user, multi-tasking operating system. With most other operating systems of this type, the central processor executes multiple user and operating system programs by "time slicing." This means that the CPU will execute a program for a fixed period (usually on the order of milliseconds), save the content of the program, and begin or resume execution of another program. Although it may appear that the processor executes these programs simultaneously, the CPU can only execute one instruction at a time, and as the number of programs (or tasks) increases, the execution time of each program will increase. Since saving and restoring the content of a program requires processor time, increasing the number of programs also increases the processor time dedicated to this function.

The PDP 11/34 was charged with gathering data from and controlling the five major mechanical plant subsystems. Also, because each subsystem might encompass many controllable elements and because of the interaction between the subsystems, a single control program capable of fulfilling all requirements would have been large and complex. It was the philosophy of the system programers that such a complex control program could be more easily written and maintained if it were divided into smaller programs. Where necessary, intertask communication would be accomplished through an area of dedicated memory common to all tasks.

While it is easier to subdivide a large program into smaller programs for development and maintenance, the procedure should be restricted to the creation of subroutines to be called from a central program core, rather than the creation of separate tasks. This is especially true when programing in a higher level language such as FORTRAN and using a compiler that does not optimize code. The separate tasks contained many duplications of FORTRAN utility routines, that greatly increased memory requirements. Intertask communication was indirect, which resulted in slower execution times.

As the control software evolved, tasks were added until the 256 Kbyte memory capacity of the PDP 11/34 was exceeded. It was also noted that program execution speed seemed to lag behind what was thought to be needed for plant control. At that time, it was decided to replace the PDP 11/34 with a PDP 11/44 for additional memory capacity and increased throughput. In retrospect, programing methods may have been the cause of the problem rather that deficiencies in the PDP 11/34.

The complex interaction between the tasks that made up the CAIS software resulted in most of the software being written in a manner assuming correct operation of all equipment. Modifying this software to take into account all possible failure modes would have been difficult and time consuming. Much of the CAIS software was never fully operational, and some was never completed, resulting in erratic operation of the plant, excessive manpower requirements for operations and low operator confidence in the system. The plant was therefore operated manually using the CAIS software only for status information.

Although the PDP 11/44 is now being used as a central computer, modifications to the control system have removed some of its control functions and planned changes may eliminate it completely. Collector field control modifications (discussed later) now allow collector field operation without the PDP 11/44. Installation of a distributed control system for the BOP is being considered, to handle all the functions that the central computer was intended to handle.

The proposed distributed control system will be a network of microprocessor-based devices with their own areas of control. The central computer (if any) will be much smaller and will operate in a supervisory mode issuing high-level commands (such as set-point and operating-mode changes) to the distributed controllers and receiving data from them. It is interesting to note that the original programing philosophy breaking the complex overall control function into smaller, easier to handle pieces is again being used. In the distributed system however, the smaller pieces are being executed by many processors rather than one.

Energy Utilization Processor (EUP): At the time of the design of the CAIS, digital data acquisition and control was evolving as the more accepted technique over analog and strip chart recording methods. To provide the necessary analog and digital input signal conditioning, A/D conversion, analog and digital control output signal conditioning, and buffering, it was necessary to design and construct a customized unit. Incorporated in this design was a set of switches in the analog panel that enabled operators to override the discrete outputs of the EUP for manual device activations. Although the EUP appears to be overly complex by today's standards, it has operated well and has required little maintenance or repair.

Many advances have been made in recent years concerning digital data acquisition and control, and many "off the shelf" systems exist to perform the functions of the EUP. Present system designs perform these functions at various nodes in a distributed network.

Intecolor 8001 Operator Consoles: Two Intecolor 8001 color computer systems were included in the CAIS to provide an operator interface for system control and status display. The units received data from and issued operator commands to the PDP 11/44 through an RS-232C serial link.

With the major problems encountered with the CAIS software, not much time was devoted to making the software fully operational on these units. Control and status information was provided to the operators through menu-driven software. Sometimes operators had to go through three menus to perform a control function. During an emergency condition, operators often handled the emergency manually, using the analog panel switchboard, rather than usimg the time required to operate the keyboard to get to the necessary menu.

Many of the software routines caused significant operational problems. For example, when selecting from the collector field control menu, the command sequence to put a defocused collector back into focus was 03, 10, 15. If the operator missed the 3 or entered an extra 0, the next carriage return would defocus the field. During their training period, virtually all operators inadvertently defocused the field at least once, making reliable and continuous operations difficult.

The Intecolor 8001 software was written and executed in interpretive BASIC language. This resulted in updates of status information and responses to operator control inputs to be excessively time consuming, which further perturbed operations during emergency conditions.

Problems with operator interface have been greatly reduced with installation of a "touch screen" status/control operator interface. This system allows operators to observe system status information and gives them the capability to control parameters by simply touching the monitor screen. For example, a pump is turned on by touching a small area on the screen labeled "ON" by the pump display. This allows operators to take control actions in the plant without loss of knowledge of the system status parameters that they are viewing. It also provides a more "friendly" environment for operators who are not familiar with computer equipment. Significant savings in time, enhanced reliability of operations, and a safer balance-of-plant control have been the result.

Collector Field Communication Processor (PDP 11/03): The PDP 11/03 computer was responsible for communication between the CAIS computer and the 114 solar collectors. Communication was accomplished by way of a daisy-chain serial link to minimize interconnection between the control room and the collector field. This method of communication, coupled with the centralized method of controlling the collectors, caused major problems during operations.

The major problem encountered with this arrangement involved the amount of time required to communicate with all 114 collector control units. Initially, 6 seconds was required, which was too long to allow proper focusing control. To reduce this communication time, the FORTRAN program running on the PDP 11/03 was compiled to an assembly listing that was modified to optimize operation. The required communication time was reduced to 3.2 seconds, but the modifications were not documented. This lack of documentation by the programers made this software impossible to modify later, and severely limited the capabilities of operational programers.

Although the new communication overhead time was improved, it was still too long to permit proper focusing control. To further reduce this time requirement, the software on the PDP 11/03 was modified to operate a third of the collector field at one time while the remaining two-thirds was given a "motor off" command.

The reason the communication overhead time was critical involved the centralized nature of the control system. To move the collector field from the stow position to focus, the CAIS computer first had to obtain from each collector its present position, then calculate the necessary motor command to move them to a desired position and then issue the motor commands. With the time lag between communications, overshooting the desired position was an inherent problem.

The controls associated with the collector field have now been replaced with a system that is more distributed. The operator interface and collector field communication are now provided by a small microprocessor-based unit in the control room. The unit continually calculates sun position and broadcasts this information to the collector field. The unit also obtains information from each of the collectors, but it is not responsible for making motor decisions for each collector. This responsibility has been shifted to control units on each of the 114 collectors.

If a collector is given a command to go into focus, the collector control unit determines the necessary motor movement required based on sun position data sent from the control room. This type of control strategy has greatly reduced the burden on the control room computer and greatly enhanced the collector field operation and total system performance.

Collector Control Unit: The collector control unit (CCU), as originally implemented, was a microprocessor-(8085) based semi-intelligent interface between the field communication processor and the control/data points of the solar collector unit. The unit included a serial communication interface, a multi-channel 12-bit analog-to-digital converter system for data acquisition, relay drivers for bi-directional activation of the three drive motors, and an automatic sun tracking system using fiber optic sun sensor feedback.

The difficulties encountered with the collector control units can be divided into seven areas: position measurement, temperature measurement, automatic sun tracking (fiber optics), error condition handling, the lack of collector status information reported to the control room, structural grounding, and drive motor problems. These problem areas and corrective measures are discussed in detail below.

(Position Measurement): The collector control units were originally designed to measure the collector position using feedback from potentiometers mounted on the polar and declination axes of movement. The original control strategy was to have the control system run the collectors into focus using the potentiometers, then place the collectors in an automatic sun-tracking mode using fiber optic sun sensor feedback. The performance of the automatic sun-tracking sys-

tem could then be checked by comparing the known sun position with the measured position from the potentiometers.

The first problem with the potentiometers occurred in 1982 when the lack of weatherproofing allowed moisture to damage many of the units. Some new ones were obtained and sealed, and others were removed from the solar collectors, reconditioned for water protection, and replaced on the collectors.

Even after the moisture problem was overcome, the potentiometers still gave erratic and unreliable position measurements. When initially running the collectors into focus using the measured position, many of the collectors would be so far off that heat damage to the collector receivers and their fiber-optic system occurred. After the collectors were placed in an automatic sun tracking mode, the measured collector position would not match the known sun position, resulting in many erroneous operator warnings. This problem was so severe that a second operator was required in the control room, to monitor these error warnings and direct as many as four collector field operators to check collectors and take corrective measures.

The replacement collector field control system, implemented in 1986, used a different method of measuring collector position -- it counted gear motor revolutions of the collector drive system. Magnets were mounted on the gear motor couplings, and Hall effect sensors were mounted on the motors to send pulses to the control unit to indicate a revolution. Two Hall-effect sensors were required for each motor. One sensor was used to indicate a revolution, and the other was used to determine direction.

This method of position measurement has proven to be very reliable, but was not problem free during initial testing. The new system was tested on Row One of the collector field for about a year before installation on the complete field. The Hall-effect sensors on Row One were sealed with epoxy and no failures occurred during the test period. When the system was installed on the rest of the collector field, the Hall-effect sensors were sealed with a rubber compound similar to the substance found on the handles of insulated pliers. Although this appeared to be a good idea at the time, this substance allowed moisture to enter where connecting wires exited the sensor. This resulted in the failure of some of the sensors. When this problem was discovered, all sensors were sealed with epoxy and no failures have occurred since that time.

(Temperature Measurement): The original collector control units used resistance temperature devices (RTDs) for temperature sensing. At the time of the design of this unit, the generally accepted method of measuring the high temperatures reached in the solar receiver was with thermocouples. Thermocouples, however, required cold junction compensation and linearization which would have greatly complicated the CCU circuitry. For this reason a high temperature RTD was selected for temperature sensing. The RTD could provide a linear temperature signal and promised to be accurate. The desired accuracy never occurred, however, as temperature measurements were erratic and unreliable. Even after calibration of the RTD circuitry, their readings never correlated with thermocouple readings at the base of the solar collector.

The frequency of RTD failures was also high, and replacement was expensive. Corrosion of the silver plated copper lead wires that connected to the RTD leads was rapid in the high temperature environment. However, the replacement of these wires with Alumel wire did not remedy the failure problem, which can probably be attributed to the fragile RTDs being assembled on site rather than factory assembled and sealed.

The new collector control units use durable type K (Chromel-Alumel) thermocouples for temperature sensing, installed by tack welding the thermocouple junction directly on the receiver coil. Recent integrated circuit development has greatly simplified the use of thermocouples for temperature measurement. An Analog Devices integrated circuit (AD595) was used, which handles linearization and cold junction compensation with an output of 10 millivolts per degree centigrade.

Although there have been no thermocouple failures at the point of measurement, problems have occurred elsewhere. During the testing of the new system on Row One, the thermocouple wire that was used had a cloth insulation. Rubbing of this wire during collector movement caused some of the thermocouple (T/C) insulation to fray and sometimes shorts occurred causing ambient temperature to be read rather than receiver temperature. This problem was overcome by installing T/C wire with a stainless steel jacket to prevent insulation fraying. Poor installation techniques occasionally allowed the wire to become hooked on the collector during movement, thus snapping the wire. Additional wire ties were used to prevent further occurrences.

(Automatic Sun Tracking): The original control mode for the collector field was to place the collector in an automatic sun tracking mode after it reached the focus position. This mode used a closed control loop, activating drive motors based on fiber optic sun sensor feedback. Originally, four sun sensors were mounted on the quadrants of the receiver face plate. The control loop activated the drive motors to balance the amount of sunlight on the fiber optic sensors.

Problems occurred with this arrangement when the collector was initially focused using poor potentiometer position measurements. On many occasions, the focal point of the collector was directly on one of the sensors, thus damaging or destroying it. Additional damage or destruction occured when the collector was placed in an automatic tracking mode, since the control loop still attempted to balance the amount of light sensed. In other words, the CCU focused the concentrated light on the weakest sensor.

Additional problems occurred during periods of low insolation when the fiber optic control system would seek the brightest spot in the sky, which in many instances was not the sun's position. The intent of the total control strategy was to utilize position tracking using potentiometers during these times; however, poor position measurement prevented this procedure. When high insolation returned, many collectors would be so far out of focus that the automated sun tracking control system would not drive the collector back into focus, or the focal point would be at a damaging position.

An improvement was made in the system by moving the fiber optic sun sensors to the outer rim of the collector. This position of the sensors used one-sun insolation levels to balance the sensed light levels and prevented the sensor damage that had previously occurred. However, the tracking problem during low insolation levels continued and the general performance of the collector field control system did not adequately improve because the measured collector positions often still did not match the known sun position.

The new collector control system does not use a closed loop tracking control system. Since the sun's position is predictable and the modified position measurement instrumentation is reliable, an open loop tracking method was used using calculated sun position data. Tracking during low insolation levels is no different from tracking with high insolation levels. This method has proven to be reliable and accurate enough so that the plant can be run by a single operator and one technician, with only a small portion of their time applied to the collector field.

(Error Condition Handling): Three major damaging conditions could exist in the collector field: loss of power when in focus, high receiver temperature, and loss of communication with the control room. The original collector field control system did not handle these conditions in the best possible manner, and problems occurred.

On power up, the mode of operation for the original CCUs was a standby mode in which all motors were off and the units awaited instructions from the control room. If a power failure occurred while the collectors were in focus, an uninterruptable power supply kept the control room computers operating; however, a standby generator was required to start and power the CCUs. In their power up mode, the CCUs remained in focus awaiting instructions from the control room. If everything went smoothly, the operators could issue manual motor commands to move the field out of focus with no damage. However, if the operator's attention was diverted during the power failure, or communication with the field could not be restored, the collectors would be left in focus without HTF flow, forcing them to an over-temperature condition and defocus. With the erratic RTD temperature readings, this was a totally unsatisfactory operation mode. Even with accurate temperature readings, damage to the HTF was possible.

This condition was avoided in the new collector field control system by programing the individual control units to drive to the stow position on power up. During a power failure, the startup of the backup generator will cause the collector field to stow without control room communication and without operator intervention.

One of the primary functions of the CCUs is to protect the collector receiver from excessive temperatures. Failure can result in damage to the HTF and subsequent plugging of the receiver coils by solidified HTF. The original CCUs performed this task by driving the polar motors east and the declination motor north or south (depending on a switch setting) for approximately 2.5 minutes when excessive temperatures were detected. Although this action protected the collector receiver, it did not always point the collector to a safe position after this period. On many occasions, adjacent collectors were damaged by optical glint from a defocused collector.

This problem was avoided in the new collector control system design. When a new CCU detects an overtemperature position, it maintains the declination angle of the sun but drives 30 degrees east of the sun to an offset and track mode. If the polar angle is less than -60 degrees, the unit will drive to the stow position. This action has been found to provide the required receiver protection and prevents damage to the collector receiver struts and adjacent collectors.

The loss of communication with the collector field from the control room is a dangerous condition since operators lose all control functions concerning collector field operation. The original CCUs had the capability of defocusing in a similar manner to an over temperature defocus when no communication was made with the control room for approximately 16 seconds. To use this CCU feature, the CCU had to receive a "timer on" command from the control room. Owing to communication timing problems with the collector field during startup this function was not incorporated into the CAIS software. Later efforts to turn on the CCU timers were unsuccessful due to the modification problems with the PDP 11/03 software.

This timer feature has been included in the new collector field control system. When the new CCUs do not communicate with the control room within 15 seconds, they will drive to the stow position.

(Lack of Status Information): One of the major operational deficiencies with the original collector control system involved the lack of reliable collector status information available to the control room operators. The original CCUs did not send information to the control room concerning motor status, temperature sensor condition, or CCU operating mode. For example, for the CAIS computer to determine that a collector had defocused because of an over temperature condition, the CAIS software had to determine that the reported temperature was too high. In many instances, communication time lags allowed the reported temperature to be less than the defocus temperature. On these occasions, the operators had no idea why a collector was driven out of focus.

The new CCUs report required operational status information to the control room. If a CCU attempts to drive a motor and does not sense a revolution in about two seconds, this condition is reported to the control room. If a thermocouple is open or an unrealistically high temperature is sensed, this condition is reported to the control room.

Operating mode status is also reported to the control room. If an over temperature condition occurs, a status bit in the communication packet is set to show the condition regardless of the current temperature. This is also done if a communication time-out defocus occurs.

(Structural Grounding): Structural grounding of the solar collectors was intended to be accomplished through a network of bare copper cable buried under the collector field. Straps from

this network were connected to the support frame of all outer collectors in the field and at regular intervals on the frame work of inner collectors. Two flexible grounding straps on each collector were used at the two axes of dish movement to ensure solid grounding of each dish.

Problems with the structural grounding of the collector field were first noticed when nearby thunder storms regularly destroyed the serial communication drivers in the collector field, as well as the PDP 11/03 control room driver connected to the collector field. Destruction of these drivers did not require a direct lightning strike, only a strike in the vicinity of the STEP site. An investigation of the collector field grounding system revealed that all grounding straps (flexible and grounding mat) were bolted onto painted surfaces. Further investigation found that the collector support structure was assembled by bolting together painted support beams, and the metal CCU enclosures were painted before being bolted onto painted support framework. These actions negated the intent of the grounding system design by preventing a solid metal connection between the collector field structure and earth ground. Testing of the grounding system found it to be inadequate.

These grounding deficiencies were corrected by removing all grounding straps and removing the paint where these straps were connected. A corrosion preventing lubricant was applied before reconnecting the straps to ensure good grounding. Seams where framework was bolted together were welded to provide solid metal continuity and an additional strap was installed on the CCU enclosure to the support framework to provide adequate grounding.

Since these corrective measures were taken, there have been no communication driver failures except on collectors 102 and 1210 and in the control room. These two collectors are the only ones with direct serial line connections with the control room. Investigations are underway to determine if grounding in the control room is adequate, and installation of fiber optic serial connections is being considered.

Testing of the grounding system also revealed that a French drain on the east end of the collector field had cut into the grounding mat and isolated the area from collector row 12 to the east fence. The subsequently installed Stirling Engine and associated weather station were left without proper grounding as a result. This was corrected by digging to the grounding mat and reconnecting the severed cable. Subsequent testing of the equipment in this area and surrounding metal fence indicate solid grounding.

(Collector Drive Motors): The collector drive motors used in the collector field are intermittent duty, 1/10 hp, 110 volt, single phase, 30:1 gear head motors. These motors, which offered the lowest cost and where a normal part of the polar and declination drive Jackuators, produced two problems as a result of their intermittent duty rating and low starting torque.

The intermittent duty rating problem is more prevalent during warm weather and occurs when the motors drive a collector for extended periods. Thermal protective devices in the motor windings open and prevent power from being applied to the windings. After cooling, the protective devices close and the motor can again be operated. Although this problem does not appear to be serious, there have been occasions when operator intervention was required to prevent collector induced receiver damage. During these occasions, motors were required to move the collectors an extended period to reach the focus position. As the collectors neared the focus position, one of the thermal protection devices opened, leaving the collector near (but not in) focus, which required the operators to defocus the collector.

The intermittent duty rating also requires additional manpower to stow the field. When driving the collectors from a west position to the stow position, up to 20 percent of the collectors will not stow because of opened thermal protection devices. Approximately 30 minutes are required for the motors to cool, which adds about one man-hour of labor per operational day because of the intermittent duty rating.

A more troublesome motor problem involves low starting torque. This problem is more prevalent during cold weather and occurs when the motor stalls during startup because of above-normal load or "resistance" torque. The source of the above-normal resistance torque is generally a "rough spot" on the Jackuator, and (if reached before the thermal overloads open) can usually be overcome by manually moving the motor back and forth until the Jackuator "rough spot" has been passed. This problem is more troublesome because it can happen at any time while tracking and requires prompt operator attention.

Drive motors at future sites should use continuous-duty motors, despite increased installation cost. When sizing the motors, spare starting torque should be provided to overcome the inevitable variances in the resistance torque of the drive assemblies. This increased starting torque will require the use of limit switches on the drive motors to prevent the motors being driven against the limits of the jackuator, which has been shown to damage mechanical components relative to system Hardware and Software Controls.

Summary:

From the time of system startup, the CAIS, as originally implemented, has been marginally functional. A goal of unattended (or, at worst, operator-supervised) plant operation has never been achieved. In addition, overall system reliability has been much lower than is needed for safe and efficient plant operation. As a result, at least two highly experienced, computer oriented operators, together with three to four support people in the collector field, have been required to operate the plant. There are several reasons:

- Inappropriate Design of the Collector Field Control Hardware and
- Central Processing Architecture
- Inefficient Programing Practices
- Poor Documentation
- Undesired Shutdowns from Insufficient Testing
- Slow Display Time on Intecolor 8001 Computers and Consoles
- Partially Tested Command Entry System Software
- Unconnected and Undocumented Control Hardware

Several design modifications have made the STEP facility more reliable and easily operated with no more than two persons with only nominal experience. These modifications include the following:

- Complete redesign of Hardware, Software and Firmware
- Removal of Concentrator Position Control from the Central Control Computer
- Elimination of PDP 11/03 Micro-Computer as Field Communication Processor
- Installation of Touch-Screen System
- Removal of Nonessential Programs

Additional modifications to the control system are being considered, including a commercial distributed-processing system using a token-based ring network. Such a system would include independent controllers for the steam generator subsystem, the electric power generation subsystem, the operator's console, and certain modules in the energy logistics subsystem. A modification of this nature would completely eliminate the need for a central control computer in the CAIS.

Many problems have been encountered and resolved with the STEP CAIS. As expected from any first-of-a-kind experimental plant, the lesson often learned was that control system design is difficult during a period of rapidly improving capability of control technology. In addition, the value of research or testing on a scale larger than the laboratory can develop and identify issues that could be detrimental if not resolved before full scale implementation of a new technology.

The approach of the CAIS programmers in dividing the control function into smaller, easier to handle pieces was correct. However, future solar system designs should distribute the control functions to many small microprocessor based units rather than to a large single computer.

3.3 ENVIRONMENTAL EXPERIENCES

Water-related problems caused many equipment failures. Excessive costs for their correction resulted from the use of significant manpower and materials to determine the failure, provide a solution, and test the results. The water issues arose from two sources: normal rainfall and humidity conditions (typical of the Southeast), system-induced problems from component failure, improper operation of equipment, or operator error. Some portion of the problem may have been due to prototype testing in the dry Southwestern climate, although some testing of collector components, surfaces and ground supports was conducted at Shenandoah, Georgia.

Most problems were resolved by a SNLA/Georgia Power operating team through redesign, waterproofing, component replacement, and system repair. Some problems are persistent and remain unresolved, such as collector film degradation. However, resolution is continuing. Other problems were corrected by operational procedure, such as the overnight "lay up" of the steam generator to prevent thermal/air pumping that caused severe corrosion of the boiler section steam tubes of the steam generator.

The following paragraphs provide the individual details of each experience, how it was resolved, and recommendations for future designs.

Rain and Moisture Issues

Rainwater Run-off Control: The drainage of rainwater from the solar collector field was a continual problem during the start up of the STEP plant. The initial installation of an asphalt-lined east-west drainage ditch at the north side of the collector field was not adequate to contain run-off and it was replaced with a larger concrete ditch. Even with the latter design, rainwater soaked into the ground and washed under the new concrete ditch and severely eroded a steep dirt bank on the north property line. Drain holes were then drilled into the side of the ditch, but this did not provide a definite control nor did it alleviate the problem.

Finally, French drains were installed at the north and east side of the solar collector field with an underground concrete barrier to prevent subsurface water penetration under the ditch and breakdown of the embankment. This last design has proven to be successful. Similar problems were resolved for the 5-acre south field that was purchased by Georgia Power to expand solar experimentation.

Control of normal and maximum rainwater run-off should be part of a normal site design process. Expensive and experimental retrofit solutions by operations personnel are not the proper solutions to what should be routine for any solar site at any geographic location. The experience to be passed along to new solar application designers is to recognize and design for the maximum expected variations of all environmental conditions such as wind, rain, snow, flood, temperature, pressure, sunshine, smog, clouds and any possible detrimental effects on the system design. These issues were considered by the STEP design team, but the control of rainwater run-off was not provided.

Motors: Early in 1982, it was apparent that there was a moisture problem in the solar collector field with the solar collector motors and potentiometers. These systems and specific components were operated and tested extensively in New Mexico at SNLA, where the moisture and rainfall environment significantly less hostile than in Georgia. Therefore since it was determined that the moisture or waterproof rating of the motors was not adequate to meet the conditions in Georgia, all solar collector drive motors were removed, their windings sealed, and replaced on the solar collectors. This correction provided satisfactory moisture protection, but some other motor operation problems persisted and are discussed elsewhere in this report.

Solar Collector Position Potentiometers: These units were not weatherproofed originally. Although they operated properly at SNLA, they did not provide reliable performance at the

STEP. The single-wound potentiometers, which determined the position of the solar collector, caused severe problems because of moisture. Therefore, all the potentiometers were removed early in the start-up phase of the program and were replaced with either sealed new potentiometers or reconditioned units. The potentiometers continued to give inaccurate position reporting to the control system.

Field Heat Transfer Fluid Piping: Another rain-induced problem that became apparent during the spring of 1983 was corrosion of the lengths of tubing that were located between the polar azimuth and declination flex hoses. The corrosion was first noted when heat transfer fluid started leaking from this section of tubing. The problem was accentuated by rain-washing of the solar collectors, when they were normally elevated and a large amount of water drained through the hole in the center of the collector onto the insulated HTF tubing section. Movement of that section of tubing during normal sun tracking caused the seals of the aluminum clad moisture barrier to be opened, allowing large amounts of rainwater to enter the section and wet the insulation.

When solar collector field operation was started, heat-transfer fluid above a temperature of 212° F would heat the wet insulation and form steam, which - in intimate contact with the low carbon steel tubing - caused corrosion at a rapid rate, resulting in leaks. The tubing section between the polar azimuth and declination flex hoses was replaced with stainless steel tubing, and the center section of the tubing was anchored to prevent flexing and opening of the moisture barrier.

Large distributed solar fields are very sensitive to care in the design, installation and maintenance of insulation and moisture barriers. Routine component maintenance and general degradation led to excessive labor necessary to maintain the integrity of the system's insulation. During normal maintenance on components, it is necessary to remove the covers and the insulation that were installed by skilled installers.

It is expensive to either maintain the necessary talent on the operating staff or to bring the installers back to the job site. For future designs it is recommended that this technical area be given additional design attention to minimize the long-term degradation that can lead to heat loss and component damage by moisture penetration. Additional research and development in several areas of field piping should be considered. Solar applications have unique problems with thermal stress avoidance and control, corrosion, thermal cycline, and flexible connections.

Collector Surface: The reflector surface of the solar collectors is 3M's FEK-244 (now called EPC-244), which is an aluminized Mylar film with an acrylic coating over the aluminum. Initial reflectance of new film is about 87 percent, but decrease to 84 to 85 percent reflectivity within a short period. For the first few years, it appeared that a rain wash would clean the reflectors and bring the reflectance back to about 82 percent. However, this reflectance has been gradually decreasing so that after 5 years it has declined to 74 percent.

Mechanical scrub cleaning of the reflectors with a soft brush increased the reflectance from 74 percent to about 80 percent, but there is a possible deterioration problem with the acrylic film in a solar environment that is yet to be quantified. This experience is of major value to solar designers and to film manufacturers. Current evaluations of reflectivity degradation are in process, along with experimental evaluation of ECP-300A, a silver-based film.

Another problem with the FEK-244 film is the delamination caused by rain and dew on the reflectors. The delamination starts at the edge of a piece of film and tunnels throughout the piece. This problem was encountered on earlier parabolic trough solar collectors before the Shenandoah solar collectors were built. A possible solution was not found by 3M until after the solar collector field at Shenandoah was complete.

The recommendation is to place half-inch wide strips of the film along the edges of the reflectors. Then, the only edges exposed to the rain and dew are the narrow strips, and when delamination occurs, it is only in the strips, which protects the major reflective surface. This technique has not been tested at Shenandoah. Collector reflective surfaces are in continuous development to reduce cost, increase life, and maximize reflectivity.

Resistance Temperature and Device Leads: A problem associated with the RTDs in the solar collector receivers was corrosion of the wire leads to the RTDs. These copper leads corroded and opened so that temperature readings were not available. The solution was to replace the copper leads with Alumel leads normally used as part of a type K thermocouple. The Alumel material is corrosion resistant, especially at the high temperatures required by the RTDs. The error induced by the difference in lead materials amounted to only a fraction of a degree Fahrenheit.

This problem was overwhelmed, however, by the continued inaccuracy of the RTDs and the problems caused by the RTD well assembly and excessive installation and maintenance labor (Section 3.2).

Contacts on the Collector Control Unit: Corrosion of gold fingered contact connections on the microprocessor boards of the collector control units (CCU), due to humidity, caused erratic operation and often system shutdown. Excessive cleaning of the contacts and occasional reseating of the boards were required. The solution could be to minimize this type of connection in favor of hard wiring where appropriate. This problem was aggravated by frequent access to the case interior as a result of the poor operation of other collector control components.

System-Induced Water Issues

Coating of the Fossil-Fuel Heater: It was not possible to measure the thermal output of the fossil-fuel heater until May, 1982 because the energy measurements depended on steady state operation of the turbine-generator. During the summer of 1982, the turbine-generator was operated at a generation level of 300 kWe, which met the original design intent. It was observed that after not operating the fossil-fuel fired heater for about one month, that a maximum of only 165 kWe could be generated by the turbine-generator. The generating capacity would increase with time so that after several days, levels of 265 to 275 kWe could be achieved.

It is speculated that the problem was initiated when the steam generator developed a leak in September, 1982, causing large amounts of vapor from the HTF to be generated and swept into the FFH with the combustion air. When the FFH was opened to repair the burner ceramics, a thick layer of white powder was found on the heater tubing. It is considered that heat transfer from the hot gas across these tubes was inhibited by this substance, however quantitative data are not available to justify this observation. (Other major problems encountered in the FFH are discussed in Section 3.4.)

Tubes of the Steam Generator: The tubes of the steam generator have suffered from corrosion on the steam side, due to the daily start and stop operation of the STEP system and the steam generator. The original design of using check valves to automatically provide low pressure nitrogen to blanket the warm steam generator after cessation of operation did not work properly. Inspection of the boiler tubes has shown a large amount of corrosion of the tubes in only the boiler, not the superheater or preheater or the sidewalls of the boiler. Replacement of the boiler tubes in late 1986 was necessary to repair the corroded boiler tubes.

There are several possible mechanical and procedural changes that will stop the boiler tube corrosion that occurs each night when the steam generator is allowed to cool. One is to ensure that the water level in the boiler is above the tube bundle (this procedure has been followed since encountering the problem); the second is to provide nitrogen gas at a positive pressure to prevent the intrusion of oxygen into the system.

Glint Damage: A significant and unexpected experience encountered in the solar collector field is the off-axis concentration of light by the solar collectors (called "glint"). It was known that concentrations as much as 60 suns occurred at eye level with the stowed solar collectors under certain conditions during preliminary testing at SNLA in 1979. However, the optical effect on piping insulation and adjacent solar collectors was not recognized.

The detrimental effect on piping insulation developed while the solar collectors were in stow. Under this condition, glint not focussed on the receiver, could melt the aluminum metal cladding on the main manifold lines at certain times of the year for certain positions of the sun. The solution to this problem was to place sheet aluminum around the insulated aluminum metal clad lines with an inch stand-off from the aluminum metal clad to provide free air movement to both sides of the sheet aluminum.

A more serious effect on adjacent solar collectors was to have glint reflected onto the back side of the reflector, heating the aluminum petals to a temperature that caused the FEK-244 film to change color or melt. The solution is to ensure that the solar collectors are never positioned so that the glint will encounter an adjacent solar collector in the same branch. This is accomplished either under the control of the operator or a computer program that can be implemented to prevent this occurrence by geometric considerations. The redesigned collector field controls use software to prevent this occurrence. This optical hazard problem was unexpected and easy to resolve, and provides a key experience that must be factored into future designs and recognized by solar plant operators.

Summary

Most of the STEP problems caused by environmental conditions were resolved by the field personnel. These problems can be minimized by a normal design process complemented by appropriate testing. Early integration of an adequate number of operating personnel can aid in the development of procedures that further reduce the number and impact of such issues. This latter approach is particularly important in the treatment of the thermal pipe insulation and the optical hazard of concentrated light.

In a system such as the STEP, where thermal losses are significant, it is important to keep the insulation integral and to eliminate the entrance of water. This is not an easy task when considering the size of the STEP collector field system and subsequent planned commercial-sized systems.

Damage to the collector surface by moisture is being resolved by new materials, designs, and mounting techniques.

3.4 PERFORMANCE OF THE HEAT TRANSFER FLUID SYSTEM

During the conceptual design phase of STEP, the value of a heat transfer fluid (HTF) that could be used at higher temperatures than in previous systems, was considered important for solar applications. The HTF would also have to have acceptable thermal properties and pumping characteristics. This recognition of values precipitated several trade studies and fluid tests by SNLA. Based on the results of the studies and tests, and on significant support from the manufacturer, a developmental polydimethylsiloxane (Q2-1162) was chosen as the HTF to be used at STEP. This fluid is now known by the name Dow Corning's SYLTHERM 800.

Although SYLTHERM 800, at a current cost of $23.50 per gallon, was more expensive than some other heat transfer fluids considered, its thermal properties and fluid characteristics made it desirable. Analysis at SNLA, and the manufacturer's data, showed that Syltherm's specific heat, viscosity, thermal conductivity, and density were compatible with the STEP conceptual system design. Also, since SYLTHERM had a low vapor pressure, some cost reduction in the HTF system was anticipated, particularly in the cost of storage and conditioning tanks and piping due to their lower pressure requirements.

Much has been learned about the use of SYLTHERM 800 as a HTF at STEP. In the following sections, the problems and experiences associated with the HTF system at STEP are discussed. Some situations were improved or problems corrected. The design and procedural actions taken to address each problem are also presented.

High Fluid Loss Rate

There were four procedures in the operating of the STEP system during which losses of SYLTHERM occurred. The first was during the supplier recommended conditioning of new SYLTHERM 800. Additional losses were experienced when used SYLTHERM was reconditioned due to moisture contamination. There was some loss of fluid associated with leakage or spillage through operator error or equipment failure during routine operation and maintenance. Finally, during normal operation, rearrangement of the polymer chain produced cyclic oligomers that were lost because they had to be vented from the system.

According to the manufacturer's original recommendations, new SYLTHERM 800 had to be conditioned to remove heat transfer system contaminants, especially moisture. The conditioning was accomplished by gradually heating the new fluid while it was circulated in a conditioning tank swept with nitrogen. Any volatiles produced by the heating process were vented with the nitrogen. From the experience of conditioning all the SYLTHERM delivered to STEP, it has been calculated that approximately 25 percent of new factory-supplied SYLTHERM was lost during the initial conditioning process. Also, when used SYLTHERM was exposed to air or moisture, the manufacturer recommended that the fluid be reconditioned again. Although the loss rate for reconditioning is usually less than the initial conditioning loss rate, repeated reconditioning contributed substantially to the total system HTF loss rate. New conditioning procedures have been implemented, which essentially eliminate fluid losses due to conditioning.

During low pressure operation of the STEP system, large losses of SYLTHERM 800 were experienced owing to venting cyclic oligomer from the large high temperature storage tank. An estimate of the amount of cyclics or volatiles vented from the system was produced by carefully weighing the cyclic filled barrels and then assuming that all barrels were filled 92 percent full before being replaced. By this method, it was calculated that 177,007 pounds of HTF was vented from the system. As of December 1986, records show that 201,472 pounds of SYLTHERM 800 had been received. This provides a total loss of almost 88 percent.

In STEP's early operating history a large portion of the HTF losses was attributed to water contamination. However, even when the water content of the SYLTHERM was low, venting vapors from the high temperature storage tank (to keep the pressure below the relief valve setting) resulted in significant losses of HTF. The original product information brochures on SYLTHERM 800 stated that "Operation with SYLTHERM 800 Heat Transfer Liquid required only nominal system pressure, even up to 750° F. The pressure is easily provided by use of a nitrogen blanket."

In August, 1985 new product information on SYLTHERM 800 was received from Dow Corning defining significantly higher "long-term equilibrium" vapor pressure (197 psia at 750° F). At that time it was recognized by the STEP staff that the HTF system was operating well below the equilibrium pressure of SYLTHERM 800, even in the lowest temperature sections of the STEP system. In the high temperature portion, (for example, the high temperature storage tank) the design operating pressure (15 psig) was significantly below the newly provided equilibrium pressure of SYLTHERM. This was also true for the conditioning system previously discussed. This information was relayed to Sandia and mutual design and modification actions to correct the problem were initiated.

The key experience gained from the use of this heat transfer fluid was the effects on system components caused by the design operating pressure, poor flow control, improper operating conditions and fluid contamination at STEP. These conditions led to loss of HTF, poor component and system performance, and plugging of collector receivers, as discussed in a following section.

The SYLTHERM 800 heat transfer fluid was operated in a system with a nitrogen cover gas pressure that was limited to 15 psig by the design of the high temperature storage tank and its relief valve setting. Usually, the nitrogen gas pressure was set for 10 psig. The pressure would increase as the fluid was heated and was vented before exceeding the 15 psig limit.

In the STEP system, the SYLTHERM 800 was heated to 750° F and pumped into the high temperature storage tank or through the steam generator where energy was extracted and the HTF was reduced to about 500° F at design conditions. Normally the tank and the cooler side of the SYLTHERM loop would be subject to the 10 psig cover gas pressure, while the higher temperature sections would be at the pump discharge pressure minus piping losses.

By examining the most recent equilibrium pressure versus temperature curve for SYLTHERM 800, it can be seen that the entire system was operating below the equilibrium pressure curve. The worst case was in the high-temperature storage tank. SYLTHERM fluid approaching 750° F with an equilibrium pressure of 197 psia was being stored in the tank at approximately 25 psia. When the high-temperature storage tank was vented to prevent overpressuring, nitrogen and cyclic vapors along with vaporized SYLTHERM 800 was vented, resulting in large losses of heat transfer fluid.

After a large amount of vented and condensed vapors had been removed from the STEP site, it was learned from Dow Corning that a large percentage of the fluid lost during conditioning, reconditioning, and operation could have been reused. Therefore the 88 percent losses shown above could have been substantially reduced. Subsequent investigation suggested that operation of SYLTHERM 800 in a similar system with nitrogen blanket gas pressures of 75 to 90 psig has shown that fluid losses were reduced to between 10 and 15 percent over a 2-year period.

The STEP heat transfer fluid system has been modified to operate at higher pressures. The low pressure side of the system was usually raised to 40 to 50 psig, but could be raised to 100 psig. This modification, which consisted of an expansion tank and column, was designed and obtained by SNLA and installed by Georgia Power. It has virtually eliminated the fluid loss problem. The use of SYLTHERM below its equilibrium pressure will be associated with other problems presented in this report. These too have been corrected by the SNLA/Georgia Power modifications.

Some losses of HTF occured during malfunctions. The necessity for a catch tank at HTF relief valve discharge lines has been experienced at STEP. The original STEP design provided for this feature, but before the tank was installed, inadvertent operation of the HTF system caused the relief valves to open. Overpressuring the heat transfer fluid relief valves in the STEP system occurred when the collector field pump was dead-headed into a valve downstream of the relief valves. An estimated 400 gallons of SYLTHERM was discharged from the HTF system and contained in the outside mechanical concrete pad area, but most of the spilled fluid was not recovered.

It is obvious that such a spill of hot fluid can also be hazardous. The catch tank has been installed and has minimized the problem, but the tank could still be overfilled and result in a loss of fluid. Another solution to this problem involved a pressure switch, installed just ahead of the relief valves. Its activating pressure is set just below the relief valve setting. The pressure switch is wired so that, if activated, the collector field bypass valve opens to provide an alternative flow path that prevents a dead heading pressure from forming.

Another operational HTF leakage problem at STEP, as with many tracking solar systems, has been flex hoses. The relative loss of SYLTHERM from flex hose leaks has been minimal. There is a problem, however, when changing leaking flex hoses. A STEP collector cannot be completely isolated from the remainder of the HTF system because there is only one hand valve for each collector. Several gallons of SYLTHERM are lost whenever a flex hose is changed, and it is not unusual for a large volume to be sprayed on the technician. Of the 512 flex hoses in the STEP system, 28 hoses have been changed since the plant was constructed. During each flex hose change operation, HTF has been lost.

The HTF loss rate, owing to leakage and spillage at STEP has been small when compared with the losses associated with required conditioning and operational venting of vapors. The occurrence of leaks and spills should be anticipated and carefully considered when designing or operating any piping system. SYLTHERM 800, with its low toxity and low freeze point, has made operational and accidental leakage and spillage an easy matter, particularly when compared with other potential heat transfer fluids and their problems. The SYLTHERM environmental and safety characteristics are highly desirable for future designs but the economic and performance issues should be further studied before a heat transfer product selection is made.

Pump Cavitation in the Heat Transfer Fluid

Pump cavitation in the heat transfer fluid system was a major operational problem at STEP. When the collector field was in focus and the pumps cavitated, the collectors would overheat and defocus. If the FFH was being used it would be tripped off by the low flow protection circuitry. It was common for operators to spend the first hour or two of morning startup attempting to alleviate the cavitation problems by repeatedly venting vapors from the HTF lines. Also, shutdowns were common during operations owing to pump cavitations when the HTF system was disturbed by operating mode changes. There are two interrelated phenomena that caused the excessive cavitation problems.

The suction side of the pump must be provided with sufficient fluid pressure or net positive suction head (NPSH) so that a pump will not cavitate. When the NPSH is marginal, any small disturbance in the supply flow to the pump inlet can cause cavitation. This situation is aggravated in systems such as STEP, with pumps piped in series, because cavitation at one pump disturbs the supply to the next pump down the line. Use of a flow-through expansion tank would have helped to alleviate this problem by providing a disengagement space for low molecular weight oligomers.

The cavitation problem was further aggravated because at the temperature in the STEP system the SYLTHERM 800 heat transfer fluid pressure was below its equilibrium pressure for the operating temperature. As the fluid approached the pump impeller, an additional, localized pressure drop occurred due to the suction produced by the impeller. These conditions increased the likelihood of fluid flashing at the pump inlet which made the fluid at the pump inlets very unstable. Raising the HTF system operating pressure, and therefore the NPSH, has eliminated this problem.

Heat Transfer Fluid Solidification in Receivers

A major solidification problem was encountered with the SYLTHERM heat transfer fluid. This solid formation resulted in the blockage of solar collector receiver tubes. The blockage appeared to have formed at the RTD thermal wells, where the flow is restricted and consisted partly of a black solid material. Dow Corning has determined it to be a deposit from the breakdown of the heat transfer fluid. The occurrence of combinations of the following four conditions led to the heat transfer fluid breakdown and resultant solidification:

- Water contamination of the heat transfer fluid
- Over temperature due to inaccurate temperature measurements
- Low flow in the receiver
- Low pressure on the heat transfer fluid.

Water contamination of the heat transfer fluid was probably the event that led to the production of the black solids that plugged the receiver tubes. According to Dow Corning, moisture in the heat transfer fluid uses up the stability additive when the fluid is heated. The combination of moisture and heat causes the additive to precipitate out the black solids that were found in the plugged receiver tubes.

Contamination of the heat transfer fluid with water was identified by Dow Corning in late 1982, as a result of routine sample analysis. The source of the water was traced to the steam generator. The leak was caused by an operational error that thermally shocked the tube sheet in the steam generator. It may be possible to design a more thermally forgiving interface between the heat transfer fluid and water systems, but the ultimate responsibility must be placed on the startup operators to make sound judgments about operations that can damage equipment. Well-considered operating procedures, with design approvals can also minimize this problem.

The accuracy and reliability of the RTD devices used in the STEP collector receivers have caused considerable problems; an inaccuracy of 50° F was common. This suggests that with a 765° F defocus temperature set point, the actual temperature of the receiver could have exceeded 815° F, leading to accelerated HTF degradation. The RTDs have since been replaced with thermocouples in the entire collector field, and, when coupled with a new collector control unit design, this problem has been eliminated.

Low flow rates through the receivers were a major contributor to the plugging phenomenon. If the flow rate through the receiver was low enough the fluid flow became laminar rather than turbulent. During the laminar flow conditions, the inside skin temperatures of the receiver tubes could greatly exceed the temperature that the RTD was exposed to in its thermal well. These very high localized temperatures accelerated the degredation of the heat transfer fluid, well before the collector received an over-temperature defocus command.

A similar situation occured with no flow through the receivers. Occasionally the no-flow condition occurred because of pump cavitations or loss of site power, and when flow was intentionally stopped to force the collectors to defocus during loss of control communications.

Laminar flow is a potential problem for distributed receiver systems if it occurs during operation of the system. Laminar flow conditions were identified as one of 3 conditions which caused the receiver plugging problem at STEP. Operators and flow control systems must be aware of the minimum flow required to keep the flow turbulent in the solar collector receivers. Even if the heat transfer fluid could survive the elevated skin temperature during laminar flow, the receiver is less efficient under this condition.

Low pressure in the heat transfer fluid system is again suspect of causing or contributing to this problem. With the pressure below the heat transfer fluid equilibrium pressure and the heat transfer fluid being heated in the receiver, it is possible that vaporization occurred in the receiver and could have caused hot spots on the receiver tubes.

The effects of a change of state in the receiver tubes is not known at present. However, this situation was improved in July of 1984. Originally the main field flow was controlled by varying the position of Flow Control Valve 6005 before the heat transfer fluid entered the collector field. It was recognized by the STEP staff that if the flow restriction was on the outlet of the collector field (rather than the inlet), then the receivers would operate at a higher pressure and better flow distribution would be established. This was accomplished by simply moving the variable positioning device from the Field Supply Valve 6005 to the Field Outlet Valve 6040.

To continue with this logic for the new modifications to the STEP system, the flow can be restricted by Valve 7150 at the HTF outlet of the steam generator. This gives not only the receivers a higher operating pressure but also the HTF transport lines up to and through the steam generator where the pressure can be dropped after the energy is extracted from the HTF and its temperature is lower. These efforts, along with pressurizing the system, have helped reduce the rearrangement rate of the HTF. However, at 750° F, the receivers would still be operating below the equilibrium vapor pressure. Use of the recently installed fossil-fuel superheater allows lower field operating temperature and higher flows and thus further receiver plugging has not been encountered.

Solidification in Sensing Lines

An attempt to minimize electrical heat tracing in the thermal storage tank for the HTF was not completely successful in practice. Bleed lines and pressure sensing lines, which were routed under the insulation next to the tank where the HTF in the tank kept the lines warm, worked successfully. But wherever the HTF lines were brought out of the tank insulation there was much difficulty with the formation of a solid cyclic oligomer of the HTF which blocked the line. The problem was solved by inserting ambient temperature fluid into the lines, to prevent the entry of cyclic material.

Summary Relative to System Performance of the Heat Transfer Fluid

The modifications made to STEP have alleviated or corrected many of the problems with the HTF system. The most persistent issue was a design operating pressure that was too low. This situation was aggravated by poor temperature and flow control and by inadequate field control, and was prolonged by failure of the operators, manufacturers, and designers to recognize the problem.

At STEP the problems associated with the SYLTHERM 800 HTF were frequent and costly. A major factor contributing to the situation was that SYLTHERM was being developed at about the same time that STEP was being designed. Some of the properties of SYLTHERM were not well established at that time. Poor communication among the program parties was also a contributing factor. The results of this communication failure were lost experimental time, extensive manpower utilization, and direct economic loss from HTF replacement, and repair and replacement of damaged components.

The association of operator error that introduced water directly into the HTF cannot be underestimated. This error is known to contribute to the high losses and the receiver plugging issue. However, the degree of association is more difficult to quantify than the equilibrium pressure or "vapor pressure" problem. Because of the price premium of SYLTHERM as compared with other HTFs, the decision to use SYLTHERM was based upon its high temperature performance and the subsequent effect on the overall and long term cost effectiveness. The cost effectiveness of using SYLTHERM, with properties as known today, in a future distributed receiver solar system needs to be evaluated. The technical lessons from STEP should be incorporated into this evaluation.

The failure to recognize the necessary increase in pressure of the HTF for proper performance is related to the project's organization. The HTF supplier was heavily involved in the basic material research in support of the STEP testing. Fluid samples were periodically and often transmitted to the supplier for analysis. The company was well aware of the collector/receiver plugging problem and pump cavitation. Temperature/vapor pressure curves were available and routinely reviewed by the operating team. The designers knew of all operating problems and HTF operating conditions. Pressurization should have been proposed and carried out significantly earlier. Within the organization of supplier, designer and operator each probably depended too much on the others to recognize this problem and to actively communicate the need for change.

3.5 THERMODYNAMIC PERFORMANCE OF THE SYSTEM

This section provides an overview of the system's thermodynamic performance (more extensive reporting is being provided by SNLA). Only the major points are made regarding the collector field's heat loss and efficiency and the relationship to the performance of the turbine generator. Details of efficiency, collector field heat loss and system availability are given in accordance with original design goals of STEP.

STEP Efficiencies

Overview: STEP can be operated using a combination of solar-derived energy from the collector field and natural-gas-derived energy from the fossil-fuel heater (FFH). From the DOE Performance Test Program, operated from April of 1984 through December of 1986, it was found that the levels of operation noted in Table 3-3 could be maintained when producing electricity, process steam, and chilled water. These electric power levels define the maximum steady-state operating capabilities of STEP achieved during this test series.

TABLE 3-3
STEADY-STATE OPERATION

Energy Source	Electrical (gross)	Process Steam	Chilled Water
Solar only (850W/sq.m)	135 kWe	600 lb/h	50 tons*
Fossil-Fuel Heater-only	210 kWe	650 lb/h	35 tons*
Hybrid mix (52 percent solar)	330 kWe	800 lb/h	55 tons*

*** United States Refrigeration Tons (12,000 BTU/H)**

Modifications to increase the air conditioning load and to provide fossil-fuel generated steam superheat have produced operating levels significantly higher in the solar-only and fossil modes of operation. The hybrid mode appears to be limited only by buildup of steam pressure in the intermediate stage of the turbine (the set point is 135 psig). By increasing the set pressure of the intermediate stage relief valve to 160 psig, higher turbine outputs are expected.

Several studies of STEP system's thermal performance were made possible by the large amount of data collected during the DOE- and SNLA-sponsored test programs. Both energy balances (first law of thermodynamics) and availability balances (second law of thermodynamics) were studied. From these studies, conclusions may be drawn about the thermodynamic design of a distributed receiver's total solar energy or cogeneration system. System efficiency, energy, and availability give a complete picture of STEP as a total energy system. An understanding of the interaction of first law and second law efficiencies and of the relationship between short- and long-term performance for STEP system can give insights of great value for future solar system designs.

Short-term analysis examines instantaneous steady-state performance measured under ideal conditions to give insight into the most favorable system performance and design. Long-term and day-long performance examine the capability of the system to compete with and displace fossil fuels.

The following sections present the results of the data collected and a summary assessment of performance.

Efficiency Measurements: The results of the DOE Performance Test Program have been summarized previously (Heckes and Stine 1986). Since a hybrid mix of solar and fossil fuel will be used in commercial operation, performance using this mode will be emphasized in this summary.

Instantaneous steady-state point performance and day-long and longer term performance, which are important to understanding STEP's performance, are presented in the following paragraphs.

(Steady-State Efficiencies): Figure 3-1, derived from data from the DOE Performance Test Program, shows the energy balance for operation using a 52/48 percent mix of solar/gas-derived thermal energy. For this operating condition, 109 of the 114 collectors were operational and the insolation was $770 W/m^2$ The collector field, connected in series with the fossil fuel heat transfer fluid heater, raised the temperature of the heat transfer fluid from 530° F to 640° F, with the fossil-fuel heat transfer fluid heater boosting that temperature to 750° F. Besides the 330 kWe of electricity that the generator was producing, STEP was supplying 620 lb/h of process steam, and 56 tons of chilled water.

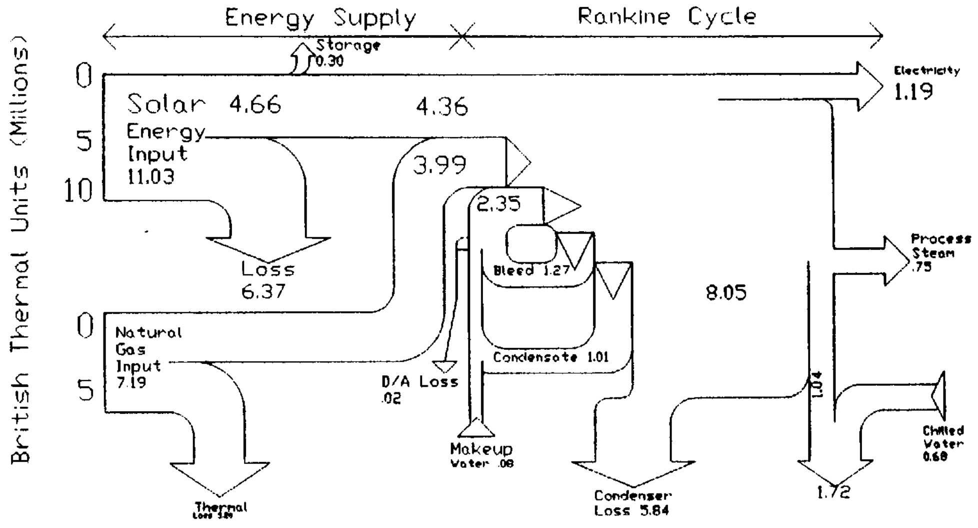

Figure 3-1: Energy balance for hybird, cogeneration operation

A summary of the operating efficiencies for this steady-state condition is given in Table 3-4.

TABLE 3.4
ENERGY EFFICIENCIES HYBRID/COGENERATION OPERATION

Collector Field Efficiency	**42.6 percent**
Fossil-Fuel Heater Efficiency	**56 percent**
Power Cycle Efficiency:	
Thermal-to-Electrical	**12.8 percent**
Thermal-to-Total Energy	**34 percent**

Total energy is the sum of electrical energy and the energy in the process steam and the steam going to the absorption chiller.

Day-Long Efficiencies: Solar energy systems usually exhibit maximum performance under steady-state operation at or near solar noon on a clear day. When operated over a day, however, performance is reduced because of heat that must be supplied to warm the system, and a higher percent of heat loss at low insolation levels. Both features have been measured at STEP along with full-day system performance on a clear day (Stine and Heckes 1987).

The amount of thermal energy required to raise the thermal mass of the collector field from ambient to its design operating temperatures (500° F in, 750° F out) is 1,500 kWh(t) (5.1 x 106 Btu). This warm-up energy is supplied by bringing the collectors into focus in the morning and circulating heat transfer fluid through collectors until the receivers and piping are heated.

An additional 2,000 kWh(t) (6.8 x 106 Btu) is required to bring the power conversion cycle up to design operating conditions. This warmup energy could be supplied either by the fossil-fuel heater or the solar collector field. For these tests, energy was supplied by the fossil-fuel heater.

The second feature affecting day-long performance is thermal loss from the collector field. Measurements show that approximately 63 percent of the beam's normal insolation falling on the concentrators is absorbed as heat in the receivers (Chon and Garcia 1986). At the design operating temperature of 750° F, the collector field (collectors and field piping) losses absorbed energy at the rate of roughly 550 kW(t). This results in a collector field efficiency of 50 percent at maximum insolation levels of 1,000 W/m^2. Efficiency declines as insolation decreases. The relationship between the energy collected and insolation for both the design operating condition and for a 625° F field outlet temperature is shown in Figure 3-2. The reduction in collection efficiency with insolation level means that less energy is collected in the mornings and in the evenings when insolation levels are low.

The combination of these effects on the STEP energy collection is shown for a typical clear day near the solstice in Figure 3-3. The shaded region (A) represents the energy required to heat the collector field to operating temperature. Shaded region (B) is the energy that cannot be collected, since the system heat loss would be greater than the input. This condition does not exist in the morning since the system starts off cold and the energy loss only increases as it heats.

The remainder of the thermal energy is supplied to the power cycle and is shown as the area under the collector field's output curve. For this typical STEP day, 9,480 kWh of thermal energy is supplied to the power cycle. This is 31 percent of the beam's normal irradiation falling on the collector field and, is significantly less than the noon-time, steady-state collection efficiency of 42.6 percent.

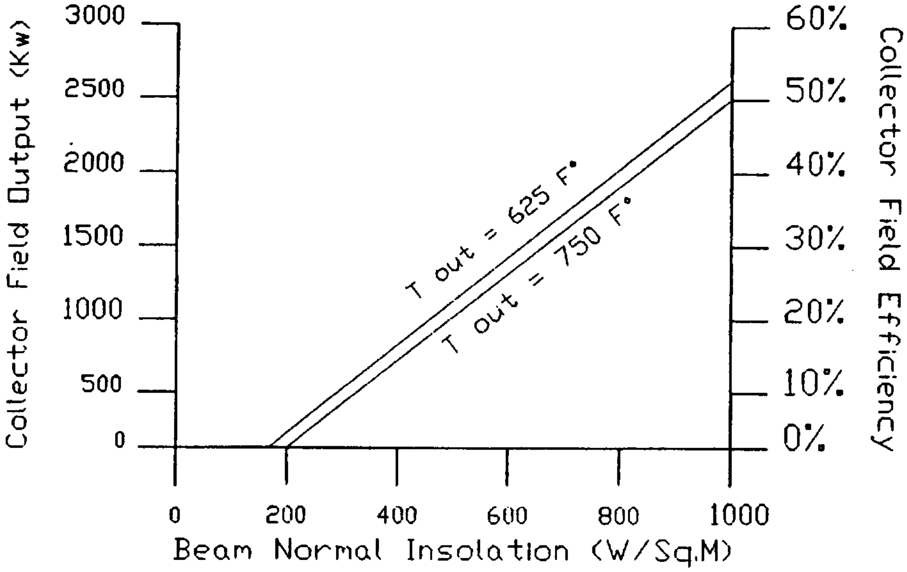

Figure 3-2: Reduction of collector field output with insolation level

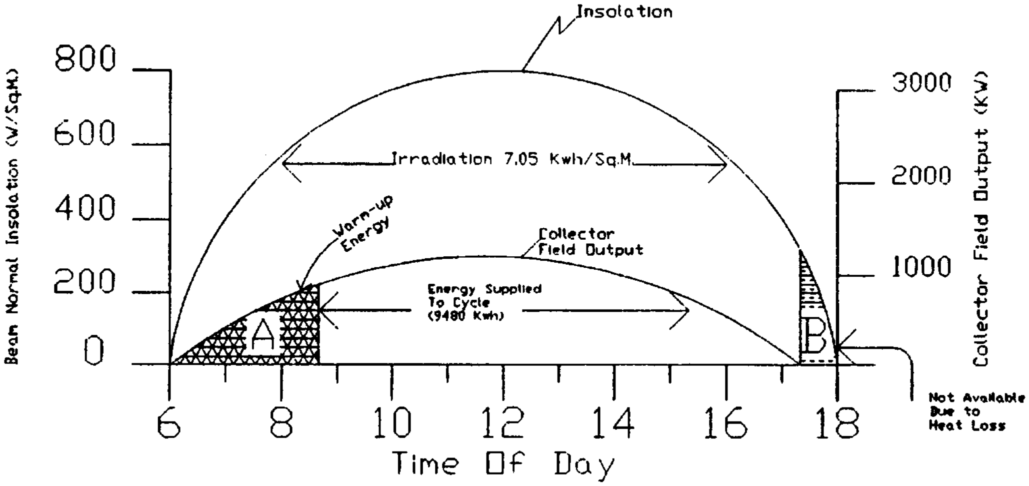

Figure 3-3: Collector field energy collected on a typical clear day

Long-Term Efficiencies: Over a longer period, the percentage of solar energy collected by a system is even less than described in the previous paragraphs. This is due to three features: cloud cover, system operating decisions, and system reliability.

The collection efficiency of the solar field decreases as insolation decreases (Figure 3-2). A curvature was expected, but because the data was limited and the tests were operated with no solar flux, a straight line was used. Over a long period, there was a mixture of clear days, cloudy days, and partially cloudy days. Therefore, the percent of the incident energy collected over all these periods was less than the percent collected over a clear day.

The second reason for lower long-term efficiency is based on operational decisions. If, as with scattered clouds, the insolation falls below the 200 W/m^2 break-even point, the system will be shut down. However, heat loss will continue until the field cools to ambient temperature. If insolation later increases, the operators could restart the collector field and collect more solar energy. With STEP, this takes considerable operating time and excessive manpower (during a time when potentially collectible energy is being lost). Depending on the character of the partly cloudy day, the decision to restart the collector field during partially cloudy weather requires judgment.

The third feature affecting STEP's long-term performance is system reliability. Failure of the full system or individual collectors during periods when insolation occurs results in less energy being collected. The redesigned collector field controls has reduced these deficiencies. New analysis of long-term efficiency will be provided in future reports.

To explore these features with STEP, a 30-day test was run in the summer of 1985 to identify the maximum amount of energy that could be produced by STEP operating as regularly as possible. In this study, it was found that over the test period, 23 percent of the beam's normal insolation falling on the collector field was collected and supplied to the power conversion cycle (Stine and Heckes 1987).

Figure 3-4 shows the incident energy and the energy collected during this test. For these data, the STEP collector field was not operated on days when the incident irradiation falling on the collector field was less than 10 MWh (2.3 kWht/m^2). On days on which the irradiation is

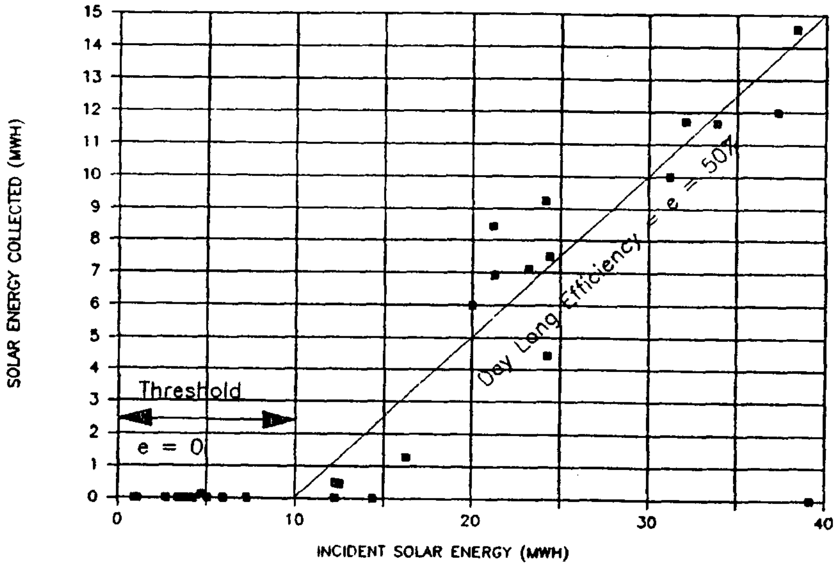

Figure 3-4: Collected solar energy during commercial operations testing

greater than 10 MWh, approximately 50 percent of the energy above this level was collected. The 10 MWh constant represents the average amount of energy that is not collected owing to heat loss, low insolation levels, operational lag in restarting the system, and operational reliability.

The impact of this irradiation threshold on year-long performance can be estimated from Figure 3-5. The cumulative probability of daily irradiation levels is based on typical values for a year measured at Shenandoah. This shows that irradiation levels of less than 2.3 $kWht/m^2$ (10 MWh on the entire field) occur 30 percent of the days during the year. However, these low irradiation days account for only 5 percent of the 7,000 MWh total irradiation incident on the collector field over the year. These data are from original experiments done at Shenandoah (Jeter).

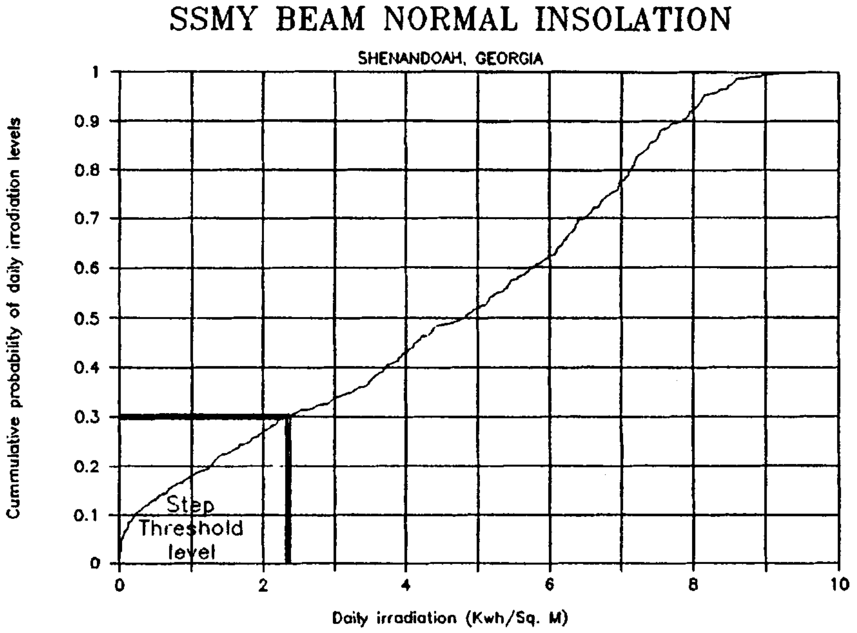

Figure 3-5: Typical year insolation levels

Summary

Large condenser losses in the energy balance are due to a system thermal design with a condenser operating at 250° F rather than at ambient temperature. Higher exhaust temperatures are required by the absorption chiller. However, since only a small portion of the turbine exhaust is used by the chiller, a better design would be to lower the condenser temperature and use second-stage bleed steam to operate the absorption chiller. An alternative would be to increase the chiller load. (These points are discussed in following sections.)

Another large source of energy losses is the fossil-fired heat transfer fluid heater. This is because it heats the fluid from 500 to 750° F. In an ideal heater, the lowest exhaust temperature would have to be 500° F. In future designs, the stack gas of the fossil-fired heat transfer fluid heater should be used to preheat boiler feedwater, an application for which heat at temperatures below 500° F can be used.

The efforts made to reduce energy losses in the STEP collector field were commendable and were considered to be successful. However, since the amount of energy not collected (approximately 57 percent) is so large, efforts to capture this energy should continue.

Heat Losses in the Collector Field

Overview: A major consideration in the design of parabolic dish collector fields is the collection and transport of thermal energy to a central point (Leonard 1983). Heat loss tests were carried out at STEP to find the extent of thermal heat loss in the collector field piping, and the receivers. Tests were done without solar flux on the receivers, using the fossil fuel heater as the energy source. Conduction and convection heat losses from the collector field's piping were measured as were conduction, convection and radiation heat losses from the receivers. Also measured was the energy required to raise the temperature of the collector field to operating temperature, called the thermal 'mass' of the field (Cummings 1985).

At normal operating conditions, the steady-state heat losses per unit of collector aperture area were found to be 130 W/m^2. The thermal mass of the collector field was found to be 2.18 kWh(t)/° F, implying that approximately 17 percent of the energy collected on a typical day is used to warm the field piping and fluid to operating temperature.

These studies show that STEP design held heat loss during startup and operation to a minimum. They also show that the most favorable operating temperature can be defined that maximizes power production efficiency, which is a function of both insolation and sun angle (Stine and Heckes 1986).

Collector Field Design: At STEP, the 114 solar collectors are aligned in 12 rows, with staggered spacing, alternating between nine and ten collectors per row. The distance between rows is 35.4 ft and the distance between adjacent collectors in a row is 28.4 ft. The collectors are distributed over a land area of 115,000 ft^2 resulting in a ratio of collector aperture area to field area (packing fraction) of 41 percent.

The diameter of the collector receiver apertures is 18 in; the inside absorber surface has a maximum diameter of 25 in, and a length of 21 in. Under design conditions, HTF enters the receiver at 500° F and leaves at 750° F.

Considerable care was taken during design of the field piping flow configuration to reduce the heat loss and thermal mass. The main supply and return manifolds are zig-zag shaped to provide for thermal expansion with a minimum of additional piping. Insulated stainless steel pipe supports are used for these lines. Different thicknesses of insulation (to 6 in) were applied, based on pipe diameter and operating temperature.

Both the supply and return pipes of the branch manifolds, and the lines to and from the receivers are nested within a single insulated jacket. The nesting of the two fluid lines within the same insulated jacket results in lower heat loss to the surroundings, and allows the transfer of a small amount of heat from the hot to the cooler fluid. Calcium silicate pipe alignment guides and supports are used for the branch manifold lines.

Two features that enhance the low-loss field piping design include upside-down valve placement, and anti-thermosyphon loops. Both features reduce heat loss from the field piping under no-flow conditions.

Steady-State Losses of the Collector Field: Steady-state collector field heat losses were measured at different collector temperatures and orientations to determine the effect of these variables on the collector field heat loss. The results are summarized and interpreted on Figure 3-6. Thermal losses in the collector field are divided into four categories: 1) heat conduction losses through the field piping insulation including main manifold, branch, and individual supply and return lines; 2) convection losses from the receiver cavity aperture; 3) conduction losses from the receiver through its surrounding insulation; and 4) radiation losses from the receiver aperture.

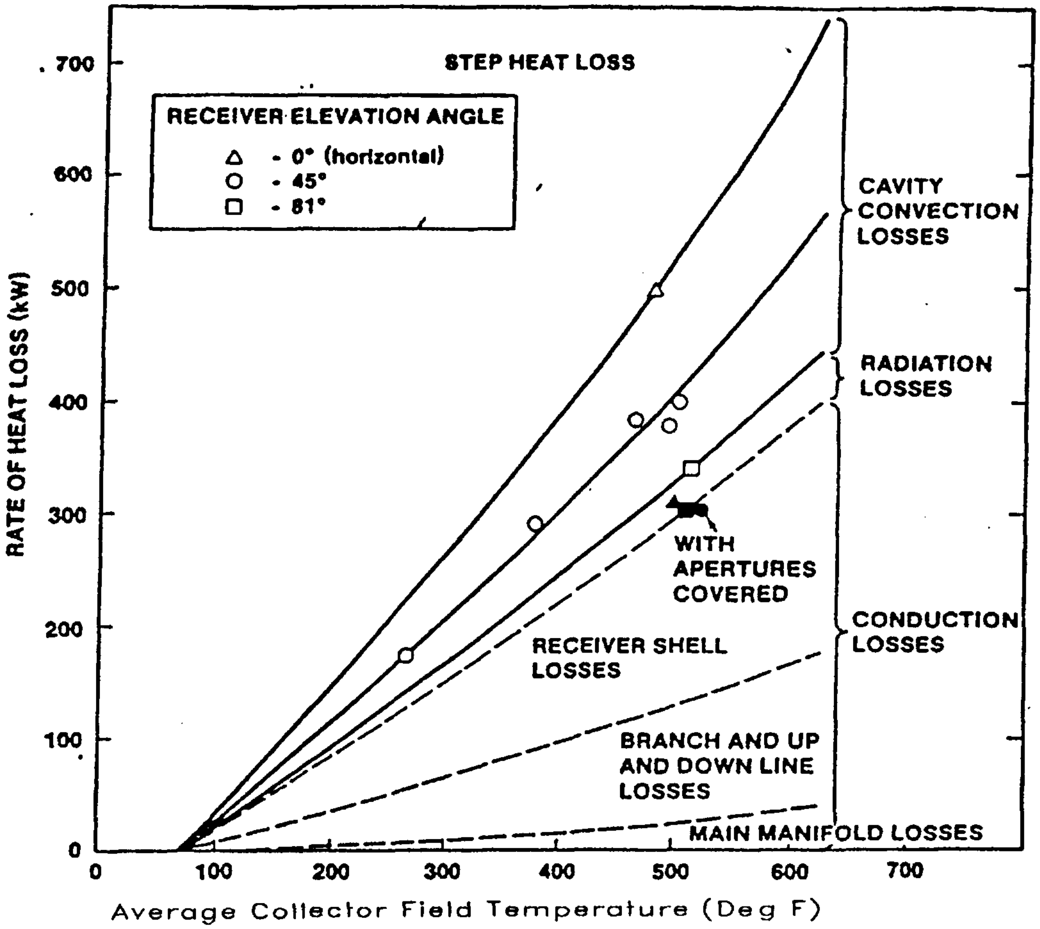

Figure 3-6: Summary of steady-state heat loss data

To determine these losses, the total field heat loss was measured at three temperatures with the collector elevation angle at 45 degrees. These data are extrapolated over the operating range of the collector field. Tests were then made to determine the effect of receiver orientation on heat loss. As shown, the heat loss changes significantly over the range of aperture orientations tested. The 81 degree orientation (solar noon, summer solstice position) was the maximum angle to which the receivers could be moved. It was assumed that the convection of energy out of the cavity receiver is minimal at this angle and represents a low convective loss condition.

The heat loss measurements (Figure 3-6) are extrapolated to the design operating condition of 500° F supply and 750° F return temperatures. The results are given in Table 3-5. The major component of heat loss is conduction of heat from the receiver cavity to the surroundings, followed by conduction loss from the branch lines and up-and-down lines to the receiver.

Table 3-5
Collector Field Heat Loss Rates at Design Operating Temperatures with Collectors Oriented at 45 degree elevation angle.

Component	Heat Loss Rate kWt	Loss per Unit Collector Area W/m^2	Percentage of Total (percent)
Main Manifold	40	9	7 percent
Branch and Up-and down Manifolds	135	31	24 percent
Receiver Conduction	225	52	40 percent
Receiver Convection	112	28	21 percent
Receiver Radiation	43	10	8 percent
Total	565	130	100 percent

To better illustrate the significance of these values, the total heat loss rates are also given in terms of loss per unit of collector aperture area. This heat loss is 130 W/m^2. This is a significant fraction of the total amount of energy absorbed by the receiver under clear-day conditions, which is approximately 400 W/m^2 when the beam normal insolation is 700 W/m^2. The heat loss rate per unit collector area is also significant because it forms the lower operating limit of the system. When the reflected radiation absorbed by the receiver approaches 130 W/m^2, there is no net collection of solar energy and the collector field should be shut down.

Operating data from previous testing show that for clear-day operations around solar noon, about 42 percent of the incident solar energy is collected and transported to the power conversion cycle and 58 percent is lost. Figure 3-7 shows a breakdown of losses at STEP and the relative magnitude of field and receiver thermal losses. The 42.6 percent collector optical losses represent optical energy lost due to the dish surface reflectance, dirt on the reflective surface, cavity absorptance, optical surface errors, positioning errors and receiver misalignment. These represent a major portion of total losses. Field and receiver thermal losses are small.

Figure 3-8 shows further implications of the thermal heat losses for first-law (energy) efficiency and second law (power production) efficiency. Because STEP is a power producing system, second law efficiency relates directly to how much power the system can produce. As the operating temperature of the field increases, its first law losses increase. This relationship is generally true for all thermal losses. However, as temperature increases the second law efficiency of the entire power cycle increases to an optimum point before it likewise begins to decline. This occurs because the definition of second law efficiency includes an ideal heat cycle along with consideration of thermal losses. Ideal heat cycles generally increase in efficiency as their thermal sources increase in temperature. At lower field temperatures, the efficiency of the ideal heat cycle increases faster than losses. After a point, thermal losses dominate the process. This effect can be seen (Figure 3-8) as the second law efficiency curves go through a maximum and then show a downward trend.

The graph (Figure 3-8) also shows that these effects are a function of insolation level and collector elevation angle. As insolation decreases and flow is restricted to maintain temperature, the net rate of energy output from the receiver decreases rapidly since thermal loss rates remain constant. This reduces both first and second law efficiencies. The effect of decreasing the collector elevation angle is similar to small angles (low sun angles) resulting in greater heat loss.

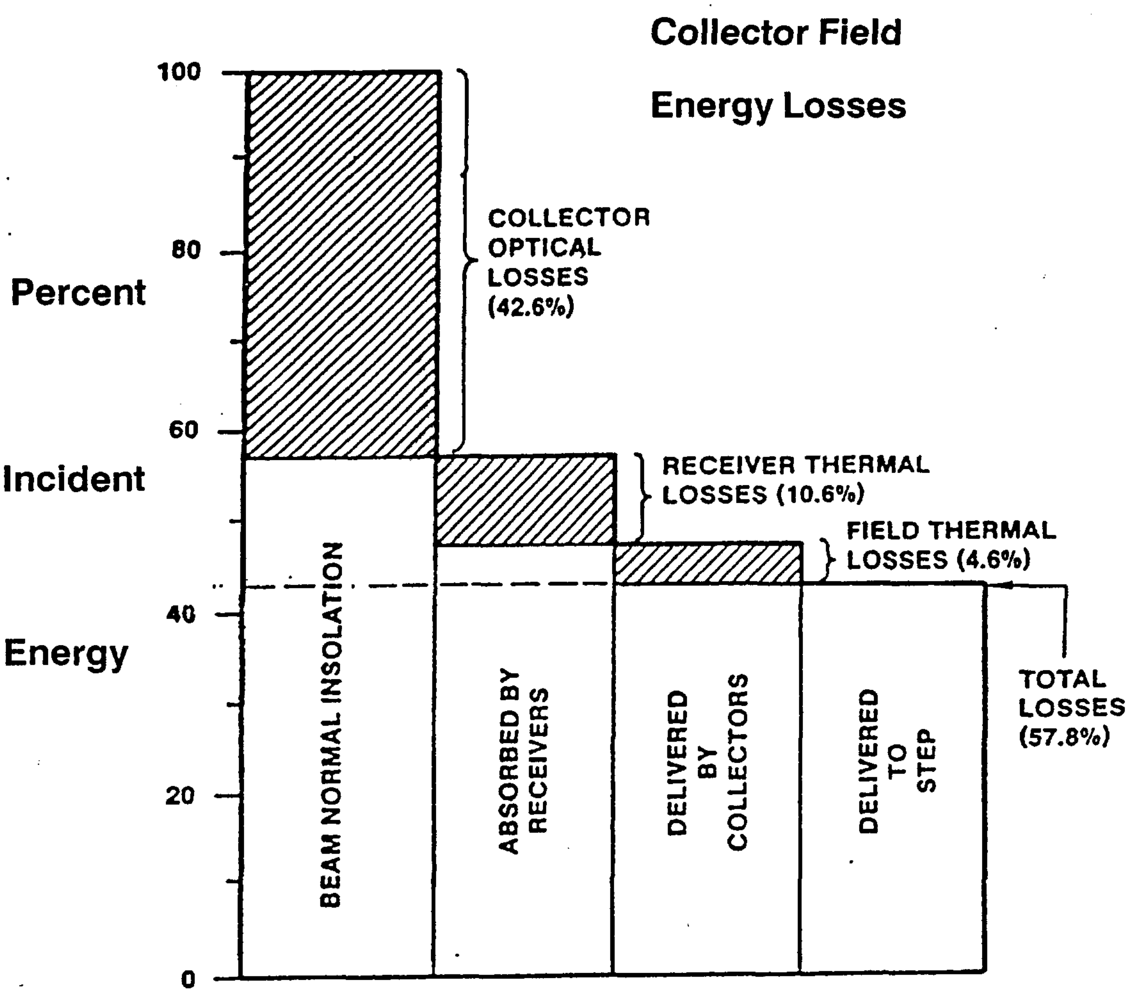

Figure 3-7: Break-down of energy losses experienced in a typical operation

Summary of the Collector Field Heat Loss: The STEP heat loss studies have shown that the warmup energy of the collector field represents 17 percent of the total energy collected on a typical day. This is a result of the excellent design effort to reduce the thermal mass of the STEP collector field. However, future designs should incorporate further efforts to reduce this loss.

The steady-state heat losses from the receiver and field piping represent 10.6 percent and 4.6 percent of clear-day insolation, respectively, with conduction losses from the receiver cavity being the largest component.

A second law efficiency study shows that large changes in the collector field's operating temperature have little effect on electrical power output. At low insolation conditions or low sun angles, power production could be improved by reducing field operating temperature. This also suggests that seasonal operating strategies could be devised to optimize the second law efficiency and thereby the power production capability of any solar thermal power producing system.

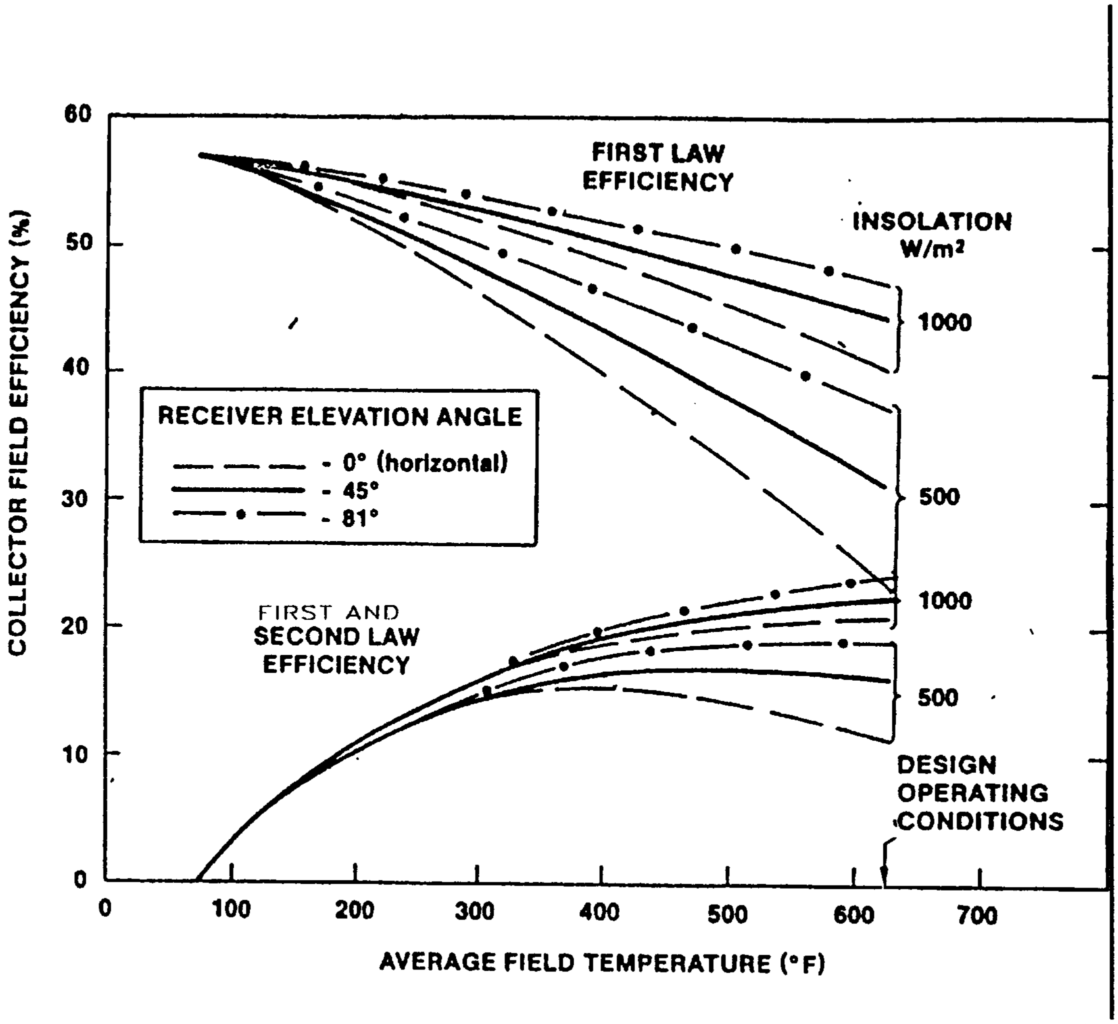

Figure 3-8: First and second law efficiencies of the STEP solar collector field for two levels of insolation and three receiver elevation angles.

STEP Performance Availability

Overview: STEP is a "total" energy thermal conversion system, with a mix of energy conversion cycles and end uses. The second law of thermodynamics provides an appropriate criterion for optimizing the energy end use mix and identifying prime components that require performance improvement. Availability, a measure based on the second law of thermodynamics, quantifies the potential of a thermal source to produce mechanical work in each of the end uses. For example, a loss of availability can be directly correlated with the loss of electrical power production.

Also, since collection of solar energy improves at lower temperatures and component heat loss is a significant term in the overall energy balance, second law considerations are important for defining the collector operating temperature that optimizes power production (Stine and Heckes 1986).

Experience: In second law analysis, a property called "availability" (also called "available energy" or "exergy") replaces energy as the object of the analysis. The availability at a particular temperature and pressure defines the maximum amount of mechanical work (and therefore electrical power) that can theoretically be extracted from the fluid, if it is permitted to cool and expand (in ideal engines) to the "dead state". The dead state is the ambient condition, where no more work can be extracted from the fluid (without external work input). The dead state is generally defined as 14.7 psia and 77° F. Unlike energy, availability can be destroyed in imperfect or real processes.

The availability of an ordinary fluid is a simple function of the enthalpy and entropy. Consequently, the availability at important points of interest in the steam and HTF streams in the STEP cycle can be determined from measurements of the pressure and temperature. The maximum availability of solar energy has been a point of discussion in the solar literature. Although the functional representatives differ significantly, the numerical values do not. All agree on a high value of solar energy availability. For this study, an availability of 95 percent is used based on the Carnot efficiency for a cycle operating between the sun's surface temperature and earth's ambient temperature (Jeter 1981). The availability of natural gas is also high. A value of 89 percent of the higher heating value of natural gas is used.

A representative steady-state case follows in which STEP is operating with both solar and fossil-fuel energy input, and is producing electricity, process steam and chilled water. The availability values are calculated from data taken from a test done on September 10, 1984.

For this case, the solar collector field heats the transfer fluid to 640° F and the fossil fuel heater continues heating the fluid to 750° F. Steam for the power conversion cycle is generated at 698° F and 690 psia.

Representative availability flows for the hybrid-total energy case are shown in Figure 3-9.

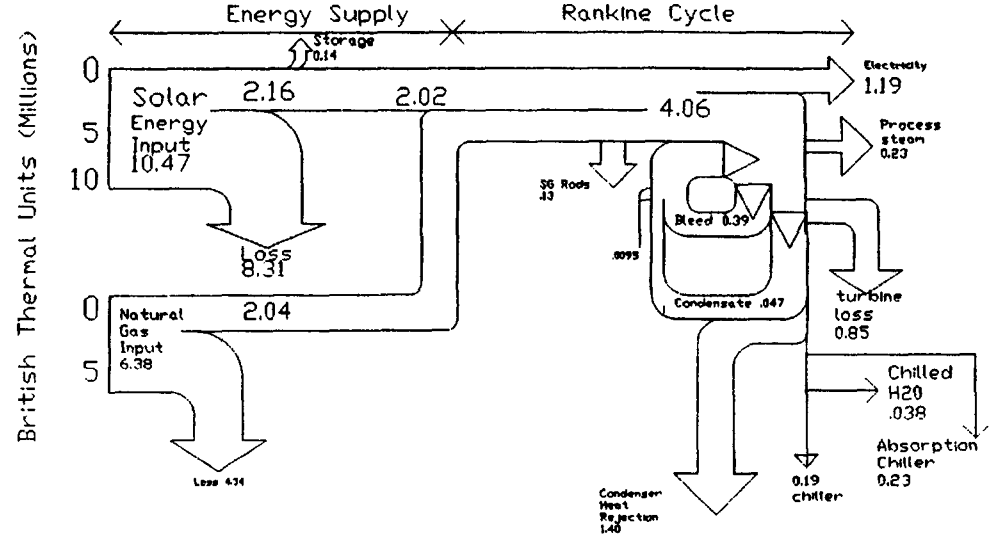

Figure 3-9: Availability balance for hybird/cogeneration operation

The solar field supplies 53 percent of the thermal energy to the power cycle, and the cycle produces 330 kWe of electricity, 620 lb/h of 133 psia process steam and 56 tons of chilled water. The availability input and output values are summarized in Table 3-4.

TABLE 3-6
AVAILABILITY BALANCE FOR MAXIMUM STEADY-STATE OPERATION PRODUCING ELECTRICITY, PROCESS STEAM AND CHILLED WATER

Inputs	
Solar Energy	**3067 kWt**
Natural Gas	**1869 kWt**
Outputs	
Electricity	**330 kWe**
Process Steam	**67 kWt**
Chilled Water	**12 kWt**

Most of the availability is lost in the collection process (Stine and Heckes 1986) due in part to the energy losses in the collector field (58 percent of the incident solar energy in this case). Availability is also lost because STEP was collecting solar energy at a maximum temperature of 640° F. If the beam radiation were collected by an ideal converter, 95 percent of its energy could be converted to work. No consensus exists on the description of such a device; possibly it must be an array of narrow band photochemical absorbers or solar cells (Jeter 1981). Thermal collectors and converters would yield lower availability until, at ambient temperature, collected energy would have zero availability.

Considerable availability is also lost by the fossil-fuel heater. This is due to energy losses and degradation of the high availability natural gas, because of the operating temperature being considerably below the adiabatic flame temperature (2,500° K). The energy loss could be minimized by using the hot flue gases to preheat incoming combustion air or preheat the feedwater. These practices, common in industrial and utility applications, would not have been economically prudent in this small-scale prototype system.

Availability economy is harder to accomplish but could be improved by increasing the temperature at which the heat is delivered. A gas-fired superheater would thus be preferred to the gas-fired oil heater, but such a unit would not have provided the experimental flexibility of the current design.

Within the power conversion cycle, the major loss of availability is at the condenser. The design of a cogeneration system supplying heat to an absorption chiller requires that steam expansion through the turbine must be stopped while the steam still has high availability. To operate the absorption chiller, the exhaust steam must be at 250° F. The amount of availability in this steam is defined by its temperature and flow rate (determined by the power being generated).

The availability loss at the condenser is greater than the electrical power produced, showing that an ideal power cycle could be added at the condenser and produce more power than the existing turbine does. The reason for this large loss is that the turbine exhaust is maintained at 250° F by the steam condenser. This is the temperature needed by the absorption air conditioner. At this temperature there is still a large amount of available energy in this steam; however, the absorption chiller uses only a small percentage of this steam and the remainder is ducted to the steam condenser where its heat is rejected to the atmosphere.

To reduce this loss, several alternatives are available: increase the demand for chilled water and supply most of the exhaust steam to the absorption chiller, operate the condenser at a low temperature (close to ambient) and use extraction steam to power the absorption chiller; or finally, one could just omit the absorption chiller and fully expand the steam to a low condenser pressure and use the additional electricity to drive a less expensive vapor compression chiller, which has about the same availability performance. Any of these alternatives reduce the wasted available energy at the steam condenser. The second law efficiencies for this example are summarized in Table 3-7 below:

TABLE 3-7
SECOND LAW (AVAILABILITY) EFFICIENCIES

Collector Field	**21 percent**
Fossil-Fuel Heater	**34 percent**
Power Cycle	**39 percent**
Thermal-to-Electric	**28 percent**
Thermal-to-Total Energy	**39 percent**
Absorption Chiller	**17 percent**

Total energy second law efficiency here is the sum of electrical availability, the thermal availability in the process steam and the steam supplied to the absorption chiller, divided by the thermal availability input. Since it is difficult to separate the system's parasitic electric usage from the electrical load transferred from Bleyle to STEP, the output used in these efficiencies is the gross, not the net electrical output.

Summary of the Availability Performance: The major sites of lost potential for producing electrical power in the STEP cycle are the solar collector field and the fossil-fuel fired heater. Some of these losses are difficult to reduce, but availability balances show their importance. The extent of the available energy loss at the power cycle condenser shows the importance of matching the size of the power cycle to the size of the absorption chiller unit, or operating the power cycle condenser at a lower temperature and using extraction steam to provide heat to the absorption chiller or omitting the absorption chiller in favor of full expansion and electric drive for cooling. Also the absorption chiller itself has a very low effective availability. Advanced chiller designs would enhance performance.

Summary Relative to System Thermodynamic Performance

The most critical influence on the thermodynamic performance of the system is the collector field's efficiency. The optical losses in the collector are most important on both an energetic and availability basis. Since heat losses are nearly fixed by the field operating temperature, a 20 percent increase in the optical efficiency (from approximately 60 percent to 92 percent) would increase the thermal energy from the collector field by 35 percent. As a consequence, the total energy provided would increase a similar fraction. It is not fully understood whether the higher optical losses are due primarily to poor surface reflectivity, excessive form error in the panels, inadequate receiver positioning and aperture sizing, or poor absorptance in the receiver. STEP represents a unique opportunity to assess these features in the field and develop corrective measures.

Thermal losses in the field have not proved to be excessive as a result of the innovative design and optimized use of insulation. Thermal shorts could be reduced if a simplified hydraulic system, with fewer control valves, could be developed. Reliable methods are needed to design and operate complex hydraulic circuits such as this that yield economical and stable systems. Uniform flow would allow higher operating temperatures and potentially greater availability production.

Another area of emphasis is in the design of the conversion plant. The current system was designed in strict accordance with the total energy concept. Both the extraction steam and exhaust steam are at elevated temperatures (250° F) and pressure, although an industrial demand exists only for the extraction steam. Only part of the exhaust steam can be used by the absorption chiller. The balance, representing an availability equal to the electrical output, is wasted in the condenser.

Future plants should be designed with due consideration of the utility of lower pressure steam. In many applications full expansion, using a condensing turbine rather than a back-pressure turbine, as the low pressure stage would be preferable. If economical, absorption cooling (preferably with a more efficient multiple effect unit or other advanced cycle) could be driven by extraction steam.

The current system is handicapped by the size mismatch between the collector field and the conversion plant. This is the unavoidable result of constructing a 114 collector array rather than the envisioned 192-collector array. This mismatch results in continual part load operation and poor performance. The small size of the collector field system also results in reduced performances in all the fluid components and machines (turbines, pumps, fans, etc.). While it was not unreasonable to construct the smallest technically feasible plant, a careful survey should be made to assess the potential for performance enhancements in a multi-megawatt plant. The result would be greater gross outputs and smaller parasitics and losses for improved total energy production.

Another inefficiency could be eliminated in a commercialized design by placing the fluid heater in the steam loop rather than the oil loop where it was required for experimental operations. So placed, the heater could serve as a superheater for peaking with solar preheat and boiling, and thereby greatly improve the utilization of the availability of its fuel. Such a design is at present under evaluation at STEP by the SNLA/GPC cooperative design and test team.

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3.6 ELECTRIC POWER PARASITICS AND OPERATIONAL MANPOWER

Electrical power requirements to run STEP auxiliary equipment such as feed pump, fans, and collector field pumps are called parasitics power (sometimes referred to by utilities as station service power). For STEP, the parasitics are viewed by many as being excessive. However, as with manpower, the use of electricity to run an experimental plant is not particularly relevant. It is anticipated that a commercial design can optimize the production of energy (not experimental information) and minimize the electrical usage and manpower to produce it. Also, STEP was scaled down from the original idea, and manpower increased the disparity between production energy and utilization of parasitic electrical energy.

Even the original larger design would not make parasitics an issue. For the concept of STEP to be most appropriate for industrial applications, it should be scaled up by a factor of 10 or more. At that level the parasitic electrical energy will consume a small fraction of the generated power. At full design performance the percentage of parasitics as installed is approximately 10 percent. With new energy conservation techniques and a reasonable commercial size plant, it is believed that a STEP design can operate at parasitic energy consumption percentage equal to conventional power plants. These values are approximately 1 percent for gas turbines, 4 percent for coal generation, and 5 percent for nuclear systems. There is nothing special about a solar plant that would prevent a designer from accomplishing similar values. However, it is useful to assess STEP from the parasitic consumption standpoint to determine the relative magnitude of the sources and suggest the methods, areas, and components in which a reduction can be met.

Operational Parasitic Power Consumption of STEP

Many electrically driven devices must operate for STEP to provide total energy to the Bleyle plant. During the tests conducted during 1984 and 1985, significant monitoring of electric consumption was conducted. Besides the requirements of the collector field and power cycle, a portion of Bleyle's electrical load is, in principle, transferred to STEP when STEP is producing process steam and chilled water. For the testing reported here, parasitic energy consumption formed a significant portion of the gross power generated. Later changes at STEP have reduced this consumption.

Measurements during the test period resulted in the data given in Table 3-8. The upper range value shows that the connected load and the average value represent the value obtained from the diversity of the loads caused by control system cycling of pumps, fans and other loads.

Table 3-8
Summary of Electrical Parasitic Power Values for STEP

Mode	Average (kW)	Range (kW)
Shutdown	37	27-47
Electric Generation only	113	90-140
Cogeneration	161	140-190

The difference between electric-generation-only and cogeneration parasitic energy consumption is primarily due to the electricity demand by the absorption chiller system, which incorporates a forced-draft cooling tower and several large pumps. The incremental parasitic load, when providing chilled water to the Bleyle plant, is approximately 50 kW. Although this parasitic demand is high, when STEP is not operating, large air conditioner compressor units are operated in the Bleyle plant, requiring approximately 100 kW. Also, the chiller is an oversized unit for the application and is being operated at only 20 percent of its maximum capability. If the unit were operated at a much higher capacity, the parasitic power consumption would remain approximately the same.

The shutdown parasitic demand for the system, 47 kW, causes energy consumption to be very high. This is particularly true since STEP weekend operation is not required by Bleyle. Also, during days with low insolation and no STEP operation, the shutdown energy is continually consumed. The STEP staff estimates that 34 kW of the 47 kW connected load can be reduced by elimination of the uninterrupted power supply (UPS), the reduction of the air conditioning load by set-back thermostats, prudent use of security features, reduced size and managed operation of the air compressor, auxiliary oil heater, auxiliary cooling water fans and pumps, and redesigned power supply system for the collector field controls.

A further assessment of the parasitic electrical energy data is shown in Table 3-9, which gives the actual electric demand for each major system and its percentage contribution of the total requirement.

Table 3-9
STEP Subsystem Measured Electric Parasitics

Subsystem	Load (kW)	percent of Total
Solar Energy Supply	41	19 percent
Fossil-Fuel Heater	22	10 percent
Power Conversion	34	16 percent
Absorption Chiller	68	31 percent
Balance of Plant	52	24 percent

The largest contributor to the parasitic demand is the absorption chiller. If additional thermal energy were available to the power cycle from a larger or improved collector field, or from additional fossil-fuel heating or superheating, the net output of the plant would increase. This would make the STEP/Bleyle combination a net power producer with the excess going into the grid. To do this, a generation level of over 300 kW must be sustained to meet the nominal 100 kW Bleyle demand plus the STEP parasitic demand. Recent solar and hybrid testing with a steam superheater and modified collector field controls routinely satisfies all parasitic and Bleyle power requirements and produces net power to the Georgia Power Company grid.

Several operating equipment design changes can be made using current technology (not readily available during the 1978 to 1980 design period) to reduce the 161 kW cogeneration power consumption. Speed control of various fan and pump motors would decrease the parasitic loads. That the large absorption chiller design load never came to fruition would allow a large reduction in the water pumps and cooling tower fan electrical consumption. The cooling tower fan load can be reduced since actual cooling loads are now known. The condenser fan motors also can be reduced.

A review of the connected load data shows that a large fraction of the loads is due to inductive motors. Reduction of power requirements for these motors is easily achieved by variable speed, solid-state motor controllers. This solution has been applied for the boiler feed pump motor. The results show a reduction of 33 percent power, a factor of 10 reduction in kVAr, with a payback period of 6 months. With extension of this technique to other motor loads, as shown in Table 3-10, it is anticipated that the STEP parasitic consumption of electric power for motors can be reduced by 25 percent.

TABLE 3-10
Motor Load Reduction Potential

MOTOR LOAD	MOTOR HP
Collector Field HTF Pump	**30 HP**
Steam Generator HTF Pump	**15 HP**
STEP AC Fan # 1	**25 HP**
STEP AC Fan # 2	**15 HP**
Steam Condenser Fan	**10 HP**
Air Compressor	**30 HP**
Chiller Cooling Tower Fan	**25 HP**
Chiller Water Pump	**40 HP**

Redesign of parallel and redundant HTF pumps, elimination of valves, excessive pipe lengths, and other system pressure drops can further reduce pumping power requirements. For example, a bypass valve (FV7111), around steam generator supply pump, has been installed and will reduce the power requirements necessary to operate the STEP system. In many systems, cooling water fans and the turbine buffer seal, vacuum pump sizes can be reduced by as much as 50 percent. Other ideas such as locating air conditioning sensitive equipment near the absorption chiller, installation of steam-driven feed pumps, and a focussed maintenance program on air leaks -- have provided major reductions in parasitic electric consumption.

Operational Manpower

Excessive operational manpower, a problem at STEP, was partially due to the experimental nature of the project. But the major excesses were caused by equipment failures, with particular impact caused by collector control system failures and the HTF performance anomalies. As these two areas are in the final stages of resolution, it appears that a commercial operational design can be achieved with a small level of maintenance and operating manpower. However, it is difficult to conceive that a central station solar cogeneration steam plant could be operated by supervisory control or remote control.

The difficulty arises from the steam portion of the system, not from the solar collector field. The recent changes in the collector field controls show that a manless operation, with occasional maintenance, can be achieved. This is an important issue since the demands for the point-focus control requirement seems to exceed those of operating and other solar energy electric power generation concepts such as line-focus systems and flat-plate two-axis photovoltaic systems. This has been one of the most important learning experiences provided by STEP.

Summary

Parasitic electric consumption at STEP and at other large solar facilities has been the subject of criticism and debate. Conventional energy conserving techniques can easily be incorporated into future designs to make large net energy outputs easy to attain. The experimental nature of STEP and other innovative solar power systems justifies an apparent excess parasitic energy consumption to maximize the collection of critical first-of-a-kind test data. Even a nominal scale-up of STEP to a reasonable commercial size when combined with known energy conserving techniques will reduce parasitics to levels experienced on conventional energy power plants.

For manpower utilization at STEP, similar arguments apply. However, the main excess manpower issue applies to the operation and maintenance requirements associated with several particular sub-systems and anomalies. These experiences are discussed elsewhere in detail.

3.7 COINCIDENCE OF SOLAR ENERGY SOURCE/APPLICATION DEMAND

The time-dependent correlation between the availability of energy sources from STEP and the utilization of the demand energy by Bleyle has presented difficult operational issues. These issues have not diminished the accomplishment of the DOE objectives, nor have they hindered the production of knitwear at the Bleyle plant. However, the efficiencies encountered for utilization of the solar resource and the requirement for excessive manpower suggest that the design and marketing of solar total energy systems for industrial application make schedules a key consideration. The design process should identify firm criteria for the time relationship of solar availability and application demand.

The specific issues relating to the time dependency range from the time necessary to heat up the large STEP system, through the hourly, daily, weekend and seasonal variation of the solar source. These areas are discussed only in regard to Bleyle plant production schedule, which is predicated on their requirements, and are independent of the energy source issue. A final area relates to the capacity/demand curve for electricity on the Southern System, which influences the operational scenario for a cogeneration or a parallel-generator-type energy system.

Several solutions to this issue are available. Some are reasonable from cost, design and operational standpoints; none was applicable to STEP but could have been added. These solutions are thermal storage, fossil-fuel hybrid operation, a 24-hour per day application; and an application that has natural storage, such as pumped hydro, or an application that is independent of a specific daily or weekly time, such as irrigation.

The most important issues concerning the time coincidence between solar energy supply and application demand as perceived from STEP operations are discussed in the following sections.

STEP System Thermal Delay

A test conducted on the STEP system produced an energy value necessary to bring the collector field temperature up to 625° F from 70° F. This value represents 17 percent of the total energy collected on a typical day. The original STEP design called for 3 days of energy storage, but the system was later eliminated. The field's thermal capacity requirement for start-up delays the supply of energy to the Bleyle plant for electricity, steam and air conditioning.

Heatup of other equipment, such as the fossil-fuel heater, the steam generator and the turbine generator, when coupled with the field heatup requirements, adds to the operational complexity of STEP. This demands extra manpower over conventional plants that have either fast response times (gas turbines) or continuous operation (coal fired plants). Not only did these warmup requirements delay supply of energy to Bleyle, but they consumed a considerable amount of energy through the daily loss schedule and from the intermittent solar source.

The nightly thermal heat loss and subsequent morning warmup requirement can be reduced by additional insulation of field components, but the pay-back period may not be reasonable. Specifically, conductive, convective, and radiant losses in the receiver have been measured to be significant. Extensive and novel design efforts were applied, such as anti-siphon pipe loops, valve orientation, pipe supports and others in recognition of this design problem. It is suggested that stronger and more focused experiments and analysis should be applied to this area. The STEP personnel and others are pursuing further reduction of losses. These thermal losses, when coupled with the time-dependent anomalies discussed below, make competitive economic solar cogeneration applications difficult to achieve.

Intermittent Solar Resource

During the 5-day-per-week Bleyle work schedule, thermal lag was aggravated by a strong hourly variation in the direct insolation necessary for the concentrating collector system. Significant data exist to document that on good solar days, as measured by the total integrated insolation, a periodic decrease of insolation was caused by clouds passing over the STEP site between 10 a.m. and noon. This condition forced the shutdown of the turbine generator but allowed continued steam and air conditioning for some time.

However, the resultant loss of field temperature usually made necessary another warmup of the field and a turbine generator restart most often near the work shift completion time for Bleyle. At this time, the Bleyle demand for steam and air conditioning was reduced and the electric demand for Southern Company system electricity increased. This typical operation, aggravated by extensive use of manpower to keep the concentrators operational during the intermittent cloud conditions, resulted in inefficient thermodynamic performance. The presence of this dynamic operational mode was predicted and was partially offset by the small thermal storage tank. The loss of efficiency and excessive use of manpower to maintain collector field operation exceeded the expectation of the operational team.

Solutions to this problem can provide continuous operational output of electricity, steam, and air conditioning. Thermal storage and fossil fuel hybrid designs are two possibilities, but neither will solve the field losses owing to multiple warmup during a daily cycle. Additional insulation can reduce the conduction losses, but the convective and radiation receiver losses are more difficult to resolve. Since this daily intermittency of the direct solar resource is prevalent in many locations, it may suggest that large thermal mass systems are less desirable than fast responding photovoltaic systems or solar thermal concentrating focal-point engine-generator systems. The documentation of the solar resource and the detailed identification of the total effect of the intermittency is the subject of a large research effort being conducted for the Southern Company service area.

Daily Demand Schedule

The Bleyle daily operational schedule begins at 6:30 a.m. when the heat-up for the steam generator begins and lights and other electric auxiliaries are also started. Shortly after, the demand for air conditioning and electricity for sewing is initiated. This demand continues throughout the day with only slight interruptions for lunch and work breaks. The day is terminated at 3:30 p.m. and all loads are precipitously reduced.

There was an original plan by Bleyle for different work hours and a second shift production schedule. However, employee preference selected the existing schedule, and output considerations eliminated the need for a second shift. Plans by Bleyle to add production space were replaced with additional design, storage and marketing functions. The result kept the steam load demand at half the capacity of STEP, and the air conditioning demand at about 60 percent of the STEP design capacity.

An additional air conditioning load was added to the STEP power plant and control rooms to more closely approach the full design air conditioning availability. Plans for venting steam to the full 1340 lb/hr to test the full load design values for STEP have not been carried out.

The impact of the 6:30 a.m. to 3:30 p.m. daily shift on the utilization of the STEP solar energy source is significant. During the winter, solar energy is not available to support the early demand for steam and electricity. During the summer, the early end of the Bleyle work day eliminates the need for energy well before the solar resource diminishes.

Perhaps if the solar system was owned and operated by the industrial plant owner, the work schedule could follow energy source/demand matchup with subsequent higher utilization efficiency. Storage systems would solve both the evening and morning mismatch, and hybrid systems would resolve the start-up problem.

These anomalies did not affect the demonstration of STEP to achieve the instantaneous design values for electricity, steam and air conditioning. However, they significantly affected the magnitude of operating manpower to operate STEP and the effective utilization of the available solar resource over the long range.

Weekend Energy Utilization

Perhaps the biggest factor in the time considerations for industrial application of solar energy resource is that most industrials operate on a 5-day-per-week basis. In fact, there is a strong movement toward a 4-day-per-week schedule. The loss of solar utilization at Bleyle is 30 percent of the solar availability. For solar electric-only systems with higher electric generation efficiencies, the loss is still significant. This fact was not a result of the STEP operation, but its impact is included here for readers and designers who are not directly involved in solar energy programs. This issue is not Bleyle specific, nor Southeast, but is applicable internationally. The residential electric utility customer is perhaps the only one who could utilize the weekend insolation for electric generation and thermal utilization for house heating, water heating and air conditioning.

The original solution to the weekend anomaly for the Bleyle design was a 3-day storage system, as has been the case for many large solar system applications. However, during the design phases, the large thermal storage system was replaced by a small system that was not intended for the weekend accumulation of energy. Hybrid systems do not solve the problem of loss of weekend solar insolation; only thermal, electric and other storage techniques appear to provide a solution.

Capacity Versus Demand

The Southern Company service area has a capacity of 30,000 MW, which is more than adequate for all Saturdays, Sundays, and the winter, spring and fall seasons. However, for the summer season, a significant problem develops near the end of the work day and into the sunset period. The demand at this time for air conditioning (both sensible and latent heat requirements) pushes the electric system beyond its capacity for this area and for the entire southeastern United States. A solar system such as STEP does not help the situation, and may actually aggravate the condition by reducing energy supply precisely when it is needed. Other solar systems, including photovoltaics and thermal parabolic troughs for absorption air conditioning, are similar in performance.

Thermal storage, electrical storage, hybrids and other energy-shift systems are required if the conventional energy demands continue. This consideration is not something special that was developed from STEP, but it does suggest that when coupled with the daily intermittency problem, additional research and development must be applied to optimize solar system applications for residential, commercial, industrial and electric power plant generation.

Winter/Summer Solar Variability

The change in length of the solar day from winter to summer, with no change in energy demand schedule from Bleyle, reinforced the time-dependent problems discussed above. More STEP operating manpower is required for summer operation and the excessive solar resource is not required by Bleyle. Thermal storage would solve this issue.

The short winter day could be enhanced by a hybrid system. This issue is not a lesson that was learned, but a fact that was amplified. Solutions can be provided, but for future system designs to be competitive with conventional energy systems, they must address the time difference in seasons, match the design with industrial operating schedules, and complement the design with energy storage.

Summary

Discussions of this operational experience are presented to amplify the areas of concern that were known during the design phase. However, the complexity of operational schedules and subsequent time-dependent energy losses of a large system such as STEP were not known. Since these issues imply that energy storage may be a solution, it is recommended future research and development, such as the work being done for chemical storage use of superconducting materials or hydrogen generation, be continued.

On the broader scale of solar energy systems for industry, these time-dependent anomalies imply the need for significant design/plant schedule consideration and specific design effort for each type of industry, and perhaps each owner. The use of a generic cogeneration design for most industries is not likely. Therefore the projected data for competitive industrial cogeneration solar applications must be based upon custom design for each application.

4.0 CONCLUSIONS

The STEP operated as a solar cogeneration concept in a technically successful manner. The specific performance of STEP, as installed, was severely limited by the programmatic decision to reduce the collector field from 192 to 114 collectors; to eliminate a multi-day thermal storage; and Bleyle's business decision not to expand manufacturing capacity (and resultant energy load). This specific performance does not affect the expected solar total energy concept performance for a commercial size system.

An important lesson learned from STEP operation is that operational costs were increased and performance decreased by failures of systems software and hardware associated with the control of flow, temperature and position for the solar collector field. Anomalies with the high temperature heat transfer fluid also contributed to excessive manpower and reduced performance. A final contribution to reduced performance is a larger than expected loss of availability in the optical portion of the collector system. Some of these problems have been resolved; others are in the process of resolution.

Operational manpower utilization and electric energy parasitics, although high for STEP, are not considered a problem for a commercial size solar total energy system. Startup, environmental, mechanical, electrical problems and operator errors were aggravating and costly, and delayed acquisition of experimental data. However, they are not expected to be a factor in a second-generation system. These problems are amenable to procedural solutions.

The STEP is viewed as an absolute success as a concept demonstration and experimental facility. Although portions of the system were derated and the expected loads never developed, the overall system worked well and continues to operate. Most of the problems encountered were solved. The technical achievements and lessons learned at STEP should be considered for use by other solar technologies in the national and international communities.

The relative economic viability of the solar total energy concept when compared to solar thermal power or process heat is not and was not intended to be provided by this program. Future studies by Georgia Power Company will utilize the lessons learned in this program, along with cost and performance data from continuing activities in the national solar thermal program to assess the future value to the Southern Company. A full-scale solar total energy conceptual design will be modelled for use in EPRI's Technology Assessment Guide for comparison to other technologies.

APPENDIX A

SOLAR TOTAL ENERGY PROJECT

SYSTEM OPERATION DESCRIPTION

APPENDIX A
PROJECT AND SYSTEM OPERATION DESCRIPTION

1.0 SOLAR TOTAL ENERGY PROJECT

The Solar Total Energy Project (STEP) is in Shenandoah, Georgia, 25 miles southwest of Atlanta International Airport, at Exit 9 of Interstate 85. It 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.

The Site consists of 5.72 acres in the Shenandoah Industrial Park adjacent to and east of the Bleyle Knitwear Plant. An additional 5-acre tract has been purchased by Georgia Power, and a research program has been initiated to support further development of solar energy. Current negotiations are under way to expand the site by adding an additional 10 acres north of the present site. This area would be used for a megawatt size power generation solar facility for either photovoltaic or Dish/Stirling electric systems.

A part of the National Solar Thermal Energy Program, initially funded by the United States Department of Energy, and under the technical direction of SNLA, STEP is the world's largest industrial application of the solar total energy concept. The objective of the project is to evaluate a solar total energy system that provides electrical power, process steam, and air conditioning for a knitwear factory, operated by Bleyle of America, Inc. Solar energy generates a large part of the electricity and displaces part of the fossil fuels normally used to run the factory and produce the clothing.

2.0 SYSTEM DESCRIPTION

A solar total energy system uses collected solar energy to supply high-grade electrical and mechanical energy and low-grade thermal energy for selected applications. STEP supplies electric power to a utility grid, and process steam and air conditioning to a knitwear manufacturing facility. Excess power from STEP is supplied to the Georgia Power Company electricity distribution network.

STEP is a fully cascaded total energy system with parabolic dish solar collectors and steam Rankine cycle power conversion system capable of supplying 100-400 kWe output with process steam extraction. The design includes the solar collection subsystem, the power conversion subsystem, the thermal utilization subsystem, and the control and instrumentation subsystem, which are monitored to provide the data necessary to evaluate STEP.

Operation: Operation of the system begins with circulation of a heat transfer fluid through the receiver tubes of the parabolic dish solar collectors. Solar radiation is focused in the receivers by the collector reflector and heats the silicone heat transfer fluid (HTF) to 750° F. The heat transfer fluid is then pumped to a heat exchanger. In the heat exchanger, the heat transfer fluid boils water and superheats the steam; the heat transfer fluid then returns to the collectors and the cycle is repeated. The superheated steam drives a turbine that in turn drives an alternator. Steam at 350° F is extracted from the turbine for knitwear pressing. The low-pressure steam exhausted from the turbine is used to produce chilled water for air conditioning, or is cooled as it passes through an air-cooled condenser. The STEP simplified flow diagram as it exists today is shown in Figure A-1. The recently added HTF expansion tank and the fossil-fuel steam superheater are shown on the figure.

Solar Collection Subsystem: The Solar Collection Subsystem (SCS) consists of an array of 114 parabolic dish collectors, each 23 ft in diameter. The heat transfer fluid flowing through the collectors, whose receivers are connected in parallel, is heated from the inlet temperature at 500° F to 750° F. The receiver is a cavity type capable of receiving an incident concentrated solar flux equal to 235 suns. The concentrated solar flux impinges upon the receiver coil's absorptive surfaces enclosed within the insulated cylindrical shell.

Each parabolic dish, assembled in the field, is made of die-stamped aluminum petals laminated with a second surface - aluminized acrylic reflective film - before forming. Each collector tracks the sun in polar and declination axes from morning to evening, and from season to season. The parabolic dish collectors are arrayed on the STEP collector field in a repeating diamond pattern.

The field piping network consists of welded pipes in the main manifolds, and steel tubing in the branches, all covered with a high-temperature insulation. The SCS provides 1 hour of thermal storage at 750° F as a buffer against transient solar conditions. Energy is stored in the silicone heat transfer fluid in a thermocline tank. A natural-gas-fired heater capable of supplying some power conversion subsystem energy input requirements is used during start up and to supplement the solar energy system as necessary. The current design modifications have removed the thermal storage tank from the system since its operating design pressure is 10 psig. Requirements for HTF operating pressure exceed this value. A column-type pressurizer tank has been added to the HTF system to provide the fluid expansion capability and the pressure requirement.

Power Conversion Subsystem: The power conversion subsystem (PCS) consists of a heat exchanger with preheater, boiler and superheater, a steam turbine-alternator rated at 500 KVA, an air-cooled condenser and condensate storage tank, make-up demineralizer, deaerator, and necessary pumps. In normal operation, steam at 720° F. and 700 psig is generated in the boiler-superheater and delivered to the turbine inlet. To enhance the performance of the STEP system a 2 million BTU/hr natural-gas-fired superheater has been added to the steam system at the outlet of the originally supplied steam generator.

The turbine alternator consists of a four-stage, high-speed (42,450 rpm) turbine, a gearbox that reduces the speed to 1800 rpm, and a 60 Hz alternator. The low pressure side of the high pressure turbine stages has an extraction port for process steam and steam for regenerative feed water provides steam to the thermal utilization subsystem (TUS).

Thermal Utilization Subsystem: The thermal utilization subsystem serves as the condensing medium for the steam and the heat source for the cooling of the Bleyle Plant. The exhaust heat from the steam turbine provides the heat input to the thermal utilization subsystem. When the turbine is out of service, steam is provided directly to the thermal utilization subsystem.

The steam from the turbine or the turbine by-pass is routed to the absorption air conditioner. The chilled water produced by the absorption air conditioner cools the cooling water supply to the Bleyle Plant and the STEP balance-of-plant steam generator room. Any excess steam is circulated through the air-cooled condenser. The condensed water from the condenser and the absorption air conditioner is then placed in the hot well and the condensate storage tank.

Control and Instrumentation Subsystem: The STEP control system, supplied as part of the original design, provides a full range of operations -- from operator control to extensive data collection for analysis of experimental operations. The control system partitions control functions between a minicomputer and its peripheral equipment and micro-processors distributed through the system. These micro-processors exercise some control functions locally.

The collector control units (CCU) located at each collector and the control and instrumentation subsystem (CAIS) are connected by redundant serial links. This allows communication among the distributed control system components by a single pair of leads. Other sensors, including the weather instruments, interact with the central control computer through the energy utilization processor (EUP).

The CAIS provides the following:

- Control of Subsystems and Components for Normal and Fail-Safe Operation
- Control Logic for Selected Operational Modes
- Collection, Monitoring of Data, and Processing of Information

In addition, operator control is provided for experimental modes to characterize system and component performance over ranges of operational parameters and to identify operating strategies for more effective electric and thermal energy displacement. The switch to the experimental modes allows the operator to initiate solar collection experiments, and to monitor and record data. Diagnostic routines may be initiated if a mulfunction occurs.

The CCUs perform the following functions:

- Receive system control information from the CAIS and provide signals to collector field control equipment, such as drive motors and valves.
- Interpret local data to identify potential hazards and initiate control actions to avoid or minimize damage to the collector.
- Maintain proper sun tracking automatically once adequate focus by central computer has been established.
- Relay data from local instruments to the CAIS for further processing or storage.

The original collector field controls have been dramatically changed to reduce maintenance, reduce operator time, and provide more accurate and reliable performance (Section 3.3). The steam plant controls are at present under redesign and modification.

System Loads: STEP loads include electric loads and process steam and cooling for the knitwear manufacturing facility. The Bleyle demand loads and the STEP design capacity values are summarized in Table A-1. Except for lunch and shift breaks, the knitwear manufacturing facility's electrical load profile is constant over a one-shift operation. Process steam at saturated conditions is required during all working hours.

TABLE A-1
STEP LOAD/CAPACITY VALUES

Energy	Bleyle Load	STEP Capacity
Electrical	161kW	400 kW
Cooling	113 tons	257 tons
Process Steam	700 lbs/hr	1380 lbs/hr

The cooling loads consist primarily of internal heat generated by the process steam, machinery, people, and building lighting and are usually constant during plant operating hours. The plant's heating, ventilating, and air conditioning (HVAC) system incorporates an economizer cycle that supplies a portion of the cooling load during the winter months. The cooling loads are met by a chilled water system supplied by an absorption chiller.

Collector Field: Portions of the collector field are surfaced with blacktop for access. The main collector supply and return lines are constructed of ASTM-A106 Schedule 40 welded pipe and run in an east-west direction. The branch lines to the individual collectors, constructed of ASTM A-192 seamless steel tubing (welded), run in a north-south direction.

The mechanical building is in the Southwest corner of the site. The building contains the control room, motor control center, absorption air conditioning unit, and turbine alternator. North of the building is the heat transfer fluid storage and conditioning equipment, including the large thermal energy storage tank, the fossil-fuel heater for the fluid, the steam generator (unfired boiler), and the collector field circulating and boiler pumps. The hardware is on a concrete pad with provisions for containing spills, and the drain system contains a separator for reclaiming the fluid. Also contained in this area is the unfired boiler's ancillary equipment. All the equipment is insulated and sealed for outdoor application.

Besides the original equipment, a pressurizer and column for the HTF, a superheater for the steam system, and a major maintenance building has been added to STEP facilities. A small hazardous fluid storage building also supports the operation. A specially designed cogeneration or parallel generator type substation provides all power to STEP and Bleyle.

Meteorology Station: In the design of advanced solar energy systems such as the Solar Total Energy System in Shenandoah, it is important that a comprehensive and accurate solar data base be available. This is important since many of the design decisions are based on estimates of system performance in specific modes of operation under representative "normal" and "extreme" conditions. In addition, concentrating solar collectors such as those in STEP can effectively collect only the direct component of solar radiation, which to date has been measured at only a few research sites across the United States. A major current program has been initiated to document the insolation of the entire Southern Company service area.

The original weather station for STEP, installed at ground level, consisted of eight solar radiation and surface weather instruments, appropriate mounting or support structures, and a compact, portable, cassette tape data logger. Although this logging equipment has produced a significant amount of excellent weather data over the 10-year program, it is being replaced with new state-of-the-art hardware and software, and is a prototype for the Southern Company service area weather monitoring network. The original station included:

Instrument	**Variable**
1. Pyranometer	**(horizontal)Global radiation**
2. Pyrheliometer	**Direct normal radiation**
3. Pyrheliometer	**Direct normal radiation**
4. Resistance thermometer	**Dry bulb temperature**
5. Humidity cell	**Relative humidity**
6. Cup anemometer	**Wind speed**
7. Wind vane	**Wind direction**
8. Pressure transducer	**Barometric pressure**

New equipment added to the meteorology station as part of the Southeastern Regional Solar Meteorological Research and Training Project at Georgia Institute of Technology, and under subcontract to GPC, includes:

Instrument	**Variable**
1. Pyranometer (unshaded)	**Global radiation**
2. Pyranometer (shaded)	**Diffuse radiation**
3. Pyranometer (tilted 34°)	**Global radiation on latitude plane**
4. Pyranometer	**Net radiation**
5. Rain gauge	**Rainfall**
6. UV pyranometer	**Ultraviolet radiation**
7. Nephelometer	**Turbidity**

SOLAR TOTAL ENERGY PROJECT
SIMPLIFIED FLOW DIAGRAM

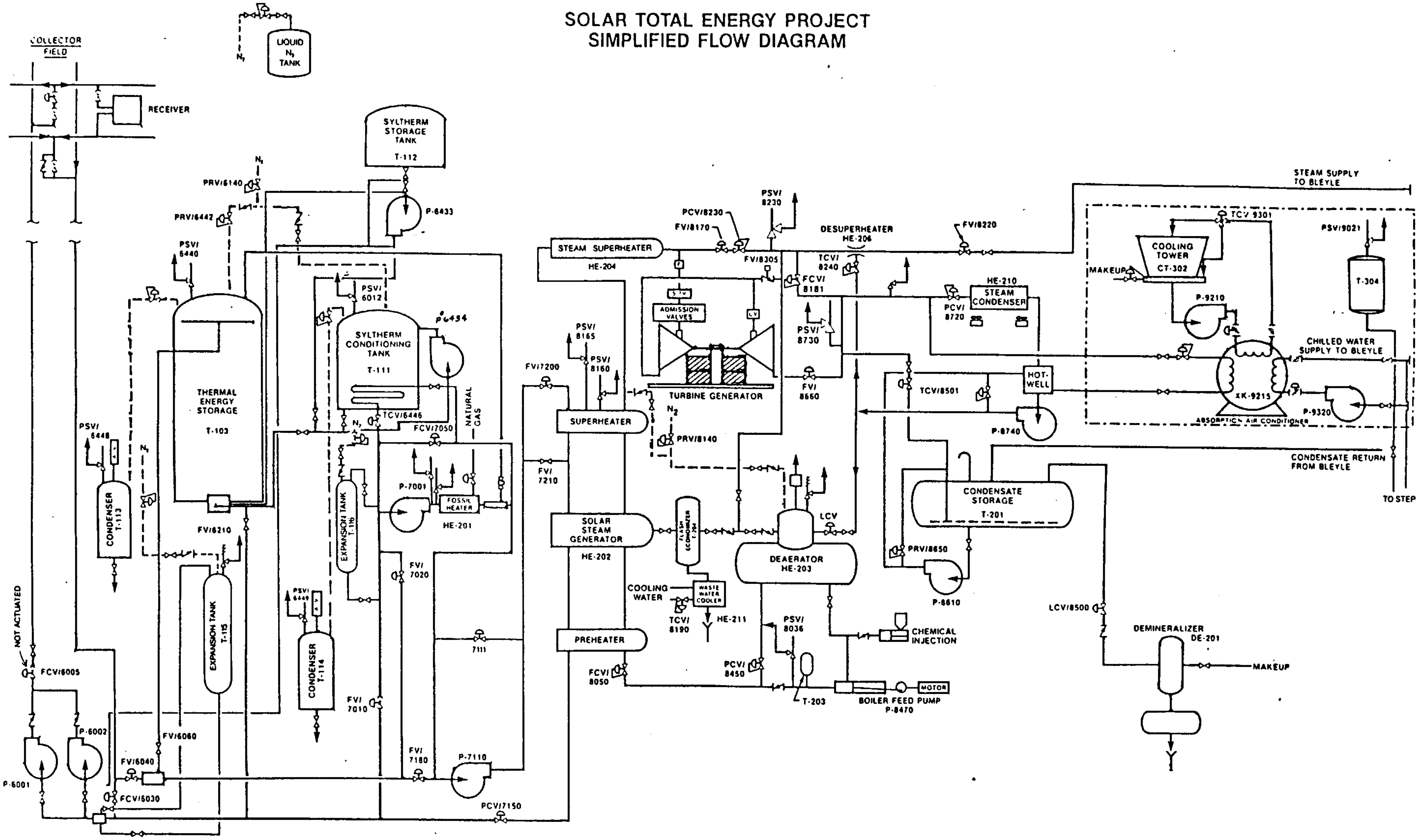

FIGURE A-1

APPENDIX B

SOLAR TOTAL ENERGY PROJECT

SUMMARY OF CHRONOLOGICAL PERFORMANCE

APPENDIX B
SUMMARY OF CHRONOLOGICAL PERFORMANCE

Summary of Performance

Construction of the solar project was completed early in 1982. During that year, startup operations were conducted by a joint operational team of Sandia National Laboratories and Georgia Power Company. Various unexpected electrical and mechanical problems provided significant information for subsequent system design applications. Most problems have now been resolved, and the program has moved through several experimental operations test phases. Several remaining areas are being evaluated and will be reported when complete. Following is a summary of major events since 1982.

Major Events for 1982

January 1982: STEP Steam System Integrity Tests were completed on January 21, with the first synchronization and generation of electricity to the 100-kW level. Manual control of the balance of plant (BOP) was also achieved during the month.

February 1982: Extracted steam was supplied from the turbine to the Bleyle Plant for dryout of thermal insulation that had been dampened during construction activities. This operation was carried out under manual control of the BOP.

March 1982: The major activity was a two-day inspection of STEP by a formal readiness review committee. No major problems were identified by the committee, but some recommendations were provided. The original motors and potentiometers for each solar collector were removed and waterproofed because of their failure rate in a high-rainfall area. By the end of March, construction was almost completed at the site.

April 1982: The Project's operational status was reviewed by the Department of Energy, Sandia, and Georgia Power. The group gave provisional acceptance based on resolution of specific problems. The major anomaly was operation of the control and instrumentation subsystem (CAIS), with the collector field subsystem (CFS), and the balance-of-plant (BOP). This computer-related problem was addressed late in the year, when a major design change was made.

May 1982: A major milestone was achieved on May 10, when the site dedication was held. More than 500 people attended the formal ceremonies, with Georgia Power Chief Executive Office Robert W. Scherer, DOE's Dr. Robert San Martin, Congressman Newt Gingrich, Sandia's Don Schueler, and Atlanta Major Andrew Young as participants.

On May 12th, the turbine-generator was synchronized to a load of 200 kW and solar-generated electricity was produced for the first time. After many problems over a 5-month period with the condensate pump, the manufacturer inspected the unit onsite and found it to be running backward owing to a directional flow arrow on the casing that had not been clarified. The pump was then made fully operational.

June 1982: The air conditioning capability for the project was demonstrated. After the integrity of the chilled water system to the Bleyle Plant was verified, the absorption chiller was started. Several days of successful operation of this air conditioning system led to a major milestone on June 15th: cogeneration with approximately 250 kW (electric) and 50 tons of air conditioning (thermal).

A leaky accumulator was removed from the boiler feedwater pump discharge. Inspection proved that the Vitron bladder would not accommodate a working temperature of 330° F. To correct this problem, an accumulator of a piston design with Vitron O-rings was purchased, but this problem resulted in 17 days of downtime.

July 1982: The reflective film on 15 solar collectors was damaged when stray concentrated light from adjacent collectors was focused on the backs of the damaged collectors. Repair of the film was completed within the month.

August 1982: Process steam was provided to the Bleyle Plant for processing needs for the first time. Process steam (5600 pounds) and air conditioning (600 ton-hours) were provided by semi-manual operation of the solar collectors. On August 20th, by pumping heat transfer fluid considerably cooler than the steam generator temperature, the steam generator was thermally shocked, causing leaks at the tube-tubesheet interface. However, this problem was not completely identified and corrected until December.

September 1982: A new type of seal was used to replace the tungsten carbide shaft seal on the steam generator HTF pump. This original type of seal had failed seven times since the pump had been installed. The new silicon carbide seal operated without problems.

Also during September, it was determined that the central processing unit (CPU) memory of the 128K-word computer was inadequate to handle multiple subsystems by CAIS. A 256K-word unit was installed to replace the 128K-word unit to handle the operation of all the subsystems efficiently. On September, 1982 for 7.5 hours, 10 x 10(6) Btu of solar steam was produced through computer control of the collector field by the CAIS.

October 1982: During October, the balance-of-plant (BOP) was operated for a significant time in the thermal energy mode. On the 15th, a typically good solar autumn day in Georgia, the solar collectors auto-tracked for 9 hours and 23 minutes, providing more than 38 x 10(6) Btu of energy. Approximately 72 percent of the energy delivered to the Bleyle Plant that day was solar derived. A total of 61040 lb of process steam and 4048 ton-hours of air conditioning were supplied to the knitwear plant for the month.

November 1982: The new PDP-11/44 computer was received in November. The STEP staff, with help from General Electric and Auburn University, preceded with the changeover by debugging efforts, check-out of the operation programs, and the creation of data analysis programs. Besides the computer work, repair of the steam generator was initiated. The problem became apparent when water was discovered in the heat transfer fluid.

December 1982: The steam generator leak was repaired, and a redesign of the nitrogen supply system, using a 315 gallon bulk liquid tank, resulted in an operating cost savings of $10,000 per year. A larger capacity air compressor was selected due to the inadequacy of the original, which became a spare. Computer control of the plant, using the new computer, was achieved in late December.

Major Events for 1983

February 1983: The electric generator was operated at full power (400 kW) and produced significant output. For instance, on February 17, 2797 kWh was generated in 9 hours at levels from 250 to 400 kW. The collector field provided more than half the energy at peak output.

March 1983: On March 8, a steady-state operation was achieved for 1 hour. During that time, a solar collector field efficiency of 52.6 percent was measured. The field thermal operating losses are calculated to be 9.3 percent of the energy at the solar collector receivers, which is considerably better than was calculated for the original design.

April 1983: A Solar Energy Training (SET) program was developed for Company and non-Company personnel. The 6-month course includes study of solar sciences; a cogeneration plant; electrical, mechanical, and chemical aspects in an industrial environment; computer science; and economics. Each year, beginning in 1984, California Polytechnic State University has provided two mechanical engineering students who receive one quarter undergraduate credit by successfully completing the curriculum. There are 4 areas of effort: classroom work, field trips, hands-on training, and a special technical thesis.

May 1983: A master plan for a Shenandoah Solar Center was developed addressing visitor accommodation, training, and testing. Additional property was purchased and a layout was designed, including a permanent building. Tours were available for school, civic, professional, and technical groups. Training was carried out on several levels. Research testing was being conducted to ensure practicable solar options and to address the questions and needs of the public.

June 1983: During the summer, the last Sandia representative left the site following strong on-site support by Sandia during construction and startup testing. The management and operation of STEP was transferred to Georgia Power Company at that time.

November 1983: A major activity in 1983 was the continuation of the check-out of the control and data acquisition system. There was great difficulty in controlling the collector field under cloudy and transient cloudy conditions. Many anomalies had to be addressed, corrected, and documented. Three people were secured to support the daily maintenance operation and provide extensive hardware and software computer expertise.

Major Events of 1984

March 1984: The continued commitment by the Southern System was enhanced by a visit from Mr. Ed Addison, president of GPC's parent company (The Southern Company). From that time, a strong management commitment has continued.

April 1984: The major event of the year was the performance of 29 specific STEP tests for DOE. The tests plan was funded by Electric Power Research Institute (EPRI). Because of budget restraints the 29 were selected from some 100 to profile the system and subsystem performances. They were executed under varying insolation conditions and varying inputs (solar only, fossil only, and hybrid) and outputs (electricity only, thermal energy only, and cogeneration). General conclusions were that STEP could produce electricity, chilled water, and process steam as designed; that the plant could be operated at increased efficiencies with specific modifications documented during test series; and that cogeneration can increase the utilization of solar-thermal energy.

July 1984: One critical anomaly related to having the solar collector fiber optic sensors near the opening of the receiver was that stray, concentrated sunlight could destroy the devices. Several staff members designed a new fiber optic system mounted on the lip of the collector. Here, seeing only one sun, the sensors avoided damage, the availability of the subsystem was greatly improved, and thermal performance remained constant.

December 1984: Following execution of the 29 tests (called Test Operations Phase Tests), plans were made from the analyzed results. It was decided by Sandia and GPC that the next step would be extended performance tests.

Also in December, the first two California Polytechnic University students successfully completed the SET course. To date there have been eight such students participating. Many advanced degrees have been received by Georgia Institute of Technology and Auburn students who have done masters thesis and doctorate work at Shenandoah.

Major Event of 1985

February 1985: An inspection of the turbine/generator was made by supplier and the STEP staff. No major wear or damage was found. At the same time, a microprocessor-based programable controller was installed on the turbine/generator, replacing the outdated mechanical relay circuitry. Maintenance requirements were reduced and performance was simplified.

June 1985: In accordance with the Sandia Statement of Work accepted by GPC as an extension of the DOE 29 test program, 30 consecutive days of operation were conducted at STEP. The plant was brought up and operated every day for 30 days. Electric power was produced every day of the test, while absorption air conditioning and steam were supplied to Bleyle during its 5-day work week and on weekends when it was requested. During the test, the plant had problems that curtailed some operation although no day was lost. The major problems were steam generator supply pump failure, FFH stack overheating, and pump cavitations.

August 1985: A second test included in the 1985 Sandia Work Statement was the execution and analysis of a continuous, 14- day STEP test. The objectives were to determine operating costs under continuous operation, to evaluate the solar contribution, to identify areas for cost reduction, and to determine the benefits/deficiencies of continuous operation. The total operation and maintenance cost was $0.19/kWh (electrical plus thermal).

Insolation during the 14-day test period was poor. The most obvious area for cost reduction concerned the collector field operational manpower demands (modified in 1986). Additional station service loads were also reduced. Test results showed some merits to continuous operation as function of control room operator costs. Operators spent 2 hours starting up the plant and another hour shutting the plant down. Later reduction in manpower requirements from system modifications have corrected these deficiencies.

September 1985: The STEP facility ownership was transferred to GPC. An accounting of all equipment was made and accepted. Continued contractual support was shifted from DOE to Sandia.

October 1985: A third Sandia program was to experimentally determine the level of heat losses from the STEP collector field and the collector field thermal capacitance. Results of the heat capacitance test showed that the collector field thermal mass was 7255 Btu/° F. A series of comprehensive tests provided data for comparison with original design values.

Major Events of 1986

February 1986: A new, superior collector field control system was designed, tested, installed and operated. This third iteration has operated reliably and accurately. It has allowed the reduction of collector field personnel from four to almost zero. A Hall-effect device counts the revolutions of the drive motors to position each collector. The use of the fiber optics, potentiometers, other resistance temperature devices, original circuit boards and software has been eliminated.

March 1986: The construction of a 40 x 60' mechanical/maintenance/ storage building was completed. A water analysis laboratory was established in the building. Shop equipment, tables, cabinets and machine tools are included. A high-efficiency lighting system and infrared heating system was installed.

April 1986: During April, a turbine mapping test was executed on the STEP system. The goal was to determine what impact resulted from operating the turbine off design conditions. Results were used to modify operational modes that enhance performance.

June 1986: Major system modifications were the key events of 1986. With the support of Sandia, a heat transfer fluid pressurizing subsystem was added to reduce pump cavitations and fluid loss through vaporization. A required replacement of a tube bundle in the heat exchanger was carried out. Also, Sandia purchased a new steam superheater, which was much more efficient than the HTF heater and should enhance significantly the plant's electrical output.

Major Events of 1987

January 1987: Analysis of the prior testing by others indicates that availability analysis of the collector field losses at STEP showed that thermal energy transport losses represent only 2.3 percent of the incident solar energy that could produce electricity. This low value shows that efforts at reducing losses other than thermal losses may produce significant increases in electrical power generation by the system. Second law efficiencies suggest that relatively large changes in collector field operating temperatures have little effect on electric power output.

In an effort to improve the STEP control and data collection system, a touch screen control program was initiated. By touching the CRT screen a pump could be started or stopped, a valve could be opened or closed, and the display could be changed. Speed of execution was greatly increased. This touch screen technology is a significant operational advantage over the menu-driven keyboard of the original design.

A thesis, "Reliability Analysis of the Solar Total Energy Project," was completed by an Auburn student who received his MSEE in early 1987. The goal of the study was to evaluate the reliability of the STEP system and predict performance in terms of significant parameters calculated using failure and repair data collected during the operation of the system. A fault tree construction was presented including a quantitative analysis of the tree itself.

February 1987: Extended operations commenced following the major modifications of 1986. A test program was scheduled during the year to ascertain the most favorable operating modes for the commercial operations phase of the total STEP test program. The success of the new collector field control system, the pressurized HTF subsystem, and the steam superheater were to be analyzed. The objective was to determine the best input for the superheater as function of solar irradiation, the most cost-effective levels of cogeneration, and the O & M cost for the retrofitted system. Reverse return collector field HTF flow and ECP 300 collector film resurfacing also were to be evaluated.

March 1987: Solar Operations was directed to chair the writing of a solar strategy for the Southern System, to be presented for approval by the Southern Company's executives. Also in March, Edward Addison returned to Shenandoah to review the latest advances in solar research and to make a television commercial for stockholders and other interested people on solar research activities.

April 1987: Since start up in early 1982 significant amounts of solar energy have been collected, and electricity, process steam, and chilled water for air conditioning have been produced in solar-only and hybrid operations. Through April, 490,547 kWh were generated, 151,428 ton-hours of cooling were produced, and 1,533,965 pounds of process steam for pressing clothes were provided to Bleyle. Collection and analysis of experimental data have contributed significantly to the national solar effort.

APPENDIX C

SOLAR TOTAL ENERGY PROJECT

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APPENDIX C
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