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Solar Total Energy Program Quarterly Report

April-June 1974

Solar Energy Projects Division 5712
Solar Energy Systems Division 5717

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Atomic Energy Commission under Contract AT (29–1)-789

Printed September 1974

Sandia Laboratories
energy report

SF 2900-QQB(3-74)

**Issued by Sandia Laboratories, operated for
the United States Atomic Energy Commission by Sandia Corporation**

SC 1004-DF (10-70)

SAND74-0208
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SOLAR TOTAL ENERGY PROGRAM
QUARTERLY REPORT
April-June 1974

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ABSTRACT

This quarterly report describes the activities within Sandia Laboratories Solar Total Energy Program during the final quarter of fiscal year 1974. Included are descriptions of the program's background, overall program plan, and the baseline design of the Solar Total Energy System.

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SECTION I

INTRODUCTION

In response to increasing public and official recognition of the pressing needs for new, nonpolluting sources of energy, exploratory system studies[1, 2, 3] concerning potential uses of solar energy have been conducted at Sandia Laboratories since 1972. These studies, which have included performance and cost evaluations, have involved the following areas: (1) solar thermal to electrical generation systems, (2) solar energy collection systems, (3) energy storage systems, (4) heat-to-electric conversion systems, (5) methods for transportation of energy, and (6) means for using thermal energy for air-conditioning systems.

The concept (Figure 1) of a cascaded solar total energy system is an outgrowth of these studies. This concept envisions a system that reduces the needs for fossil fuel energy by using the sun as the supply of a wide range of energy needs. Energy collected at a central area is used to provide electricity, space heating, air conditioning, and hot water. Such a system could (1) offer a significant savings in fossil fuel, (2) be economically competitive with existing energy systems in the future, and (3) minimize harmful effects on the environment.

In system operation, a working fluid is heated in the receiver tubes of the solar collectors by reflected and focused solar radiation. This fluid is pumped to the high-temperature storage tank. On a demand basis, fluid is extracted from this storage to the toluene boiler which produces vapor to power the turbine/generator. The boiler can also be operated from a fossil-fuel-fired heater to insure continuity of operation during extended cloudy periods. Low-quality energy is extracted from the turbine condenser and stored in the low-temperature fluid storage tank. On a demand basis, fluid is extracted from this storage to power heating, air-conditioning, and hot-water-heating components.

To determine the technical and economic feasibility of the solar total energy concept, a comprehensive hardware program has been initiated at Sandia Laboratories. Additional objectives of the overall program are (1) to encourage private sector participation in the program and in the development of components for the system, (2) to determine those areas of research and development that offer the greatest payoff, and (3) to develop and validate a systems analysis computer program capable of evaluating the great number of possible combinations of total

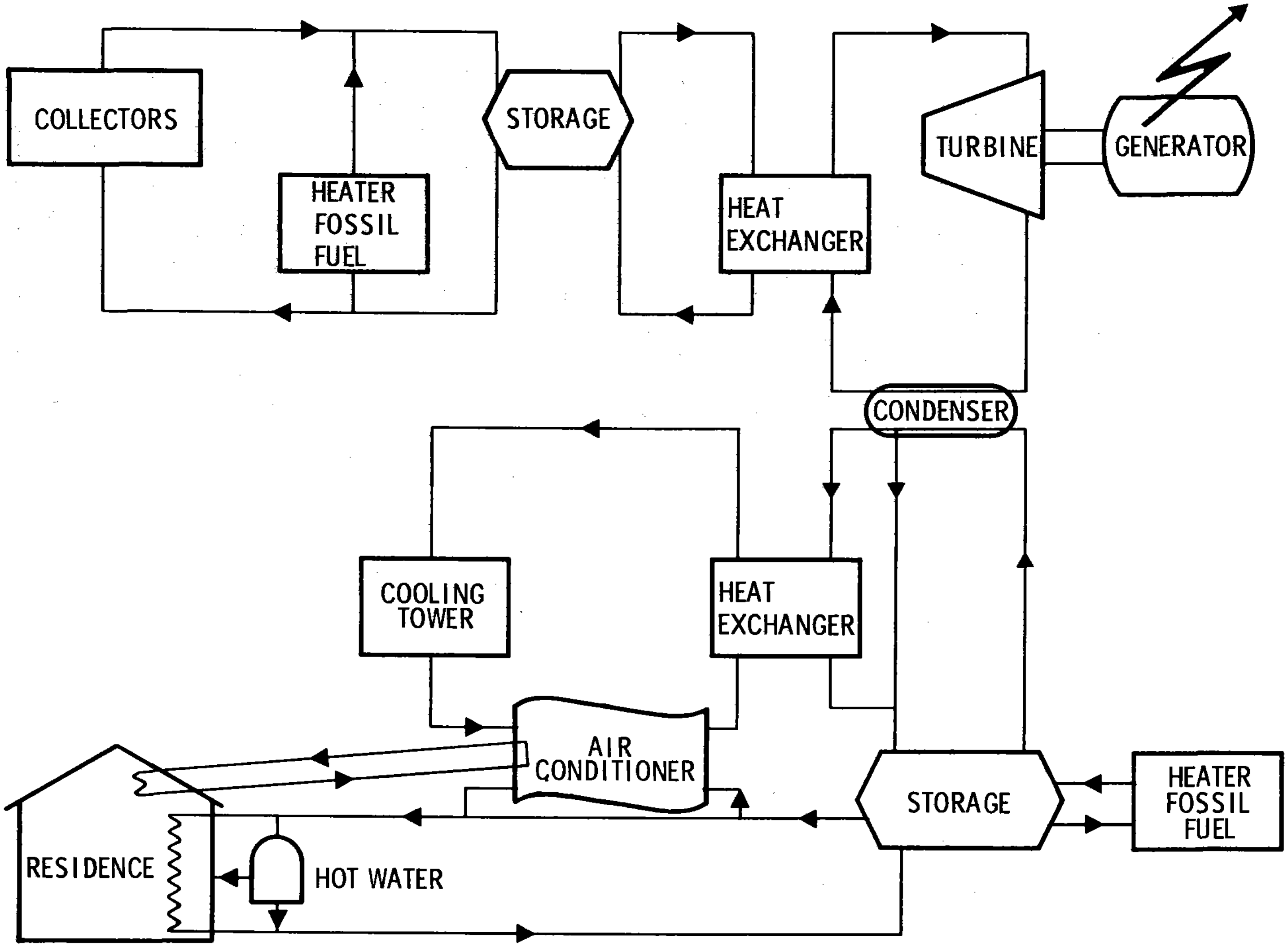


Figure 1. Cascaded Solar Total Energy System

energy system configurations. A grant from the National Science Foundation (No. AG-564) to continue the latter activity and extend analysis to a widespread range of potential applications and system concepts was received late in this quarter.

The overall Solar Total Energy Program consists of seven phases of which the work being reported in this document is the conclusion of Phase III. The program, which was initiated in 1972 with background research and exploratory analysis, has progressed to the present hardware state in which the test bed Solar Total Energy System will be used to provide power for the Solar Project Building. The program will conclude with the construction and operation of a solar total energy pilot plant expected to be achieved in cooperation with commercial interests.

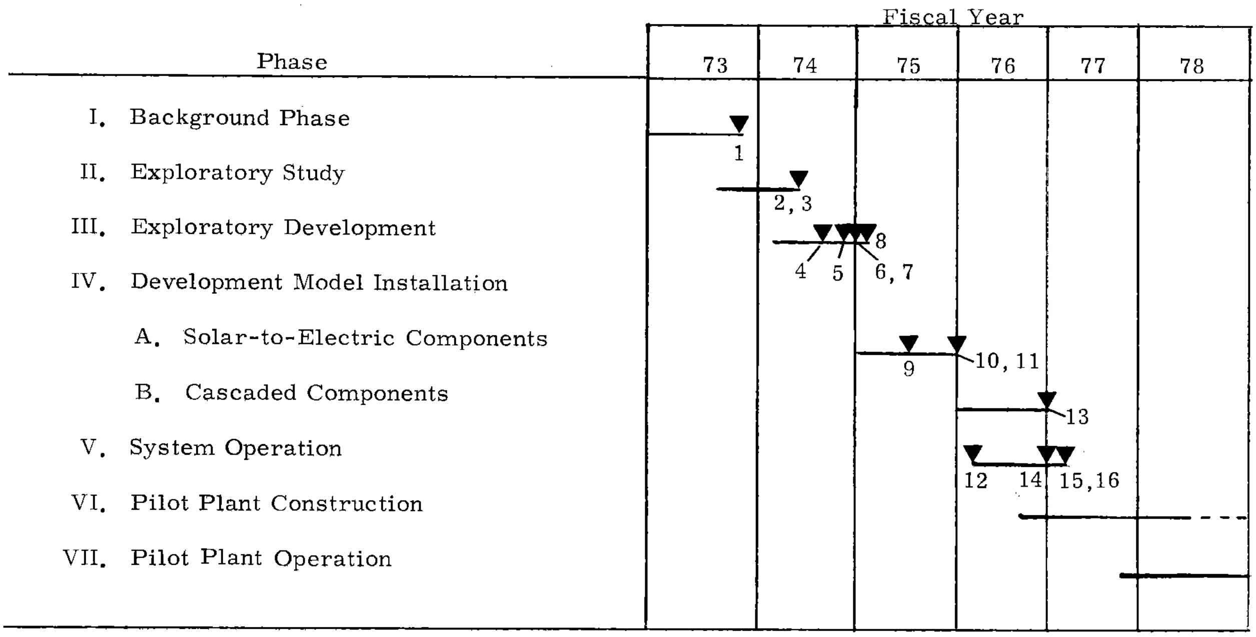
As FY74 ends, Phases I, II, and III, which have emphasized preliminary studies and designs, are completed. Phase IV-A is scheduled to begin in July 1974.

Phase IV-A is the pivotal phase in that it marks the transition from the analysis and design effort to the hardware and construction effort. Approximately 25 percent of the high-temperature solar-to-electric portion of the system is to be put into operation during this phase. Data collection in the high-temperature regime is of primary importance because little operating experience in this area has been accumulated.

During Phase IV-B, the remainder of the solar-to-electric components will be added, and the cascaded low-temperature portion of the system (heating, air conditioning, and hot water) will be installed.

Phase V will consist of operating the test bed Solar Total Energy System under various conditions to gather and analyze sound engineering data which can provide a basis for the design of the pilot plant and for future solar energy systems. During this phase, the feasibility of powering and heating the Solar Project Building will be demonstrated.

Phase VI and VII will consist of the design, construction, and operation of a pilot commercial solar power plant. The overall Solar Total Energy Program plan and major milestones are illustrated in Figure 2.



Milestones:

1. Completion of Phase I
2. Preliminary system design complete
3. Economic evaluation complete
4. Collector evaluation facility complete
5. System analysis program operational
6. Baseline system design complete
7. Phase IV-A proposal submitted
8. Phase IV-A supplementary proposal submitted
9. System analysis program loads profiles established
10. Partial collector field, storage, and turbine-generator test bed complete
11. Solar and weather input data established
12. Initial operation of partial Solar Total Energy test bed
13. Remainder of Solar Total Energy System completed
14. System analysis program refined and revalidated
15. Operation of complete Solar Total Energy System
16. Demonstration of Solar Project Building
17. Pilot plant designed
18. Pilot plant operational

Figure 2. Solar Total Energy Program schedule and milestones

SECTION II

HIGHLIGHTS

The following activities and milestones highlighted the reporting period:

- Collector evaluation facility completed and operational.
- An interactive computer graphics capability added to shadowing program, SOLR.
- Systems analysis computer program, SOLSYS, operational.
- Solar Total Energy System baseline design completed.
- Two full-size 2.7- x 3.7-m (9 x 12 ft) reflectors received.
- First vacuum-jacketed receiver tube fabricated.
- Design of collector field automatic control system initiated.
- Grant received from NSF (AG-564) for support of system analysis effort.

Reports and Presentations

The following reports were published and presentations were delivered in support of the Solar Total Energy Program during the reporting period.

Reports

Proposal for AEC/DAT, and the National Science Foundation Cooperative Support of Solar Total Energy Project Activities, Sandia Laboratories, Albuquerque, New Mexico, Solar Energy Projects Division 5712, SAND74-0141, July 1974.

A Proposal to NSF to Sponsor Phase IV-A of a Solar Total Energy Program, Sandia Laboratories, Albuquerque, New Mexico., Division 5712, SLA-74-0332, June 1974.

M. W. Edenburn, Performance of a Focusing Cylindrical Parabolic Solar Energy Collector: Analysis and Computer Program, Sandia Laboratories, Albuquerque, New Mexico, SLA-74-0031, April 1974.

C. E. Robertson and J. N. Banker, A Photographic Technique to Determine the Apparent Energy Distribution of the Solar Aureole, Sandia Laboratories, Albuquerque, New Mexico, SLA-74-0090, March 1974.

W. H. McCulloch et al., The Solar Community--Energy for Residential Heating, Cooling, and Electric Power, Sandia Laboratories, Albuquerque, New Mexico, SLA-74-0091, April 1974.

G. E. Brandvold, Solar Total Energy Community Project, Sandia Laboratories, Albuquerque, New Mexico, SLA-74-0124, March 1974.

James F. Banas, Interactive Analysis of Solar Energy Systems, motion picture produced for the Directorate of Advanced Planning and Analysis, by Motion Picture Production Division, Sandia Laboratories, Albuquerque, New Mexico, June 1974.

Presentations

R. P. Stromberg, Solar Energy, IEEE Power Group, Albuquerque, New Mexico, May 22, 1974.

R. P. Stromberg, Sandia Solar Energy Program, Soviet Visiting Group, Los Angeles, California, June 24, 1974.

SECTION III

SYSTEM DESCRIPTION AND STATUS

This section presents the detailed status of each program task. These tasks are as presented below:

Task 1	Program Management	
Task 2	Systems Management	
	2.1	Systems Engineering
	2.2	Systems Analysis
Task 3	Collector Field	
	3.1	Reflectors and Structures
	3.2	Receivers
	3.3	Tracking and Control System
	3.4	Fluid Transfer System
	3.5	Cooler
Task 4	High-Temperature Storage	
Task 5	Turbine/Generator System	
	5.1	Boiler
	5.2	Turbine
	5.3	Rankine Loop Heater
	5.4	Turbine Heat Exchanger
	5.5	Cooling Tower
	5.6	Load Bank
Task 6	Instrumentation and Control System	
Task 7	Collector Test Facility Operation	

Task 1 - Program Management

The activities of this quarter resulted in the publication of a proposal[4] to the National Science Foundation for funding support of Phase IV-A of the Program.* This proposal was submitted to the AEC for forwarding to NSF.

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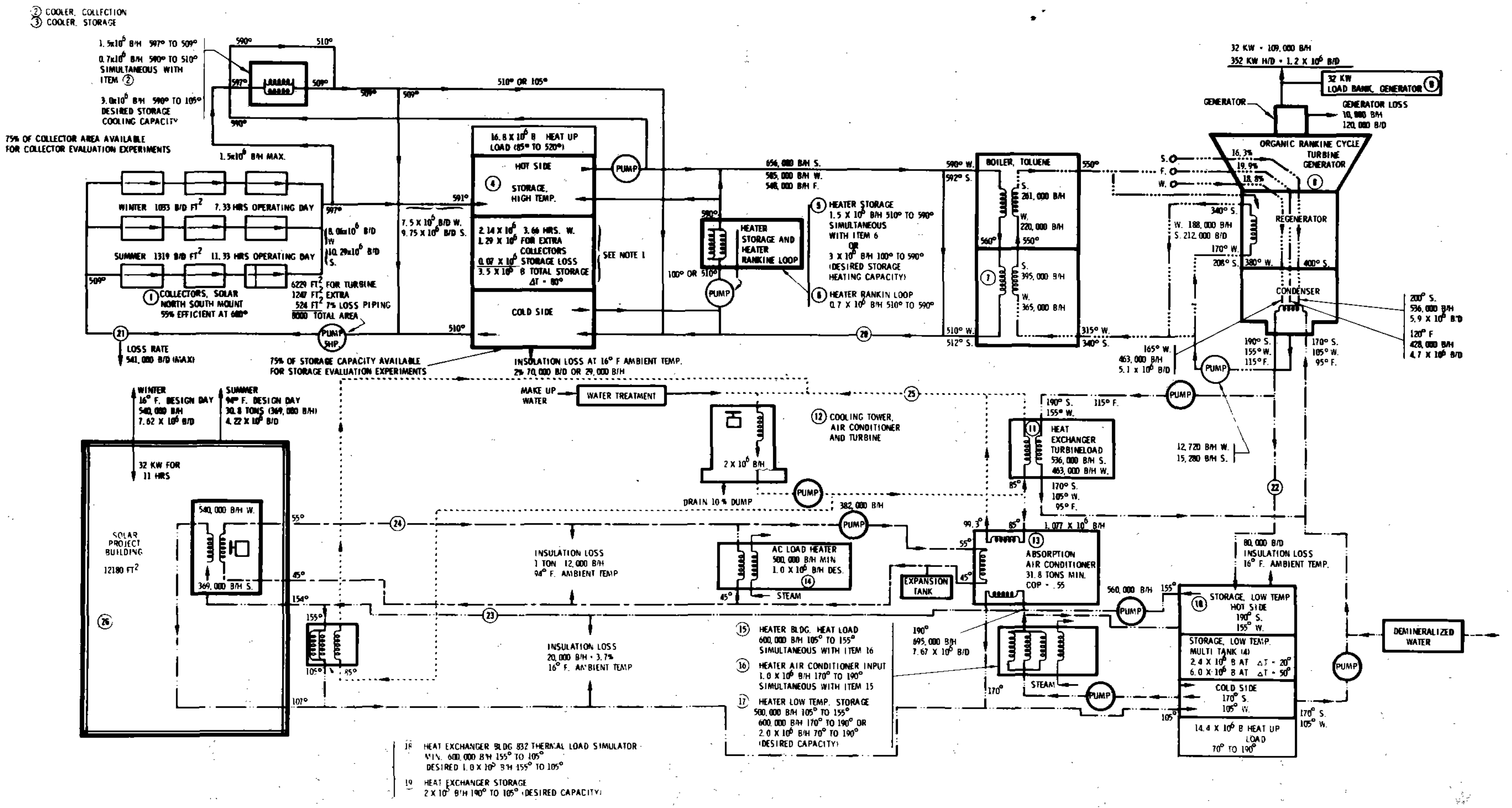
*Subsequently, during July 1974, a supplementary proposal[5] was submitted to AEC which requested joint program funding from AEC/DAT and NSF.

Task 2.1 - System Engineering

The system engineering efforts during this quarter resulted in the establishment of the Solar Total Energy System baseline design (Figure 3). The system is sized to collect sufficient solar energy to fulfill the daily electrical requirements of a building. The building (Solar Project Building) selected for this purpose, which is 1132 m^2 (12,180 ft^2) in size, houses the solar engineering project offices as well as other laboratory staff. From a system load point of view, this building's power requirements are equivalent to those of approximately 12 residential houses of 186 m^2 (2000 ft^2) each. The building's electrical load is 32 kw for 11 hours per day, a total of 352 kw-hr.

For any capital intensive system, overall economics are most favorable when system use is maximized. For a solar total energy system as required for the Solar Project Building, which has a constant electrical load and a cyclic low-quality heat demand for heating and cooling, optimum utilization of the most expensive system components--collectors and high-temperature storage units--will occur when the system is designed to meet the constant electrical load and not the peaks of the cyclic heating and cooling load. The waste heat from the turbine/generator is sufficient to meet approximately 70 percent of the peak building heating and cooling needs and will be supplemented on peak load days by use of fossil fuels. This technique permits the turbine/generator to be operated at better cycle efficiency, which is of primary importance because cycle efficiency and collector field area are inversely related.

The turbine/generator is designed for a condenser output of 68°C (155°F) to be used for hot water and heating during all of the year except midsummer when the condenser output will be 88°C (190°F) for air conditioning. These different summer and winter turbine condenser operation temperatures result in a higher cycle efficiency in the winter. Fortunately, the larger efficiency is obtained in the winter when the total daily solar input is at its minimum. With N/S-oriented collectors, the summer solar input can be approximately 50 percent larger than the winter input, primarily because of the longer daylight hours. For the Solar Total Energy System, cycle efficiency is 18.8 percent during most of the year and 16.3 percent in the summer; therefore, more thermal energy is required in the summer. The fact that the increase required is only about 15 percent and not the 50 percent potentially available will allow a further decrease in the required collector area because collectors can gather more energy in summer than in winter from the same area. The collector field area is sized at 743 m^2 (8000 square feet), which is sufficient to produce 352 kw-hr per day at winter solstice with an adequate margin. The collectors used are North/South-oriented parabolic trough type with active tracking. In that Albuquerque is at 35 degrees north latitude, a normal polar mount of the tracking collector would result in an elevation of 35 degrees from the horizontal. However, to more nearly balance the winter and summer output of the system, the elevation angle has been biased toward winter operation by increasing the elevation angle to 45 degrees. This results in an estimated winter solstice energy collection of 11,730 kj/m^2-day (1033 Btu/ft^2-day) instead of the 10,913 kj/m^2-day (961 Btu/ft^2-day) which would result from a 35-degree orientation. The 45-degree orientation still allows in excess of 15 percent more energy to be collected during the summer when the Rankine cycle must be operated at reduced efficiency.



NOTES:

1. 1.29×10^6 EXTRA STORAGE WILL ALLOW FOR EXTRA STORAGE CAPACITY OF 2 HOURS IN WINTER AND 5 HOURS IN SUMMER.
2. ALL COMPONENTS AND PIPING IN THE GLYCOL WATER LOOP SHOULD BE SIZED FOR GLYCOL WATER MIXTURES. HOWEVER INITIALLY THE SYSTEM WILL BE OPERATED USING WATER ONLY.

S. = SUMMER OPERATION
W. = WINTER OPERATION
F. = MAX. EFF. OPERATION

CODE FLUID LOOPS

GLYCOL WATER (SEE NOTE 2) —— · · ——
WATER, CHILLED —— – ——
THERMINOL 66 ————
TOLUENE —— · · · · ——
WATER, COOLING TOWER - - - - - - - - - -

COMPONENTS LIST

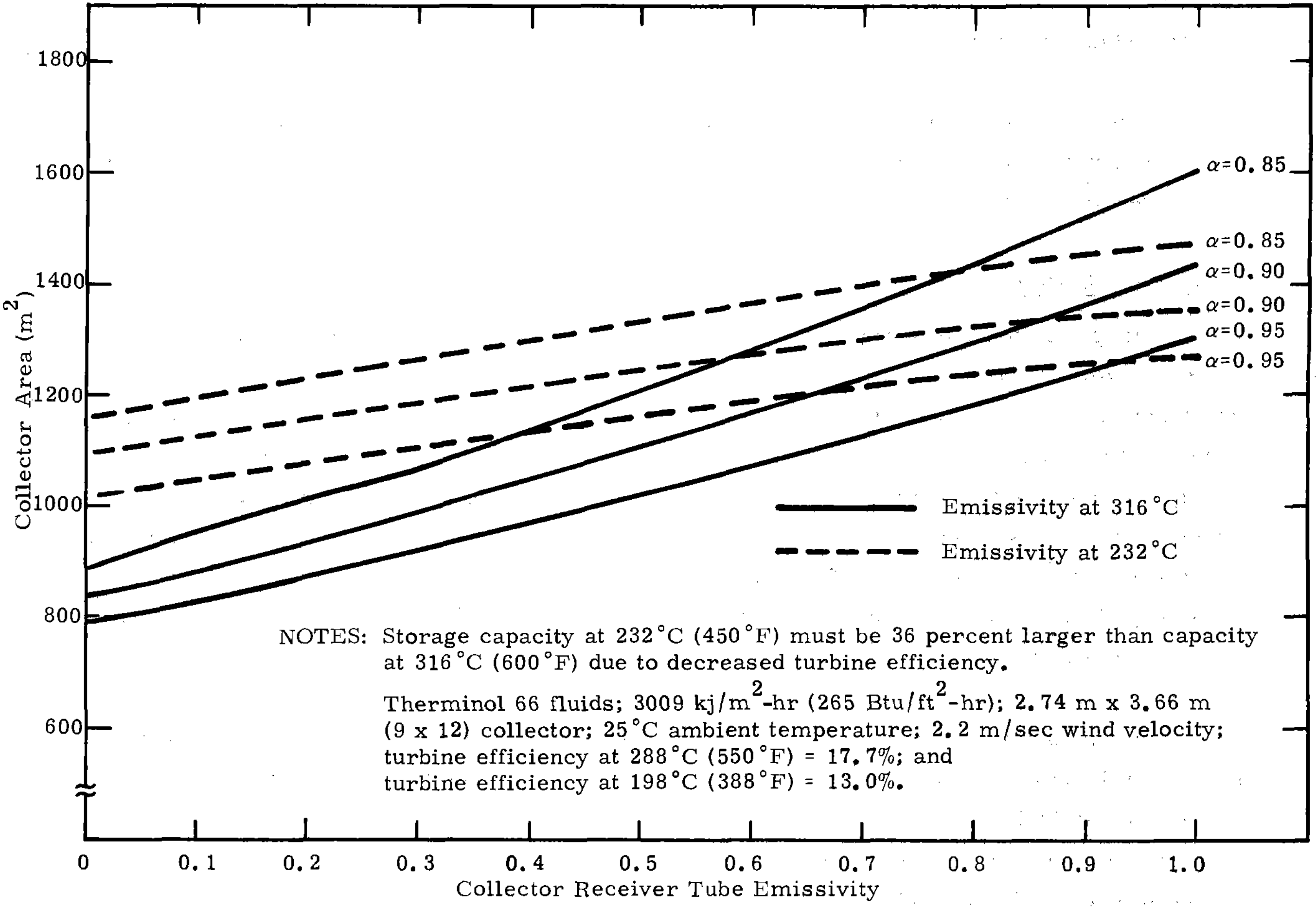
1. COLLECTORS, SOLAR
2. COOLER, COLLECTOR
3. COOLER, STORAGE
4. STORAGE, HIGH TEMP
5. HEATER, STORAGE
6. HEATER, RANKINE LOOP
7. BOILER, TOULENE
8. ORGANIC RANKINE CYCLE TURBINE-GENERATOR
9. LOAD BANK, GENERATOR
10. STORAGE, LOW TEMP
11. HEAT EXCHANGER, TURBINE LOAD
12. COOLING TOWER, TURBINE AND/OR AIR CONDITIONER
13. ABSORPTION AIR CONDITIONER
14. AIR CONDITIONER LOAD HEATER
15. HEATER, BUILDING HEAT LOAD
16. HEATER, AIR COND. INPUT HEATER
17. HEATER, LOW TEMP STORAGE
18. HEAT EXCHANGER, BLDG. 832, THERMAL LOAD SIMULATOR
19. HEAT EXCHANGER, STORAGE
20. THERMINOL LOOP, STORAGE TO TURBINE
21. THERMINOL LOOP, COLLECTOR TO STORAGE
22. GLYCOL LOOP, TURBINE TO STORAGE
23. GLYCOL LOOP, STORAGE TO LOADS
24. CHILLED WATER LOOP
25. COOLING TOWER LOOP
26. BUILDING MODIFICATIONS
27. INSTRUMENTATION AND CONTROL

Figure 3. Solar Total Energy System schematic

Cycle efficiency is primarily determined by the fluid supply temperature and the fluid exhaust temperature. Turbine inlet temperatures are often limited by the turbine working-fluid properties. The selected turbine uses toluene at 289°C (550°F). To provide an adequate temperature drop through storage, the collector output temperature must be 316°C (600°F). The heat transfer fluid selected for the collectors is Monsanto Chemical Therminol 66 (T-66) which has a maximum usable temperature of 343°C (650°F). Actually, a solar total energy system could be operated with lower collector temperatures, but at the expense of decreased cycle efficiency. For instance, a 232°C (450°F) collector system would result in 13-percent cycle efficiency. Whether this lower cycle efficiency would be detrimental to overall system performance would depend on many factors such as collector efficiency, storage cost and materials, and low-temperature energy requirements. Figure 4, which illustrates the relation of collector area, receiver tube emissivity, and operating temperature, indicates the desirability of using a higher collector temperature if receiver tube emissivity is less than about 0.8. In that emissivities of 0.3 or less are anticipated for the system, a 316°C collector operation can have definite economic advantages. In addition to economics, the 316°C system offers increased facility flexibility for use as an experimental test bed in that it can be operated at lower temperatures.

In comparison with the cost of using energy directly, storage imposes an economic penalty on the system because of the cost of the storage facility. Consequently, the fossil-fuel supplement to the Solar Total Energy System is most effectively employed to minimize the requirement for storage. The Solar Project Building requires electrical service from 7:00 AM to 6:00 PM; during the winter, the collectors operate effectively from 8:20 AM to 3:40 PM. Consequently, the system needs 3.66 hours storage in the winter and almost no storage in the summer. Regardless of economic penalties, storage has been included in the system design to make the system more flexibile and to provide a means for evaluating techniques for decreasing storage costs. These considerations are discussed more fully under Task 4 (High-Temperature Storage). The high-temperature storage system allows for turbine/generator operation which provides for the 3.66 hours needed during winter solstice and for operation during some periods of cloudiness.

The Solar Total Energy System was designed to maintain flexibility and maximize the usefulness of the system as a test bed for other solar energy studies. The Solar Project Building retains a redundant fossil-fuel system so that the Solar Total Energy System is not enslaved to the building indefinitely. Each major component of the system can be operated independently so that several component experiments can be conducted concurrently. Maintaining this flexibility requires an unrealistic amount of electrical power for pumping and control. For this reason, these functions will utilize commercial power.



NOTES: Storage capacity at 232°C (450°F) must be 36 percent larger than capacity at 316°C (600°F) due to decreased turbine efficiency.

Therminol 66 fluids; 3009 kj/m^2-hr (265 Btu/ft^2-hr); 2.74 m x 3.66 m (9 x 12) collector; 25°C ambient temperature; 2.2 m/sec wind velocity; turbine efficiency at 288°C (550°F) = 17.7%; and turbine efficiency at 198°C (388°F) = 13.0%.

Figure 4. Collector area versus emissivity versus operating temperature

Some examples of independent component operation are as follows: (1) collectors can operate to storage or to an air-cooled heat exchanger, (2) high-temperature storage can be operated from the collectors or from a fossil-fueled heater and can be exhausted to the turbine/generator or to an air-cooled heat exchanger, (3) the turbine/generator system can operate from storage or from the fossil-fueled heater and can exhaust to a cooling tower or to the low-temperature storage, (4) electrical load can be either the actual building or a 32-kw (max) load bank which can be used to simulate load profiles, and (5) the low-temperature storage can be supplied from the turbine or from a steam heater and can exhaust to the building heating and cooling loads or to an air-cooled heat exchanger simulating these loads.

Where there is no substantial penalty to economics or performance, components are oversized to increase system flexibility. Construction of the facility will be such that all components can be readily replaced.

Task 2.2 - System Analysis

A large computer program (SOLSYS) for analysis of energy systems has been in the process of construction since last summer. The executive program has been completed, and is now operational. A number of subroutines have been written, which act as mathematical models of equipment such as turbines, air conditioners, and storage systems. Several information subroutines describing the weather conditions, sunlight, and various loads such as hot water or electricity have also been constructed to allow analysis of various systems such as the Solar Total Energy System. Analyses of a 1000-house solar community and the Solar Total Energy System are underway. It was to further these activities that the National Science Foundation grant mentioned earlier was received.

Many minor improvements have been made in the analysis program to make it more accurate and efficient. A major program modification to improve efficiency has been partially completed. A distribution system subroutine has been added to the component library expanding the program's capabilities. A solar-weather data magnetic tape has been obtained from Aerospace Corporation and is being modified to be compatible with the analysis program.

The Computer Program for Analysis of Energy Utilization in Postal Facilities (commonly called "Post Office Program") written by General American Transportation Corporation has been purchased and is nowavailable as a permanent file of the computer. The major effort now is in modifying this program for use in SOLSYS and to provide ease of use. As originally written, the Post Office Program requires a tremendous amount of input data which makes actual use of the program tedious. In order to minimize the amount of necessary input data, a load program is being formulated. This load program assumes that any building is composed of rectangular subunit building blocks. Given the physical dimensions of the building block and the number comprising the building, the load program calculates all the geometric and positional parameters of each wall in the building. Also, the weather information subroutines are being modified to be compatible with the weather information in SOLSYS.

Data on the residential electric power consumption for a group of 474 residences located in a well-established area of Albuquerque has been provided by the Public Service Company of New Mexico. The data provides the power consumed at 15-minute intervals spanning a 13-month period from May 1973 through May 1974. The data are being digitized. A computer program is being prepared to conduct analytical studies of the data and to prepare the data in a format appropriate for incorporation in the energy systems analysis program.

Task 3 - Collector Field

The solar collectors consist of reflectors, support structures, receivers, and a tracking and control system. In the baseline design, the collectors are designed to collect 8.7×10^6 kj/day (8.26×10^6 Btu/day) of solar energy in winter and 11.13×10^6 kj/day (10.55×10^6 Btu/day) in summer. This energy is focused on a receiver tube through which T-66 heat transfer fluid flows. The fluid inlet temperature is 265°C (510°F), and the output temperature is 316°C (600°F). Maximum heat flow rate is approximately 1.58×10^6 kj/hr (1.5×10^6 Btu/hr).

The computer program which predicts collector performance is presently operational. Using the latest predicted input data, the program is predicting collector outputs substantially higher than those used in the baseline design.

A ray trace computer program is being developed which will take into account such things as the changes in reflection and absorption with incidence angle and wave length, and the variation in intensity across the solar diameter. These effects can be significant in collectors that are not always nearly normal to the sun, such as E/W or fixed flat plate collectors.

The reflector design features lightweight, high-strength materials and assemblies configured to provide adequate support in high winds. Structural integrity will be achieved either by the use of structural sandwiches constructed of thin high-strength skins on lightweight filler center sections or a ribbed fiberglass-reinforced plastic shell. The latter is typical of the methods used in fabrication of fiberglass boat hulls.

The reflective materials being considered include the following:

1. Alcoa Lighting Sheet, Type I, Class M (Alzak).
2. Various films or combinations of films such as polyester, Teflon, and acrylic (in conjunction with aluminized reflector surfaces). These films are used to achieve the properties required for transparency, bondability, moisture, resistance, etc.

3. Acrylic sheets 0.76 to 1.52 mm thick (0.030 to 0.060 inch) laminated with reflective surfaces.
4. Glass sheets with various reflective coatings. Glass could be common thin sheet glass 3.175 mm (0.125 inch) annealed and sagged to proper parabolic contour or chemically strengthened glass 1.02 to 2.04 mm (0.040 to 0.080 inch) which may be sagged prior to strengthening or flexed to the required shape after strengthening.

Thin liquid resins which harden after application to any of the reflective surfaces are used to minimize abrasion caused by wind and dust and to prolong useful life.

A development effort will be required to determine which of the above candidates will be used in quantity procurement. Several of these materials will be applied to full-size troughs for evaluation as part of the proposed program.

Several mounting structure designs have been investigated from the viewpoints of simplicity, structural analysis, and cost. Another important consideration in the design of mounting structures for this particular collector field is versatility. The structural design must permit maximum flexibility in the investigation of various types of collectors and various collector spacing.

Designs investigated for N/S polar mounts have been welded steel pipe or aluminum tubing frameworks, large steel pipes set in concrete, reinforced concrete structures or beams, wooden pilings, and earthen mounds with minimum concrete support pilasters. Preliminary analyses have been made on several concepts, and detailed stress analysis has been made on the welded-steel-pipe design.

The mounting structure design is influenced by the rim angle of the parabolic trough, the receiver tube location, the trunnion location, and the plumbing interconnections for the heat transfer fluid.

The first full-scale 2.7 x 3.7 m (9 x 12 ft) reflectors (Figure 5) have been received and are presently undergoing evaluation testing. These reflectors were constructed using fiberglass layup techniques and are surfaced with Alzak reflective aluminum.

The activity associated with the design of receiver tubes which will be compatible with total energy delivery needs includes analytical models, calculations, and prototype hardware. Among the variables being considered are:

1. The balance between the flow rate for the necessary increase in working fluid temperatures and the film coefficient of heat transfer necessary for effective heat transfer.

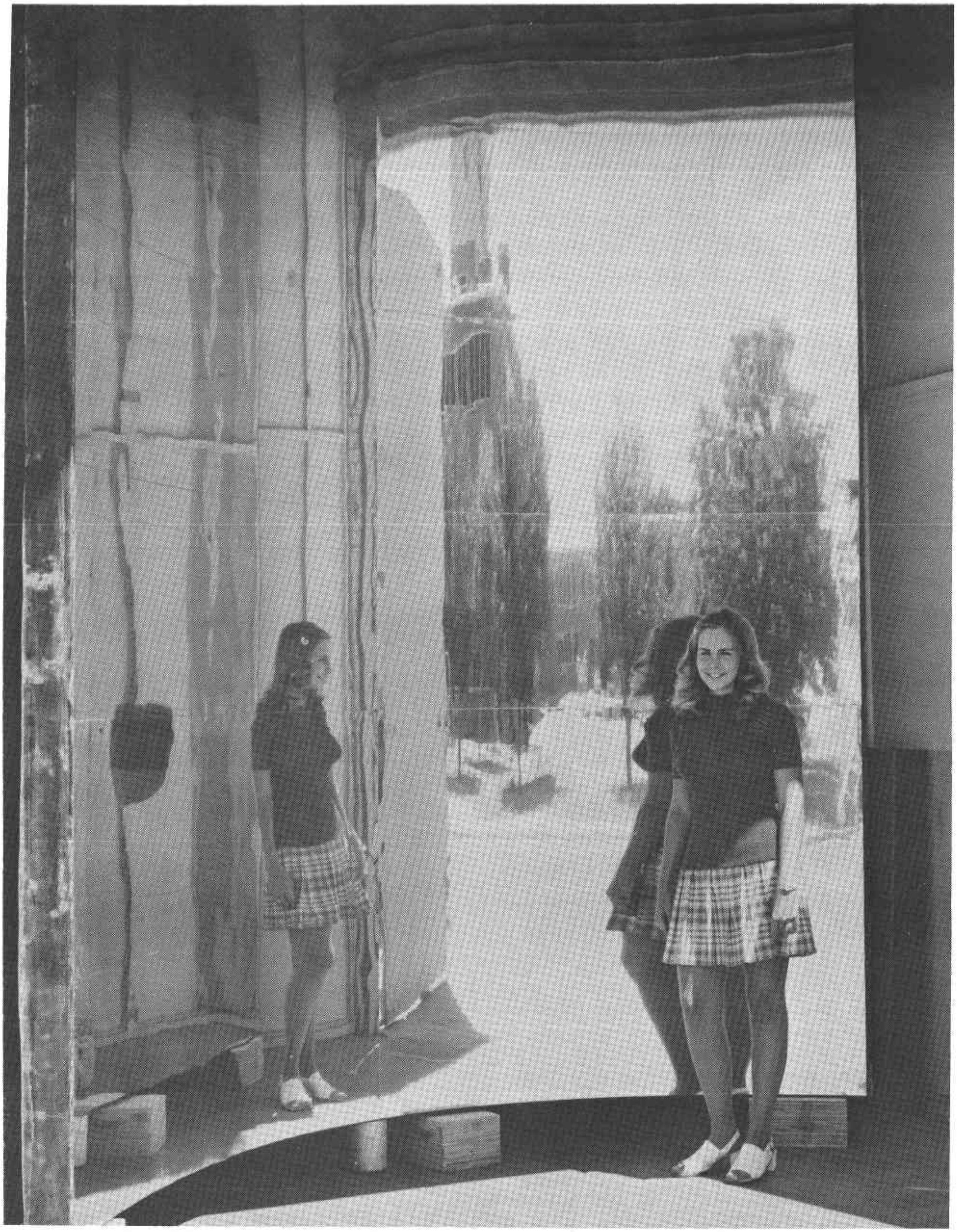


Figure 5. First full-scale 2.7- x 3.7-m parabolic reflector

2. The influence of flow restrictors on efficiency.
3. The effects of glass envelopes and insulations on receiver heat balance.
4. The influence of coatings on absorptivity, thermal transport, and emissivity.
5. The influence of tracking errors, diffuse reflectivity, and reflector aberrations on receiver design.

The first vacuum-jacketed solar receiver is now available for testing. The coating on the receiver tube is Pyromark paint. This is a nonselective coating which has an emissivity and absorptivity of approximately 0.98. This assembly will be used as a reference for evaluating future coatings. Receiver tubes with a black nickel selective coating have also been received. Black nickel has an absorptivity of about 0.9 and an emissivity of about 0.4.

A detailed study[6] of the optimum rim angle of a concentrating solar collector has been conducted and the optimum angle has been determined to be 90 degrees. The analysis includes the effect of tracking errors, reflector errors, the sun's angular width, and a receiver tube tangent angle which will preclude significant photon reflection.

Calculations also indicate that an increase in receiver tube coating absorptance has a much greater impact on collector efficiency than a similar decrease in coating emittance (Figure 4). Therefore, the coating goals are an absorptance of 0.95 and an emittance of 0.3. These values have been achieved in the laboratory with lead sulfide on flat plates.

The tracking and control system for the baseline collector field consists of an optical photoelectric solar sensor and associated electronics and drive system. The tracking system will be designed to maintain a tracking error of less than 0.25 degree. The drive motor will run intermittently as required by the tracking system.

Several options are under investigation to determine whether multiple collectors can be driven from a common tracking and control system. These options include chain drives and torque tubes. In that the tracking rates are low, fractional horsepower electric motors can be used to provide sufficient torque for driving or holding the collectors against wind loads.

Aerodynamic loading data (lift, drag, and torque) have been used in designing drive systems. The design goals are to survive a 40-m/sec (90-mph) wind and operate in winds of 13 m/sec (30 mph).

A computer program, SOLR, which utilizes computer graphics has been devised to determine the collector field performance for any particular array and number of collectors, for any particular day or time of day, for any orientation or tilt, and for any specific spacing between collectors. The program is capable of correcting for shadowing by neighboring collectors, for sun

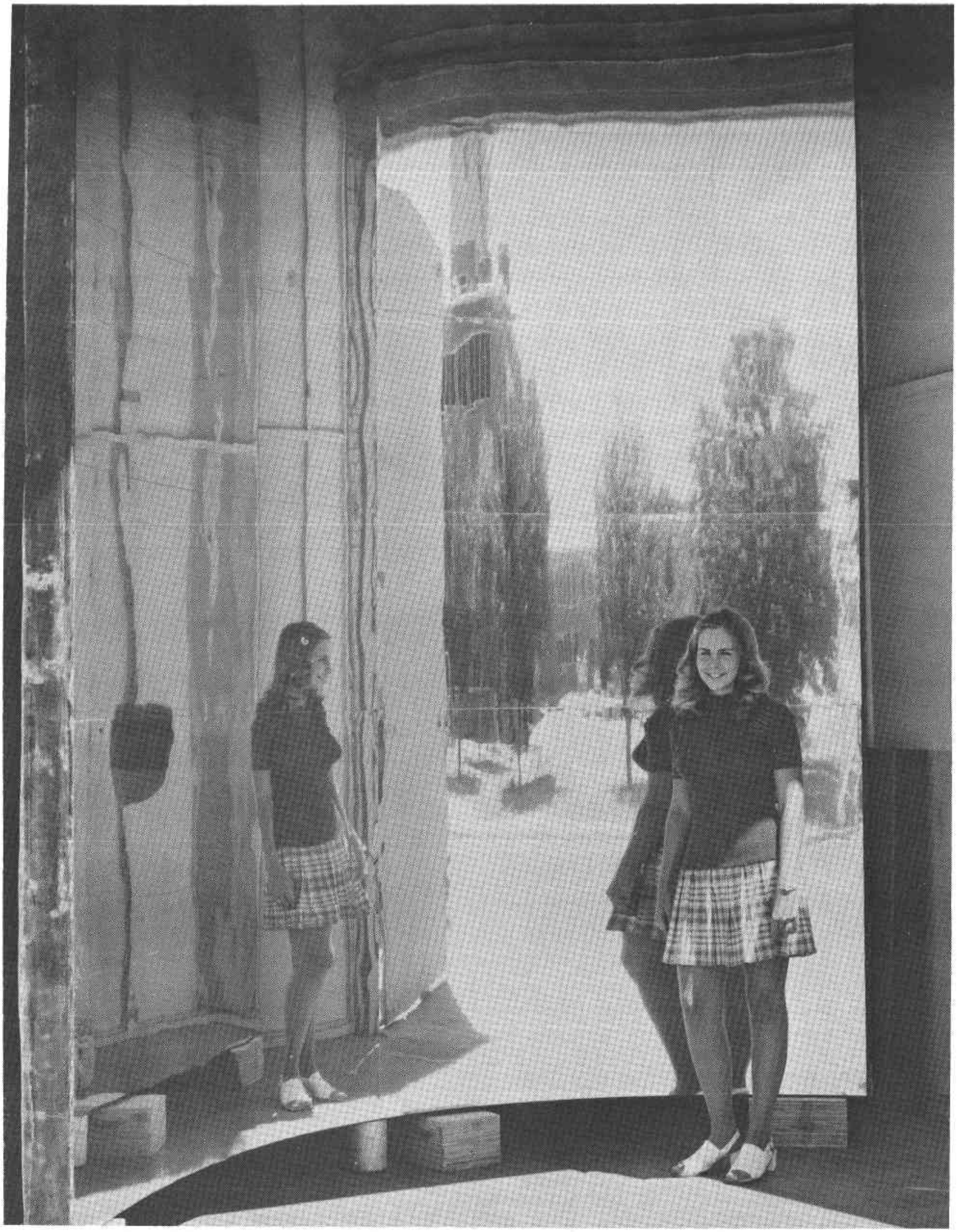


Figure 5. First full-scale 2.7- x 3.7-m parabolic reflector

declination, and for reflector/receiver efficiency; it is also capable of integrating the daily heat input to the heat transfer fluid. This program will be a vital tool in the selection of the various design and layout parameters of the collector field. A motion picture[7] which shows the operation, output, and flexibility of this program has been produced.

The fluid transfer system for the collector field consists of the pipelines, pumps, and control valves for circulating the heat transfer fluid through the field. When the full collector field is in operation, T-66 will be pumped from the cool side of the high-temperature storage tank, through the collectors, and back to the high-temperature side of the tank at a peak heat flow rate of 1.56×10^6 kj/hr (1.5×10^6 Btu/hr).

The temperature of the T-66 as it returns to the storage tank must be maintained at or above 310°C (590°F). The temperature of the fluid is regulated by varying its flow rate through the collectors. As the solar intensity drops off (because of the sun's position or a passing cloud), the flow rate must be lowered in order to maintain a constant output temperature. The control of the flow rate by conventional techniques, i.e., compressed-air-actuated control valves and fixed-speed centrifugal pumps, requires unnecessarily high pumping energy. To preclude this, variable-speed pumps and control valves requiring very small pressure drops will be used.

Thermal losses from the pipelines in the collector field can be categorized as daytime and nighttime losses. The daytime losses are the steady-state losses occurring while the high-temperature T-66 is being circulated through the pipelines. The nighttime losses are the transient losses that occur as the pipeline, the fluid it contains, and the pipeline insulation cool down toward the ambient air temperature. These thermal losses could represent a considerable portion of the energy collected; therefore loss minimization techniques must be applied.

The most important factor associated with thermal losses is the total length of pipeline in the collector field. The insulation material for the pipelines is the next important factor. Because of the high cost of superinsulation materials and techniques, only commonly used pipeline insulation materials may be considered. Laminated construction of a variety of commonly used preformed pipe insulation materials appears satisfactory. An example would be to place on a 316°C (600°F) pipeline concentric layers of calcium silicate, fiberglass, and a low-density polyurethane foam. Here, the calcium silicate is a good high-temperature insulation, the fiberglass is a better medium-temperature insulation, and the low-density polyurethane foam is an excellent low-temperature material.

It has been suggested that wherever possible the pipelines be buried underground to further reduce heat losses. However, preliminary analysis has shown that, although the losses may be reduced during the daytime by up to 20 percent, the nighttime losses negate the daytime savings because of the thermal mass of the ground which would need to be reheated each morning.

For a half-inch pipeline, a 288°C (550°F) average operating temperature, and a laminated insulation design, the curves in Figure 6 show the 24-hour winter thermal losses.

Frictional head losses in the pipelines add to the thermal losses. These losses have been expressed as collected pump energy because some of the energy from the collectors must be consumed in pumping fluid through the lines. A tradeoff exists between insulation losses which increase with pipeline diameter and the collected pump energy which increases with decreasing pipeline diameter. Furthermore, because of pump and turbine efficiencies, much more energy must be collected than is used to overcome pipe friction. Figure 7 is a plot of these losses as a function of pipeline diameter. For example, in the case of a 1-1/2-inch-diameter pipe, the net 24-hour loss would be about 2.7 Mj/m-day. The pipeline length for the baseline-design collector field will be about 450 meters. The total losses then would be about 1200 Mj/day, of which 180 Mj/day is collected pump energy (adjusted for pump and turbine efficiencies). This loss would constitute about 14 percent of the collector field output at winter solstice, which is the worst case. However, in the final design of the collector field, various pipe diameters will be used to minimize fluid transfer losses, and an actual loss of 10 percent at winter solstice is predicted.

A mathematical model of the collector field, capable of transient analysis, is being constructed for the purpose of studying potential control problems. The model will include heat transfer characteristics of the pipelines, the performance of the pump and control valves, and the input of the collectors.

The collector and storage cooler, which is used to support tests of other components, acts as a simulated thermal load to dissipate the thermal energy from the collector field or from the high-temperature storage tank. The cooler is capable of dumping heat at rates in excess of the collector field output of 1.58×10^6 kj/hr (1.5×10^6 Btu/hr) and the turbine/generator demand of 0.74×10^6 kj/hr simultaneously. The cooler will also be used to decrease the temperature of stored T-66 from 310°C (590°F) to ambient at a rate of 3.17×10^6 kj/hr.

Task 4 - High-Temperature Storage

The high-temperature storage tank accepts 310°C (590°F) T-66 from the collector field or from the heater and delivers T-66 to the toluene boiler or to the cooler. The storage tank must be capable of storing T-66 at 310°C from the collector field and must have an adequate capacity to furnish 3.7×10^6 kj (3.5×10^6 Btu) of thermal energy with a temperature drop of 26°C (80°F). The tank must be insulated so that a 2-percent 74×10^3 kj energy loss in 24 hours is not exceeded.

The storage tank makes use of stratified storage in which high-temperature fluid from the collector field or the storage heater is pumped into the top of the tank, while cool fluid to be reheated is drawn from the bottom. The separating interface or thermocline between the hot and cold fluids moves up and down as the ratio between hot and cold fluid varies. The use of the thermocline eliminates the need for a moving bellows or diaphragm and/or another tank.

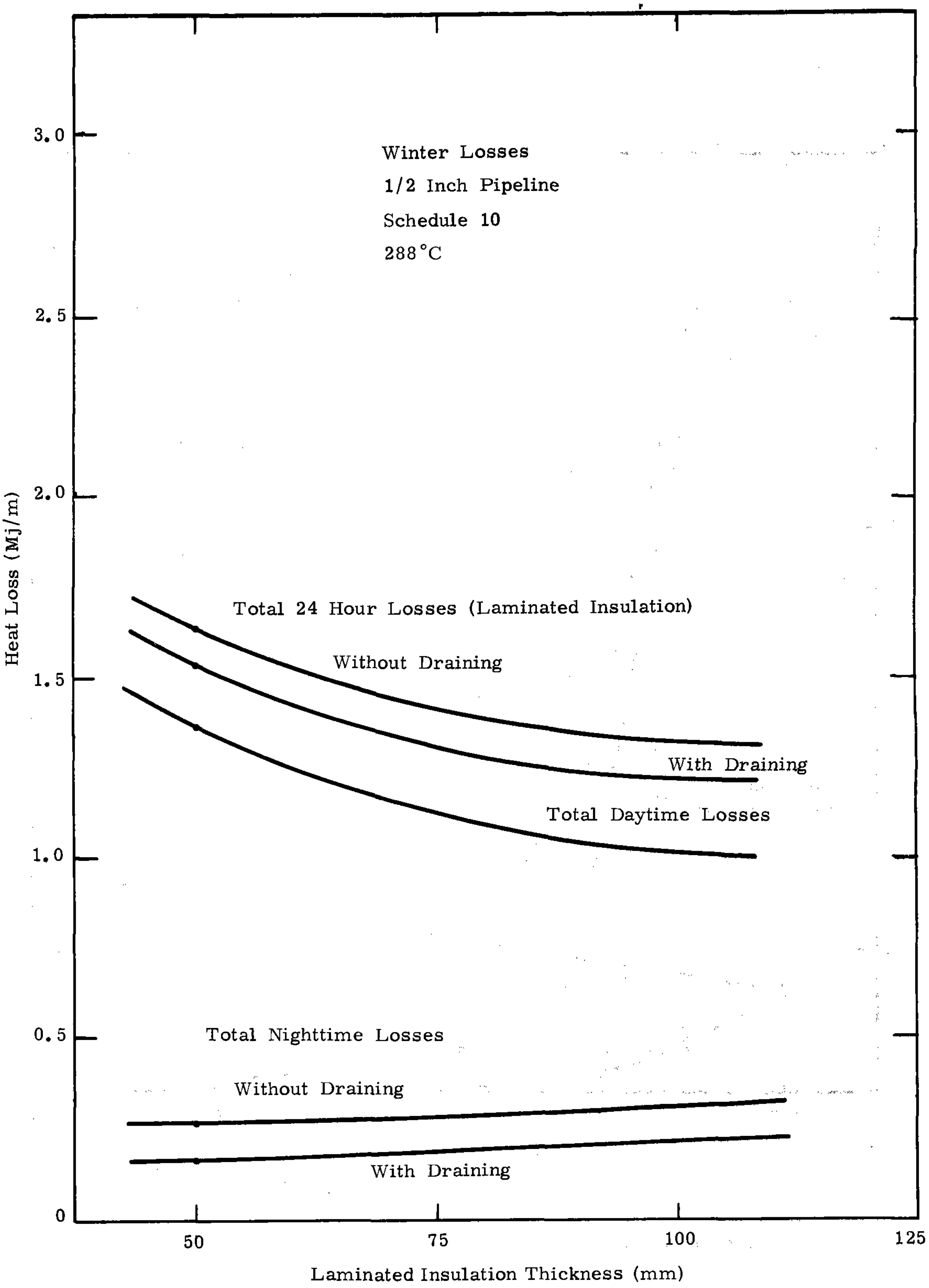


Figure 6. Winter pipeline losses

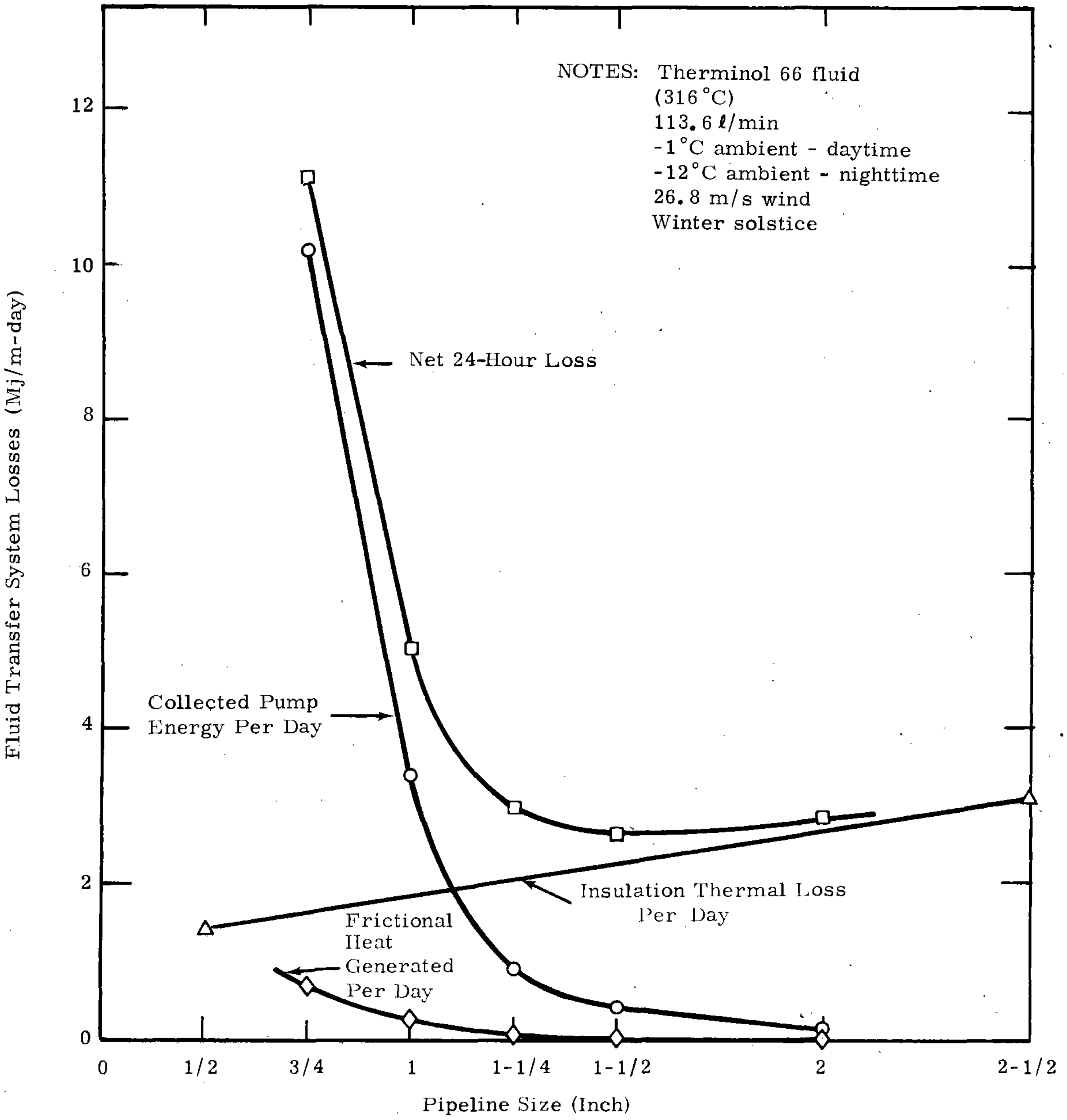


Figure 7. Fluid transfer losses versus pipeline diameter

As in the case of the collector field, the high-temperature storage capacity to be installed during Phase IV-A will be about 25 percent of the 3.7×10^6 kj described above. The tank to be used for Phase IV-A is an existing experimental system which has a volume capacity of 7570 liters (2000 gallons). The remainder of the high-temperature system will be installed during Phase IV-B.

Sufficient T-66 to operate our system has been procured and is being stored. The 7570-liter storage tank and related equipment has been ordered by Sandia Laboratories, Livermore with delivery expected the first of August.

A flywheel energy storage system is being investigated for use in the solar energy test facility. A flywheel has a potential advantage over sensible heat storage because the energy is stored after the efficiency losses of the turbine thermodynamic cycle have been incurred, therefore requiring much less storage capacity.

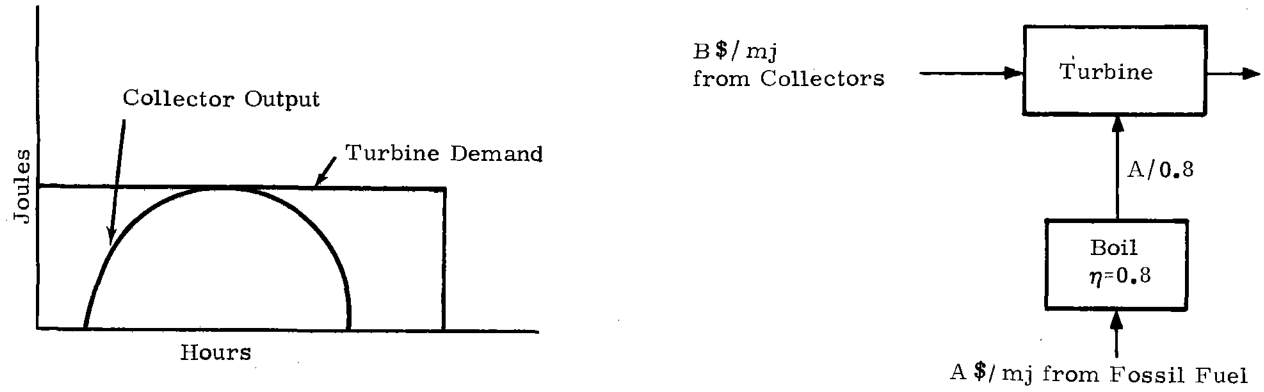
The effect of storage capacity on system cost for the Solar Project Building design has been analyzed. Storage allows the delayed use of some solar energy, but the energy delayed must bear the complete cost of storage. Figure 8 indicates the effect of storage on solar energy cost. From Figure 8.a, it can be seen that solar energy will be economical when solar energy costs, B, are less than fossil-fuel energy costs, A/0.8. Storage adds a cost penalty to the energy stored, S (Figure 8.b). This means the storage cost penalty, S, must be equal to or less than the difference between solar and fossil fuel costs (B - A/0.8) for storage to be economically attractive. However, economics is not the only consideration. Storage will always be required for maximum fossil fuel savings and as a buffer between collectors and system load. At present, it is felt desirable to maintain the large storage capacity specified on the baseline design in order to better evaluate methods and systems to decrease storage costs.

Task 5 - Turbine/Generator System

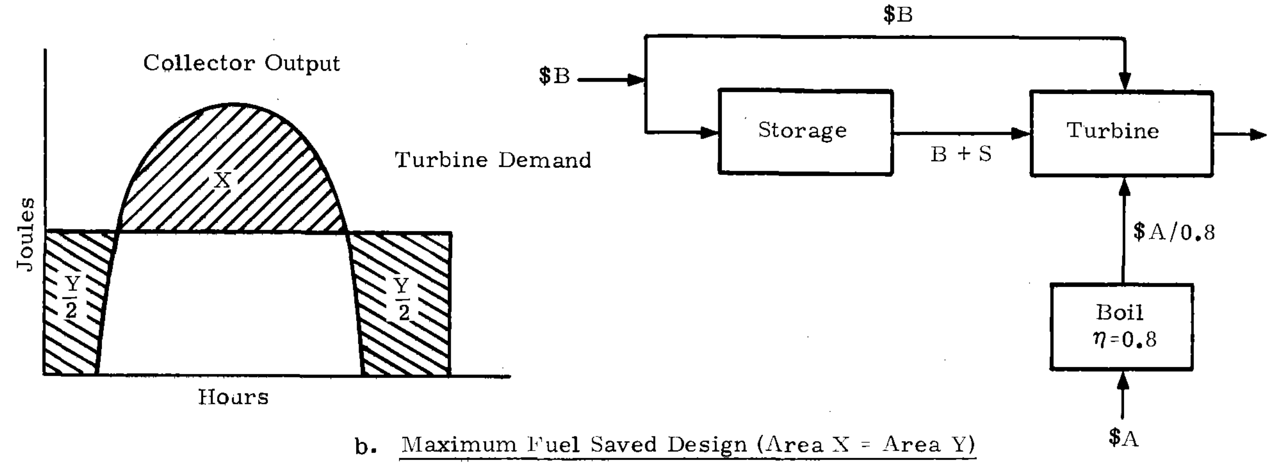
The turbine/generator, which operates on an organic Rankine cycle, uses toluene as the working fluid. Figure 9 is a temperature-entropy (T-S) diagram which illustrates the turbine/generator's operating Rankine cycle.

In operation, saturated toluene vapor from the boiler expands through the turbine and drives the generator to an electrical output of 32 kw. Superheated vapor leaves the turbine at 193°C (380°F) and passes through a regenerator where it is further cooled to a 74°C (165°F) saturated vapor.

The toluene vapor is then condensed at constant temperature; its heat of vaporization is imparted to the condenser cooling fluid (glycol/water) which becomes the energy source for the low-temperature portion of the system. The temperature rise in the condenser cooling fluid will be from 41°C (105°F) to 68°C (155°F) in the winter and from 77°C (170°F) to 88°C (190°F) in the summer. The liquid toluene is pumped from the condenser back through the regenerator where it is reheated to 157°C (315°F); it then reenters the boiler where a new cycle begins.



a. No Storage Design



b. Maximum Fuel Saved Design (Area X = Area Y)

Figure 8. Effect of storage on solar energy cost

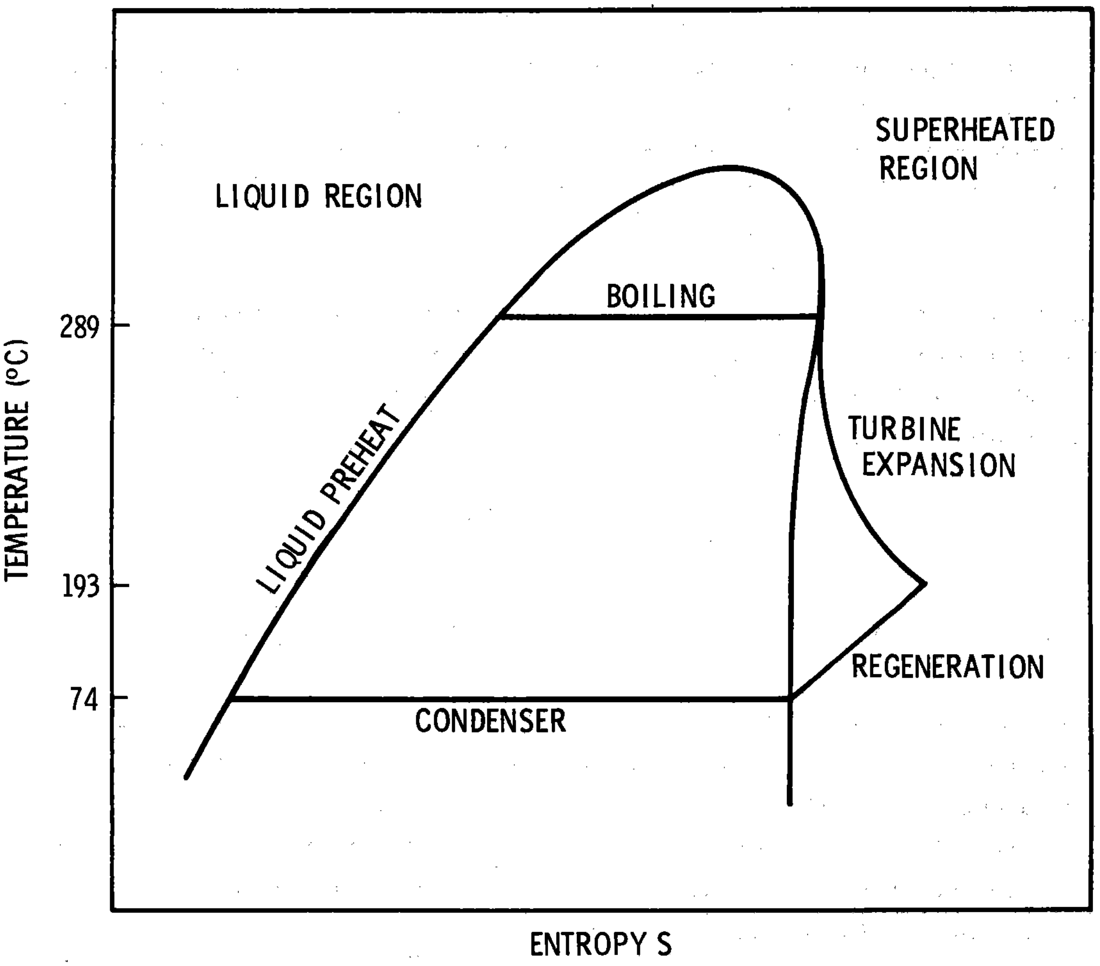


Figure 9. Baseline Rankine cycle T-S chart

The 40-kw(e) organic Rankine cycle (ORC) turbine/generator has been purchased from Sundstrand Aviation. It has not yet been physically delivered because the design modifications to meet the specific requirements of the system have not been completed.

The Rankine cycle shown in Figure 9 represents the baseline design. However, investigations into other cycles are continuing, and could result in major changes to the baseline design. Presently a superheated Rankine cycle is under investigation and is discussed below.

Generally, organic Rankine cycles are most efficient when the amount of superheat is minimized. This is true of the baseline system just discussed. However, the incorporation of small amounts of superheat into the cycle permit significant increases in the effectiveness of high-temperature storage by increasing the temperature drop of T-66 as it passes through the toluene boiler.

Figure 10 is a temperature-ENTHALPY chart which is a graphic representation of a heat balance in the toluene boiler. Only the portion of the Rankine cycle involved with heat addition and exchange in the boiler is represented. The straight lines 4, 5, 6 and E, F, G represent $\dot{m}\Delta H_{T-66}$ of T-66 as it passes through the boiler, where

$$\dot{m} = \frac{\text{mass flow rate of T-66}}{\text{mass flow rate of toluene}}$$

$$\Delta H_{T-66} = \text{change in enthalpy of T-66} = C_p \Delta T_{T-66} \, .$$

The dome-shaped curve represents the temperature-enthalpy characteristics of toluene. The numbered points on the figure represent the present, nonsuperheated toluene cycle. Path 1 to 2 represents heating of liquid toluene and 2 to 3, the boiling of toluene. Point 4 defines the starting point of line 4, 5, 6. Note that 4 is on the maximum storage temperature line and that 3 is on the maximum cycle temperature line. The difference between 3 and 4 is the temperature difference between the T-66 entering the boiler and the toluene leaving the boiler. Line 4, 5, 6 represents $\dot{m}C_p\Delta T$ of the T-66 as it passes through the boiler. In order for the boiler to operate the $\dot{m}C_p\Delta T$ line must not intersect the knee of the toluene line at Point 2. The enthalpy change from 4 to 6 is the same as from 1 to 3. The intersection of line 4, 5, 6 with line 1, 7 defines the ΔT experienced by T-66 as it passes through the boiler. This is equivalent to the ΔT in storage.

The lettered points represent superheating of the toluene. The process A to B is the heating of liquid toluene; B to C is the boiling of toluene; and C to D the superheating of toluene vapor. E defines the starting point of line E, F, G. Notice that line E, F, G misses the knee of the toluene curve at B by the same amount as the previous line 4, 5, 6 missed the knee at 2. The slope of E, F, G is much steeper; it intersects line 1, 7 at a much lower point, which indicates a much larger temperature drop, δT_s, in the T-66 through the boiler. Slight changes in the location of points 1 and A will occur as the amount of regeneration varies.

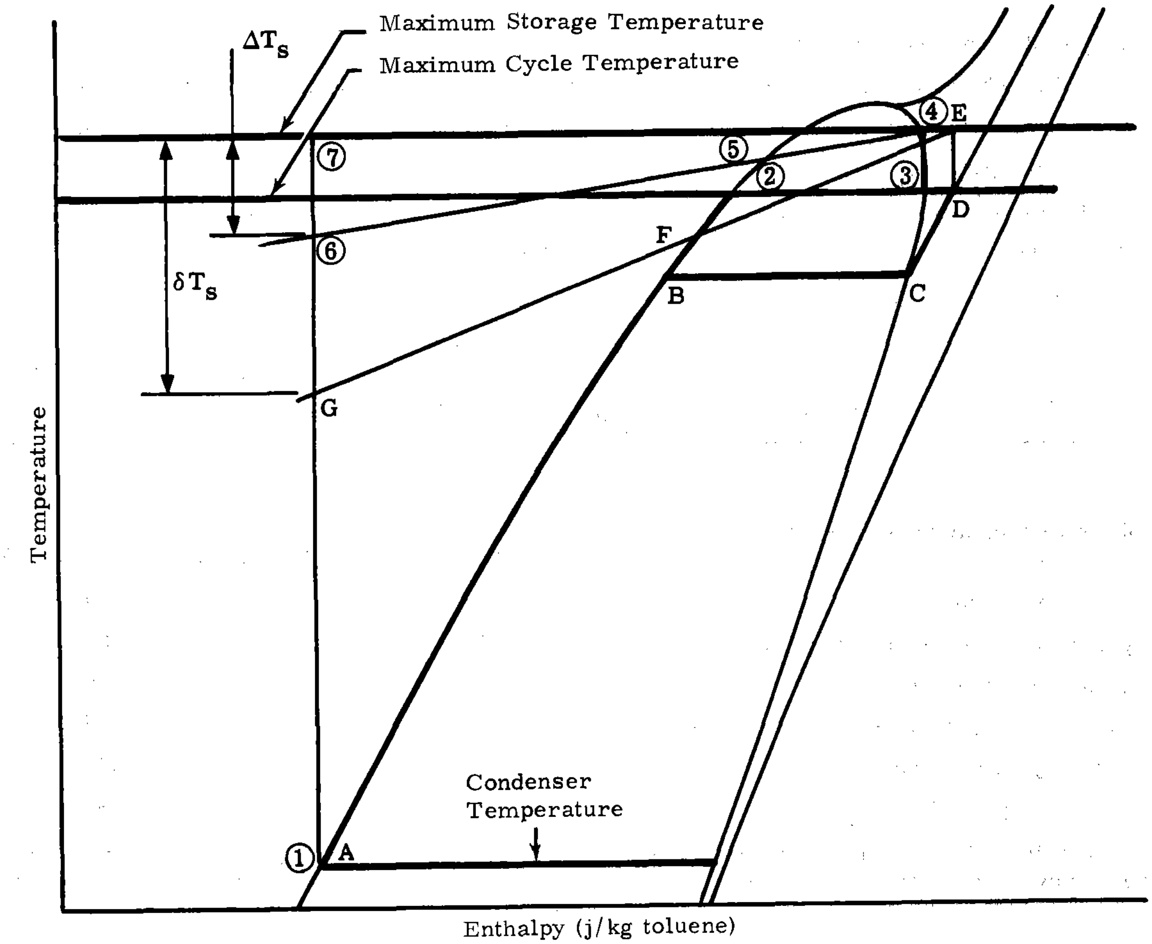


Figure 10. Toluene boiler heat balance

The increased temperature drop increases the effectiveness of storage:

Energy stored $Q = MC_p \Delta T_s$, where

M = mass of storage material (T-66)

C_p = specific heat of T-66

ΔT_s = temperature drop of T-66 in boiler

If ΔT_s is doubled and the desired value for Q is fixed, the required amount of storage fluid can be cut in half. The baseline design shows this ΔT to be 44°C (80°F) or the difference betwen 310°C and 266°C (590°F and 510°F); use of the superheat cycle would double the ΔT_s to 88°C (310°C to 222°C). It appears to be desirable to boil at 232°C (450°F) and superheat to 288°C (550°F) because the resulting reduction in storage size and cost offsets the reduction in cycle efficiency caused by superheating. Table I is a tabulation of cycle temperatures and efficiencies for various levels of superheat.

TABLE I

Toluene Rankine Cycles with Superheat 40 kw(e)*

	Superheat Conditions					
Boiling temperature °C/pressure kPa (abs)	304/3482	288/2813	260/1944	232/1282	204/806	177/476
Storage temperature (°C)	310	310	310	310	310	310
Superheater exit temperature (°C)	304	304	304	304	304	304
Degrees of superheat (°C)	0	17	44	72	100	128
Condenser temperature (°C)	74	74	74	74	74	74
Rankine cycle efficiency (%)	24.0	23.7	23.1	21.9	20.9	17.9
ΔT in storage (°C)	35	73	130	170	195	210

*These calculations are for a best-effort system, i.e., turbine efficiency = 80%, regenerator efficiency = 90%, generator efficiency = 90%, nozzle efficiency = 95%, and pump efficiency = 60%.

The storage and Rankine loop heater provides a fossil fuel energy source which will simulate the collector field output. The heater will be connected in such a way that the high-temperature storage tank and the toluene boiler can be heated simultaneously. Hot fluid can be supplied to the storage tank at a rate of 1.58×10^6 kj/hr (1.5×10^6 Btu/hr) and to the toluene boiler at 0.74×10^6 kj/hr. The heater will also be used to increase the temperature of the stored T-66 from ambient temperature to 310°C. The heating rate for this use will be 3.17×10^6 kj/hr.

The toluene boiler is used to transfer heat from the T-66 which has been stored in the high-temperature storage tank to the turbine working fluid, toluene. The toluene is heated from a 171°C (340°F) fluid to a 288°C (550°F) saturated vapor. This is the first step in the turbine/generator's Rankine cycle. At maximum load conditions, 0.70×10^6 kj/hr at a 44°C temperature drop will be extracted from the T-66.

The load bank will serve as a dummy load to simulate the electrical loads on the turbine/generator output for the Solar Power Building or other system configuration. The load bank has a capability of 32 kw(e).

Task 6 - Instrumentation and Control

The instrumentation and control system is designed to monitor the working fluid temperatures and fluid flow rates throughout the system and to maintain these at proper levels.

A secondary capability which is vital to the engineering test bed concept is that the performance of any portion of the installation can be calculated and displayed in real time and the data recorded for future use. Permanent records of performance can be teletype printouts, hard-copy printouts or graphs from the oscilloscope display, or data on magnetic tape.

Control of the solar total energy installation will be automated through a minicomputer. A control strategy will be programmed into the minicomputer so that, by monitoring instrumentation points throughout the system, the minicomputer can make decisions on the proper time to start and stop pumps and when to open, close, or change settings on valves, etc. Control strategy modification can easily be accomplished through program changes. Several control strategies can be preprogrammed and implemented immediately.

A minicomputer is not required simply to control the system. The concept is to be able to quickly change operating modes and control strategies, to find optimum modes and strategies, and to define the interrelationship of the various major components in the system (collector fluid, storage, turbine, etc.). Rapid analysis and optimization of performance should be enhanced by ease of changing set-points, operating modes, or control strategies.

The more important minicomputer peripherals will be:

- Teletype terminal for programming and for generating a hard-copy printout of operating-mode or performance data.
- Oscilloscope display for visual presentation and including a hard-copy capability.
- Digital magnetic tape recorder for compact permanent retention of data. The tape format will be compatible with the large scientific computer tape decks so that any of the data can be used to input the systems analysis program.
- Controls interface which, when commanded by the minicomputer, will monitor and change set-points, control power relays for pump and fan motors, and control on-off or variable position valves.
- Analog-to-digital converters on such instrumentation outputs as temperatures, flow rates, ambient air temperature, air speed, dew point, solar radiation input, control valve settings, switch positions, and turbine/generator output power.

Most of the minicomputer system for test control and data acquisition should be delivered during July. Parts of the system have been received including the teletype terminal, hard copy printer, magnetic tape recorder, and memory disc.

Task 7 - Collector Test Facility

An instrumented test facility designed for the evaluation of collectors is presently operational. This facility (Figures 11 and 12) consists of the fluid transfer and control hardware necessary to operate and test collectors. The facility enables measurements of collector performance by providing a means for controlling the input temperature and flow rate of the fluid and for monitoring the output temperature. Simultaneously, the intensity of the sun and other meteorological data are measured. The facility characteristics are as follows:

Fluids	Water to 232°C (450°F), 3448 kPa (500 psi) Heat transfer fluid to 343°C (650°F), 483 kPa (70 psi)
Flow Rates	0.38 to 38 lit/min (0.1 to 10 gpm) at 0.5% accuracy
Fluid Capacity	95 lit (25 gal)
Fluid Temperature Control ..	± 1/2°C of selected temperature
Heater Rate	3°C/min with T-66
Data	Temperature and flow rates recorded real time
Collector Cooling Capacity ..	1,055 to 63,300 kj/hr (1,000 to 60,000 Btu/hr)

A Hewlett-Packard 2116C minicomputer has been integrated with the instrumentation to provide for automated system control and data reduction. Printouts and graphical presentations can be made for all test results.

The facility is designed to obtain maximum versatility of collector testing. Long lengths of flexible hose have been provided so that other collectors can be installed with minimum effort. Instrumentation and control points are incorporated in the facility so that no collector modification is required for testing. The facility is available for other users as scheduling permits.

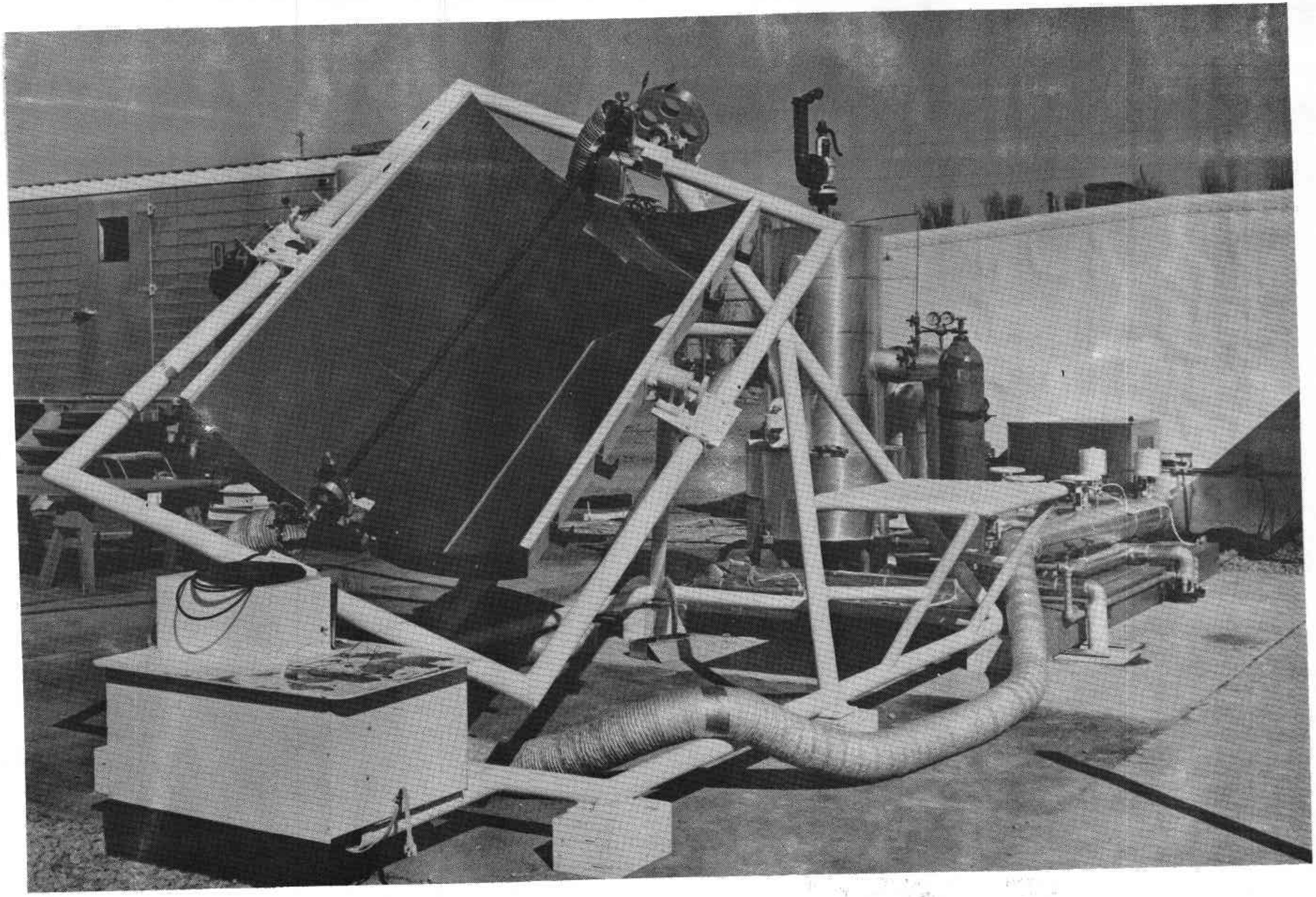


Figure 11. Collector evaluation facility

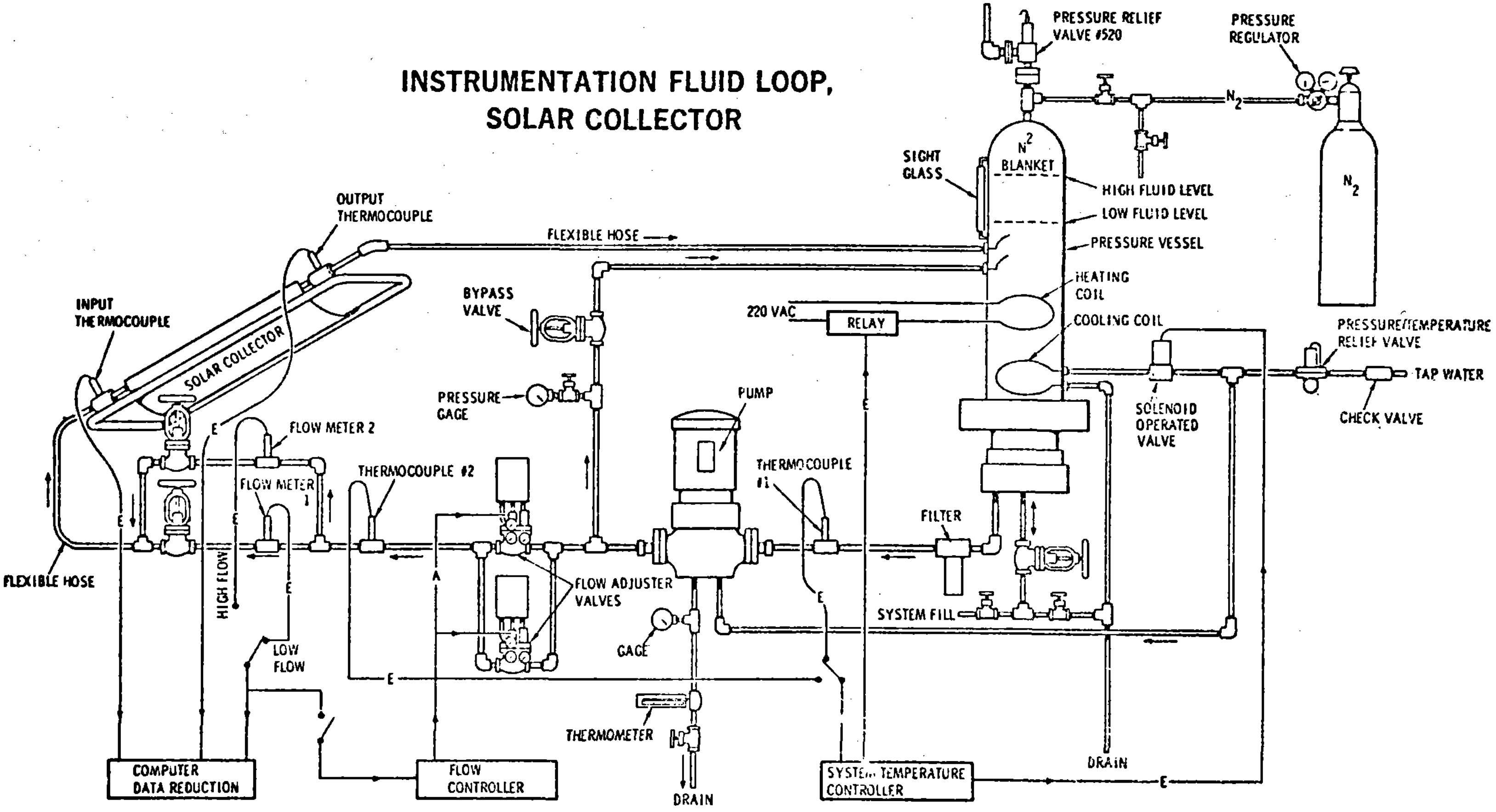


Figure 12. Collector evaluation facility schematic

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