A-1734

FINAL REPORT

PROJECT NO. A-1734

SOLAR POWER SYSTEM AND COMPONENT RESEARCH

DESIGN, CONSTRUCTION, CHECKOUT, AND SOLAR TESTING OF THE MARTIN MARIETTA-GEORGIA TECH BENCH MODEL SOLAR HEATED STEAM BOILER (GEORGIA INSTITUTE OF TECHNOLOGY EFFORT)

By

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ABSTRACT

Martin Marietta Corporation, Georgia Institute of Technology, and Centre Nationale de la Recherche Scientific (CNRS) have collaborated on the design, construction and testing of a one-megawatt, bench model, solar heated steam generator. This cavity-type natural circulation power boiler, designed to provide superheated steam at 8275 kPa (1200 psi) and 512° C (955° F) was engineered specifically for testing and evaluation at the French CNRS 1000 kW Solar Furnace located in the Pyrenees Mountains in Southern France.

After completion of the boiler in February 1976, it underwent a rigorous test program that consisted of cold flow tests at Martin Marietta, (Phase I), hot checkout at Sandia Labs' Radiant Heat Facility (Phase II) and solar performance tests in France (Phase III). Preparations were begun for a fourth test phase at the U. S. Solar Thermal Test Facility. Because of schedule changes at the new facility these tests have been postponed indefinitely.

This final report outlines Georgia Tech's contributions to all phases of the program. Separate reports will be issued by Martin Marietta Corporation and CNRS concerning their contribution to the program.

Georgia Tech had three basic areas of responsibility. One was to coordinate the experimental program at CNRS to ensure smooth interfacing of the bench model boiler with the 1000 kW solar furnace. This task necessitated the characterization of the facility, preparation of detailed interface drawings, and the design, construction and characterization of a large, water cooled flux redirector. A second area of responsibility concerned the thermal and pressure stresses of the boiler. This task involved the conduct of a thermal and pressure stress analysis of the boiler design to insure compliance with the ASME Boiler and Pressure Vessel Code, the placement of thermocouples and strain gages on the boiler, and the collection and interpretation of stress data during all test phases. A third area of responsibility was the conducting of a comprehensive water quality program to clean and maintain the water-side surfaces of the receiver. This task included the initial cleaning of the newly constructed receiver, the design and construction of a makeup water delivery system, the provision for sampling points at strategic locations within the boiler loop and the conducting of continuous chemical analysis of water quality during all tests.

This report also summarizes plans and preparations for the possible Phase IV testing of the receiver at the U. S. Solar Thermal Test Facility.

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I. INTRODUCTION

Martin Marietta Corporation, Georgia Institute of Technology and Centre Nationale de la Recherche Scientifique (CNRS) have collaborated on the design, construction and testing of a one-megawatt, bench model, solar heated power boiler. The boiler was designed as a cavity-type central receiver, but was engineered specifically for testing and evaluation at the 1000 kW Solar Furnace operated by CNRS, an agency of the French government. This facility, which is located in the Pyrenees Mountains in southern France, was at the time of the tests the only solar facility suitable for the testing of large scale solar equipment. CNRS collaborated in the testing phase of the program.

After its completion in February 1976, the boiler underwent a rigorous test program that consisted of cold flow tests at Martin Marietta, Denver Division (Phase I), hot checkout at Sandia Labs' Radiant Heat Facility (Phase II) and solar performance tests in France (Phase III). Preparations were begun for a fourth test phase at the U. S. Solar Thermal Test Facility operated by Sandia Labs in Albuquerque. Because of schedule changes at the new facility, however, these tests have been postponed indefinitely.

Georgia Tech had three basic areas of responsibility during this project. One was to coordinate the experimental program at CNRS to ensure smooth interfacing of the bench model boiler with the 1000 kW solar furnace. This first task necessitated a characterization of the facility and the preparation of detailed interface drawings. A second area of responsibility concerned the thermal and pressure stresses of the boiler. This task involved the conduct of a thermal and pressure stress analyses of the boiler design to insure compliance with the ASME Boiler and Pressure Vessel Code; the placement of

thermocouples and strain gages on the boiler; and the collection and interpretation of stress data during all the test phases. A third area of responsibility was the conduct of a comprehensive water quality program to clean and maintain the water-side surfaces of the receiver. This task included the initial cleaning of the newly constructed receiver, the design and construction of a makeup water delivery system, the provision for sampling points at strategic locations within the boiler loop and the conducting of continuous chemical analysis of water quality during all tests.

The activities undertaken to support each of these three general areas of responsibility will be summarized in Chapters II, III and IV, respectively. All are described in greater detail in Quarterly Reports 1-6 for D.O.E. Contract No. E-(40-1)-4921 and Semi-Annual Report No. 2 (Quarterly Reports 7 and 8) for D.O.E. Contract No. EY-76-S-05-4921. Conclusions will be discussed in Chapter V.

II. INTERFACE BETWEEN THE BENCH MODEL RECEIVER AND THE CNRS FACILITY

Before the 1 MW bench model receiver could be tested at the French Solar Furnace, Georgia Tech had to characterize the relationship between the receiver and the solar facility, and make necessary preparations to ensure a proper interface between the test facility and the test object.

A. Basic Description

The CNRS facility consists of 63 heliostats positioned on eight terraces of a hillside and facing a parabolic concentrating mirror on the north side of the laboratory building. The concentrating mirror, which measures 54 m wide x 40 m high, redirects the sunlight onto a target area in the focal building, where test apparatus can be mounted for irradiation. The facility is shown schematically in Figure 1. The parabolic concentrator is shown in Figure 2. Test equipment can be situated on a platform in the focal building, and support equipment may be installed in a work area below this test platform. The focal building also houses freight and personnel elevators, a machine shop, and a control room for the heliostats.

Each of the 63 heliostats consists of 180 back-silvered glass facets, 50 cm square, mounted flat on a tracking structure. The tracking structures are driven hydraulically and controlled electronically, with an accuracy of $\pm$ 1 minute of arc. The heliostat field as seen from the heliostat control area is pictured in Figure 3.

B. Flux Redirector

The radiation at the focal point of the CNRS Furnace subtends an angle from 40 degrees below the horizontal to 74 degrees above the horizontal. By

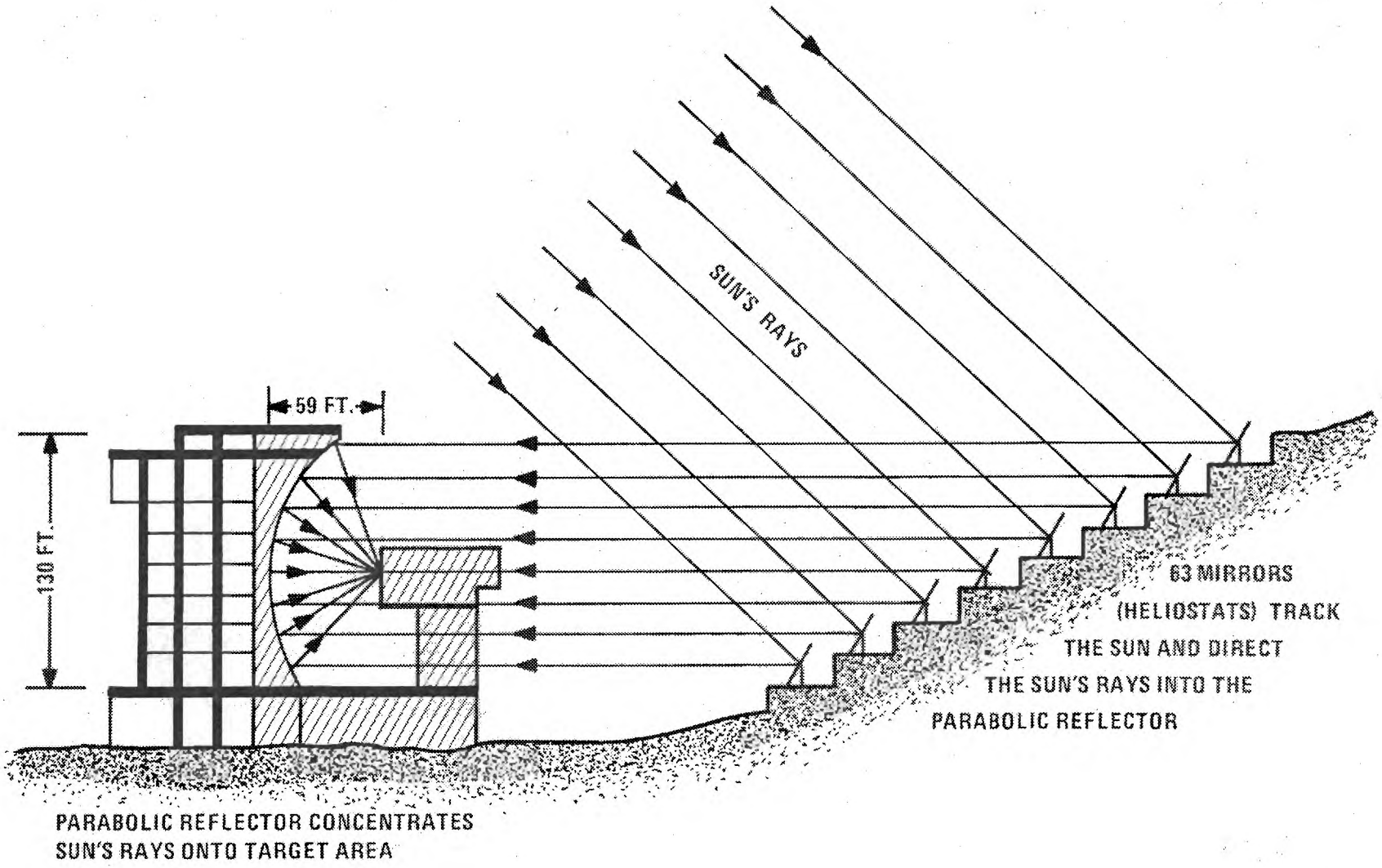

Figure 1. Schematic of the CNRS 1000 kW Solar Furnace.

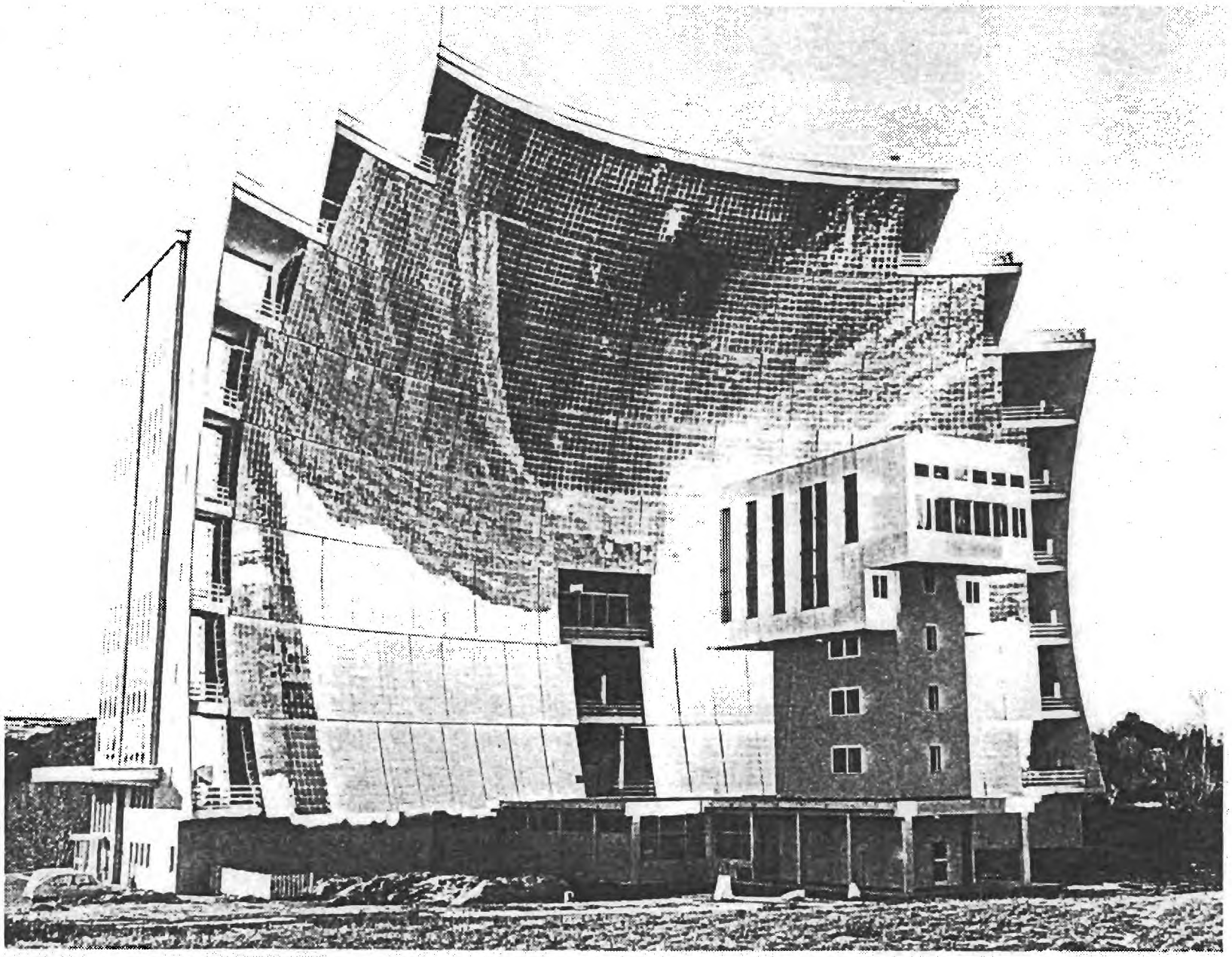

Figure 2. CNRS Laboratory, Parabolic Concentrator and Focal Building.

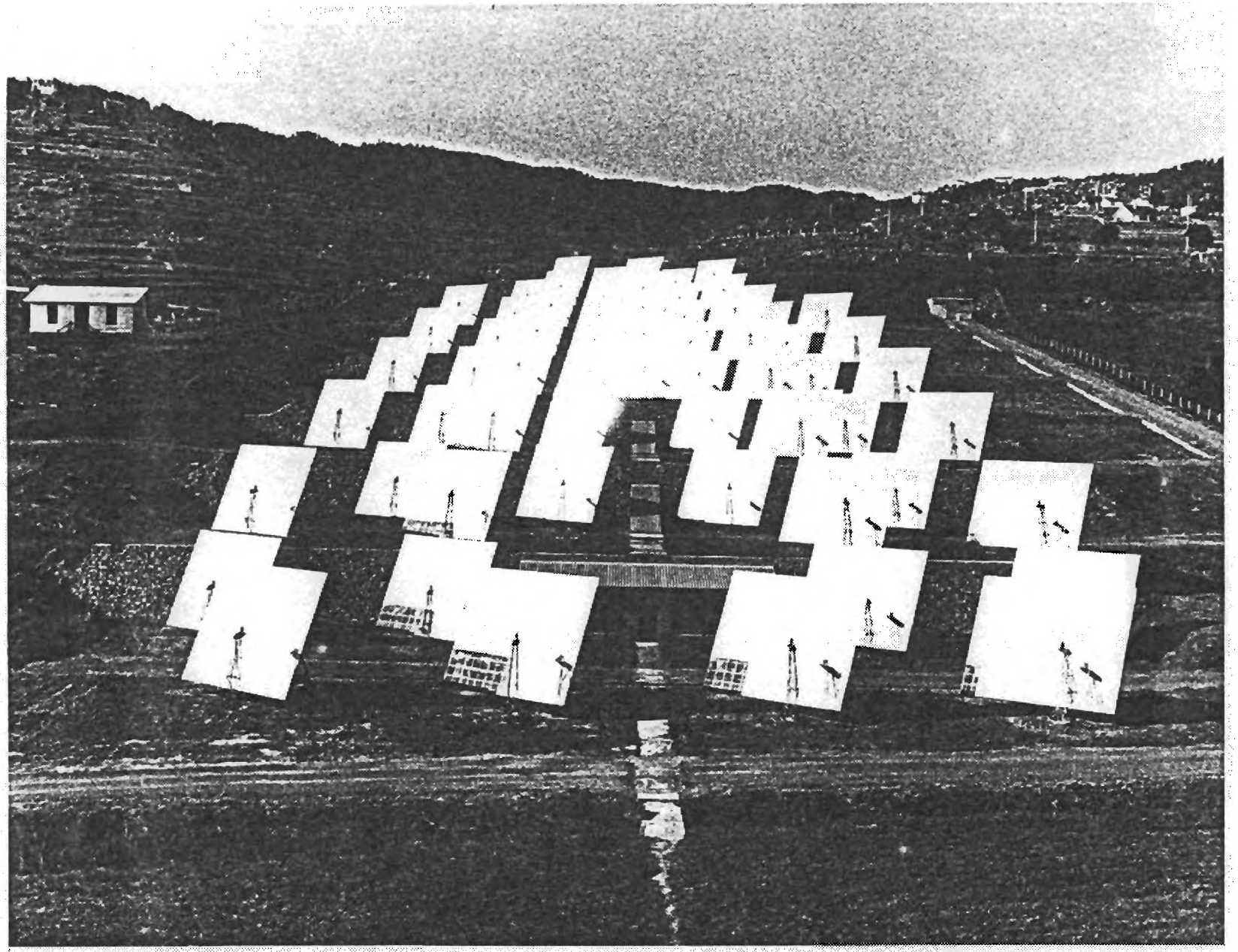

Figure 3. CNRS Heliostat Field As Seen From the Heliostat Control Room.

contrast, the 1 MW bench model receiver was designed for conventional northward facing central receiver solar stations where the viewing angle is expected to be 90 degrees (± 45 degrees). Thus, one of the first requirements to adapt the boiler to the test facility was the construction of a water-cooled flux redirector to intercept the wide angle CNRS radiation and reflect it into the boiler cavity at more suitable angles.

To accomplish this task, Georgia Tech designed and built a flux redirector. It is a truncated cone, with a base diameter of 40.2 inches, half angle of approximately 10 degrees and height of almost 20 inches. Figure 4 shows the relationship of the cone to the boiler. The cone substrate was copper, which was trued and polished, then plated with nickel, repolished and finally given a coating of BERAL* by vacuum evaporation. The finished mirror, shown in Figure 5, had a reflectivity of 85 to 87 percent.

During the solar test this flux redirector performed satisfactorily, and the temperature of its reflective surface never rose above 70° C. The reflectivity of the surface did diminish to around 82 percent during the test program because of outgassing of organics from the receiver during the first few hot tests and also because of fouling by insects attracted to the bright region.

C. Flux Characterization

A second piece of equipment essential prior to the actual tests in France was a dummy cavity receiver, of the same size and shape as the actual receiver. It was used both to characterize the radiation distribution to be experienced by the actual receiver and to determine the location of the radiation from

*Trade name of material developed by Dudley Le Roy Clausing Co., Skokie, Illinois.

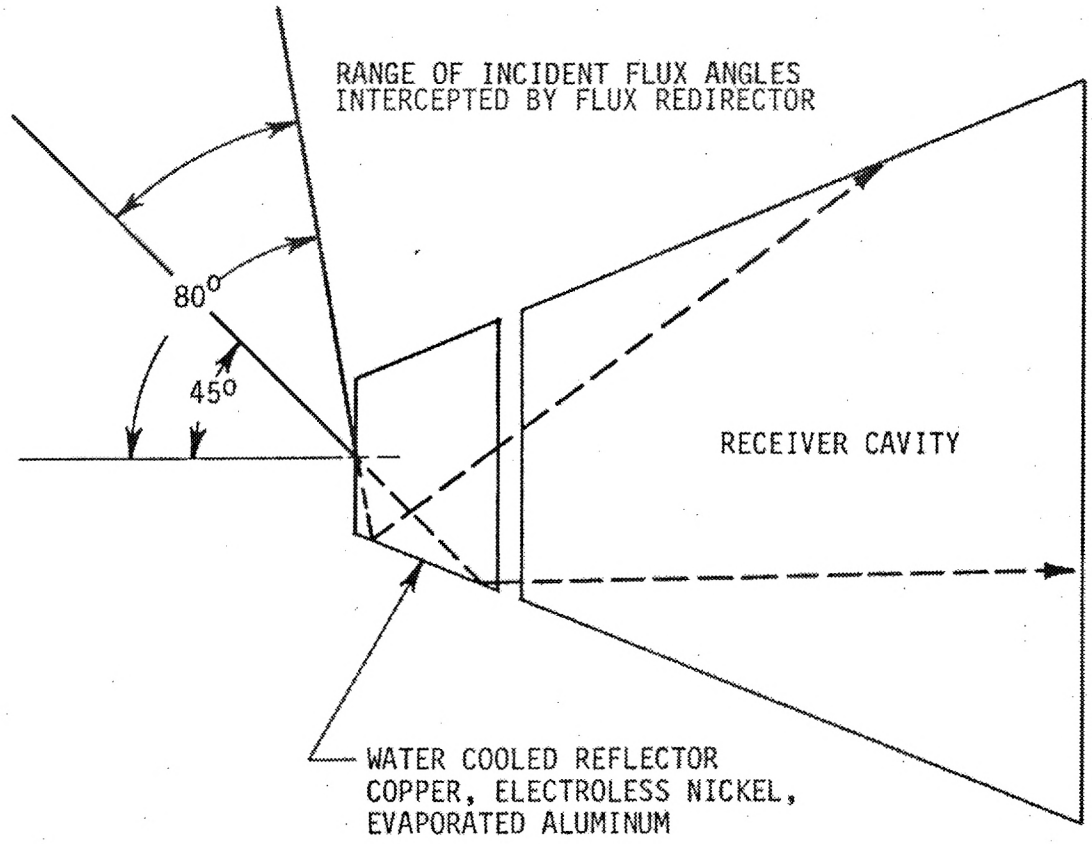

Figure 4. Flux Redirector Concept for Bench Model Receiver.

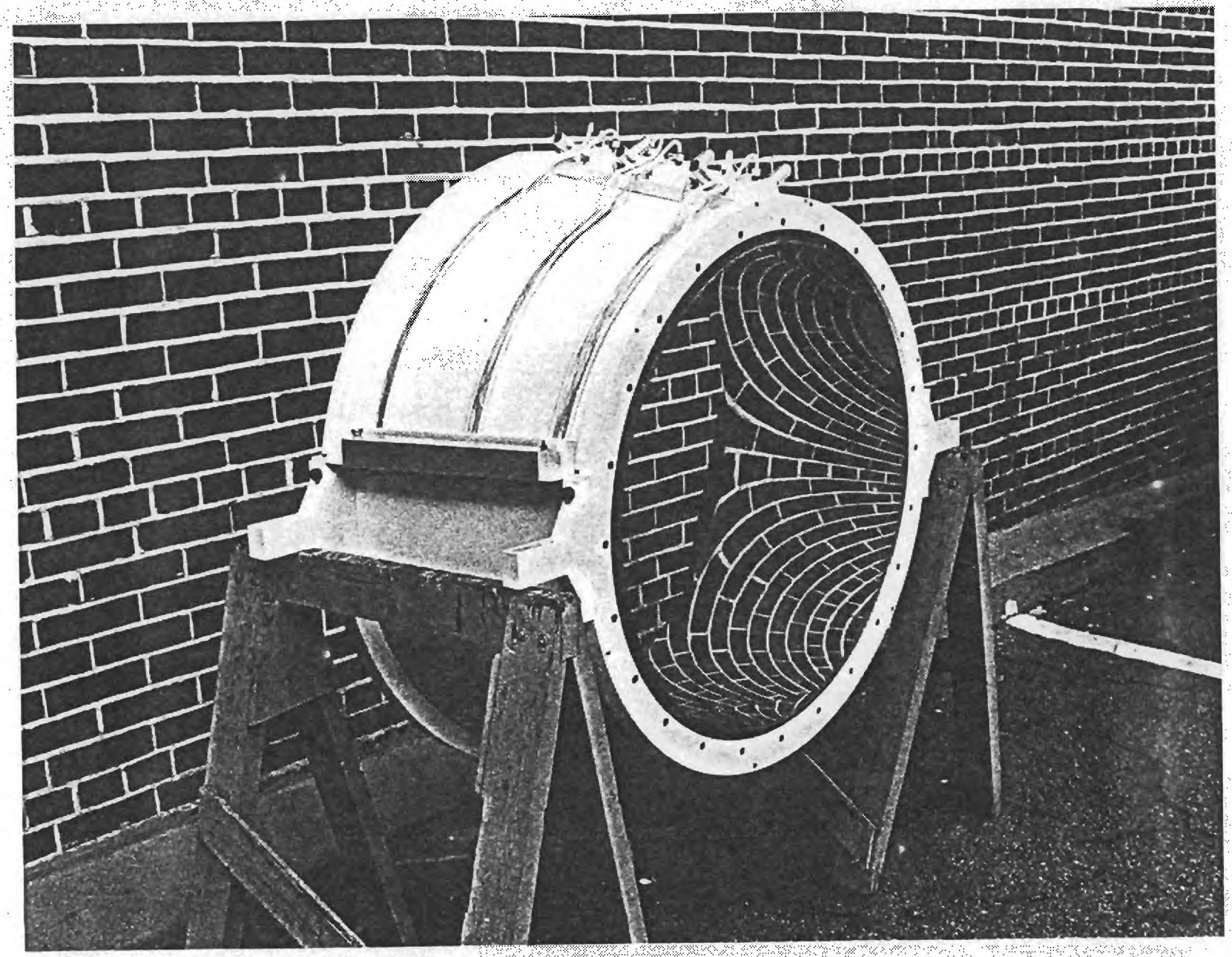

Figure 5. Completed Bench Model Flux Redirector.

each individual heliostat within the CNRS field. The dummy cavity built for these purposes is shown in Figure 6. Its surfaces were coated with the same high absorptivity black paint used to coat the tubes of the real receiver.

A third piece of equipment designed for the tests in France was an emergency shutdown shutter capable of closing within 1 to 3 seconds. The focal room doors at the CNRS Solar Furnace require 1 minute to open or close.

A team from Georgia Tech tested both the flux redirector and the dummy cavity in France in November/December 1975. The first series of tests were used to characterize the flux environment within the cavity. Four heat flux calorimeters were magnetically attached to the walls of the cavity and exposed to the radiation for several seconds at a time (response time for the Gardon-gage type calorimeters* used was typically less than 200 msec). These four calorimeters were successively moved to different locations within the cavity until a total of 216 data points had been obtained. Figure 7 illustrates the equipment and technique. The data were normalized to an insolation of 1000 watts/meter^2 with the aid of CNRS insolation monitoring equipment and a fifth water-cooled reference calorimeter.

The measured flux data were used both to generate flux contour maps (see for example, Figure 8) and to determine the integrated flux on each wall of the receiver. The results were valuable input in designing the cavity, in deciding where to place strain gages and in comparing calculated flux distribution with the experimental data.

Once the flux distribution had been characterized, the dummy cavity was used to help determine the location within the cavity of the radiation from

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*Obtained from Hy Cal Engineering Company, Santa Fe Springs, California.

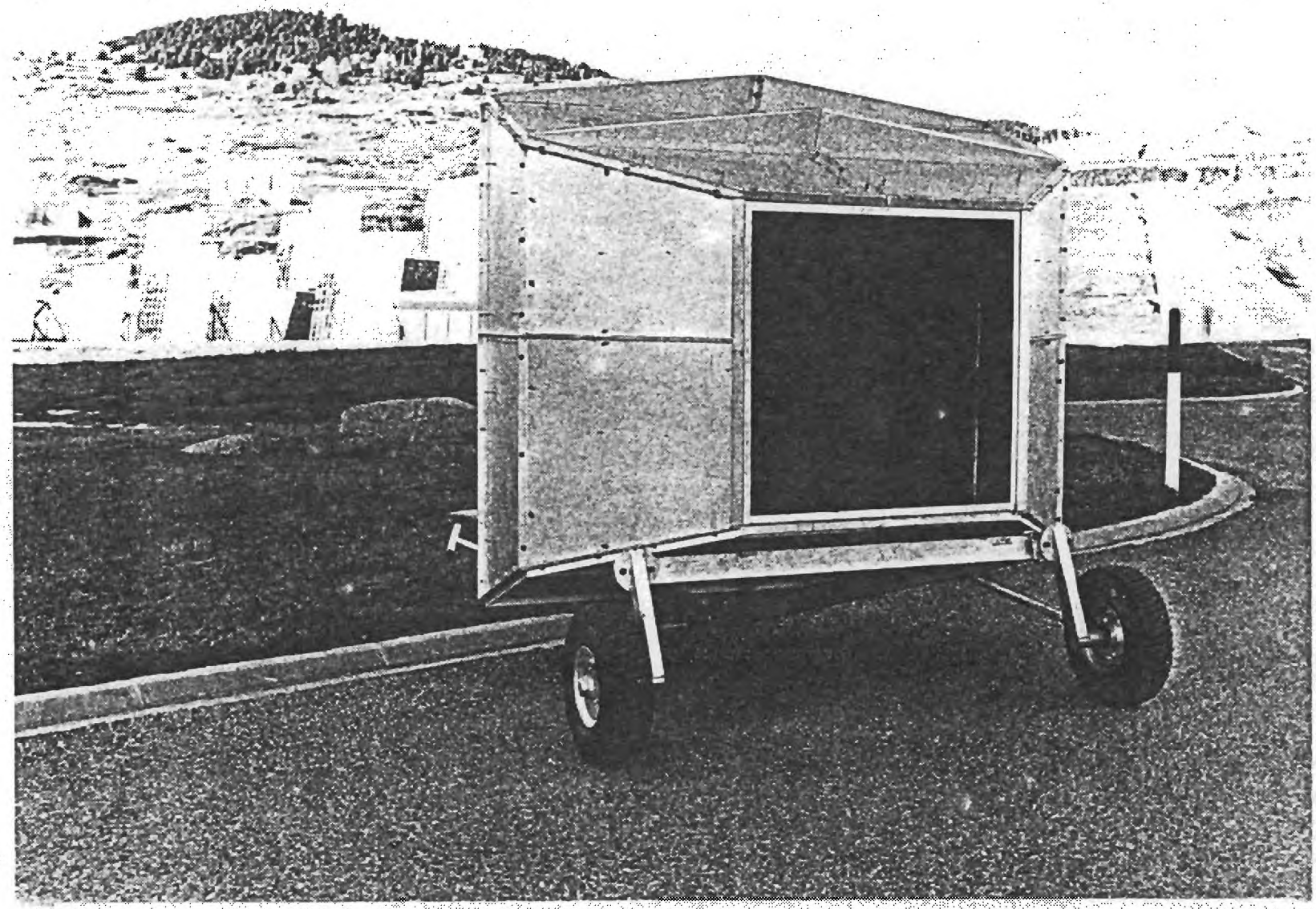


Figure 6. Dummy Cavity Receiver Used in CNRS Flux Mapping Project.

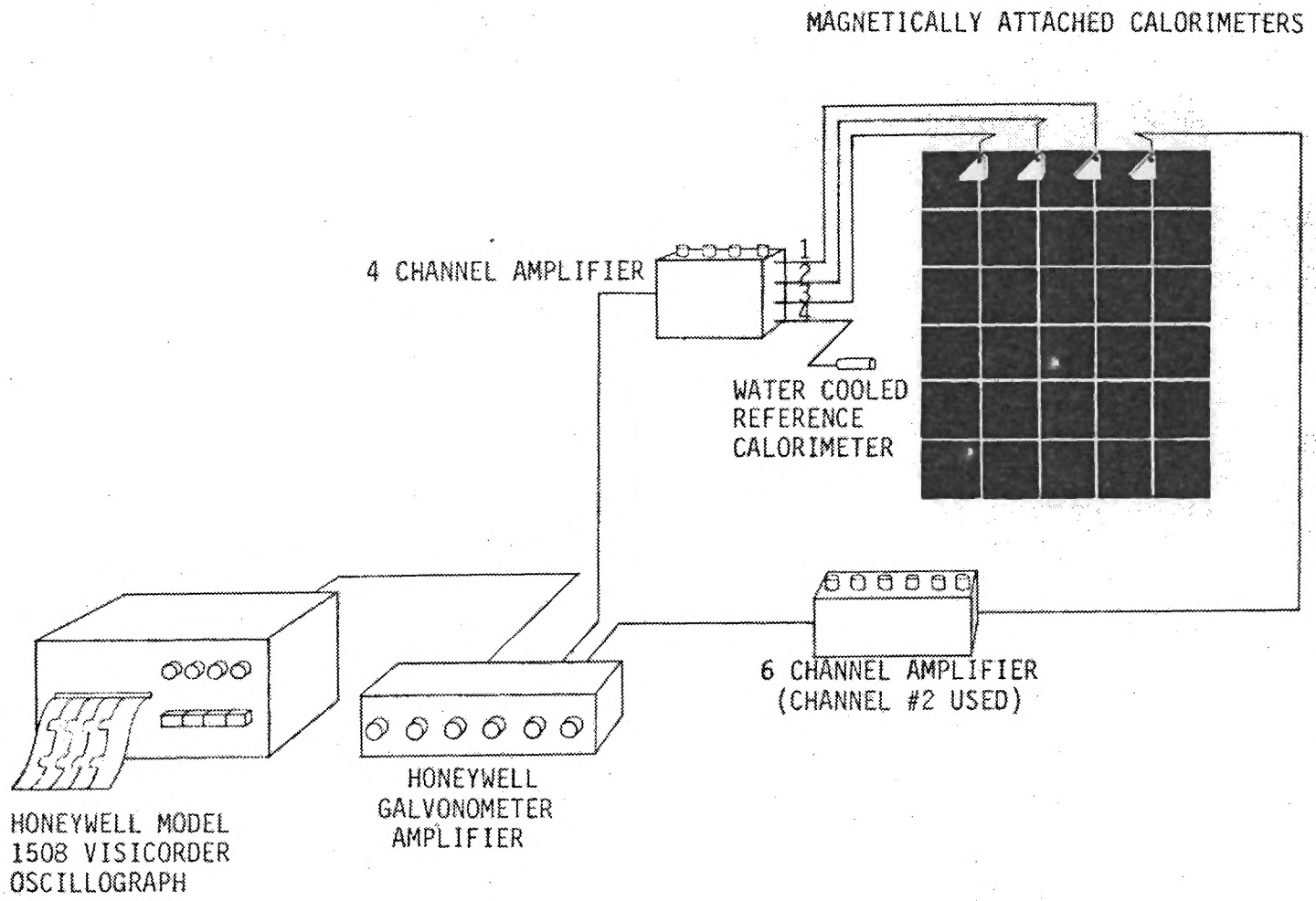
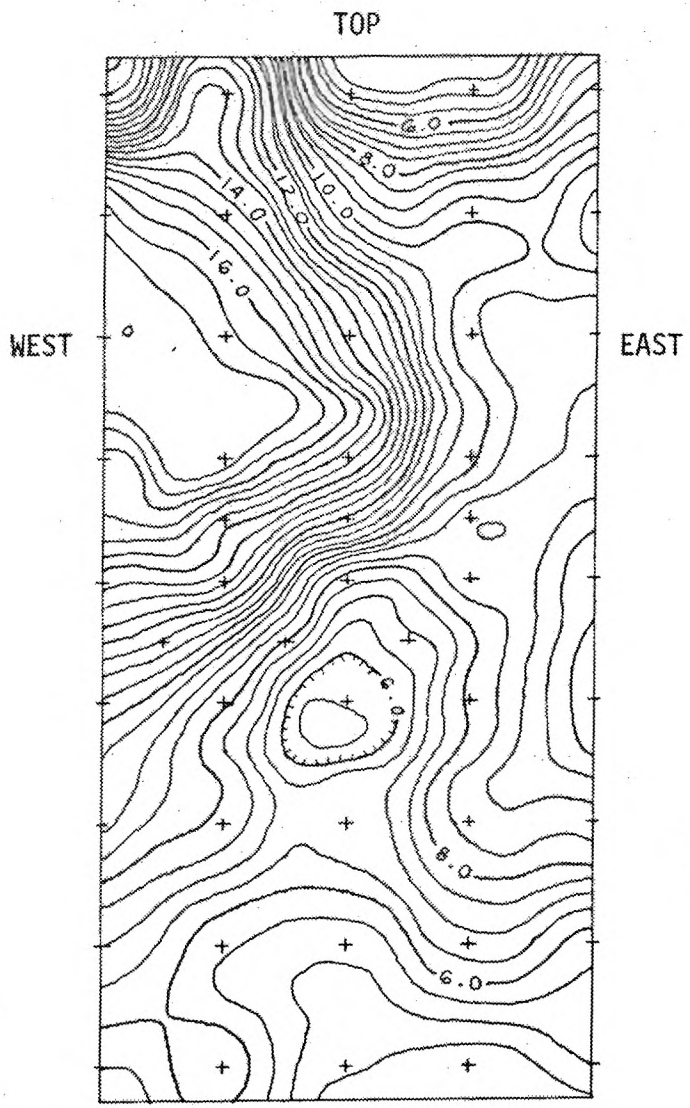


Figure 7. Schematic of Equipment and Technique Used to Collect Incident Heat Flux Data in Dummy Cavity.



Flux units are watts/cm^2.

Data normalized to insolation of 1000 w/m^2.

Figure 8. Contour Map of Rear Superheater Heat Flux.

each individual heliostat. For this purpose the inner walls of the cavity had been marked with a grid and the front panels were removed for easy observation (see Figure 9). The location of each beam was identified visually and photographically. This information enabled the formulation of a start-up procedure for shining radiation gradually onto different sections of the receiver, beginning with the preheater section and ending with the superheater.

In addition to the designing and building of the flux redirector and dummy cavity, Georgia Tech also prepared detailed interface drawings in preparation for the Phase III test.

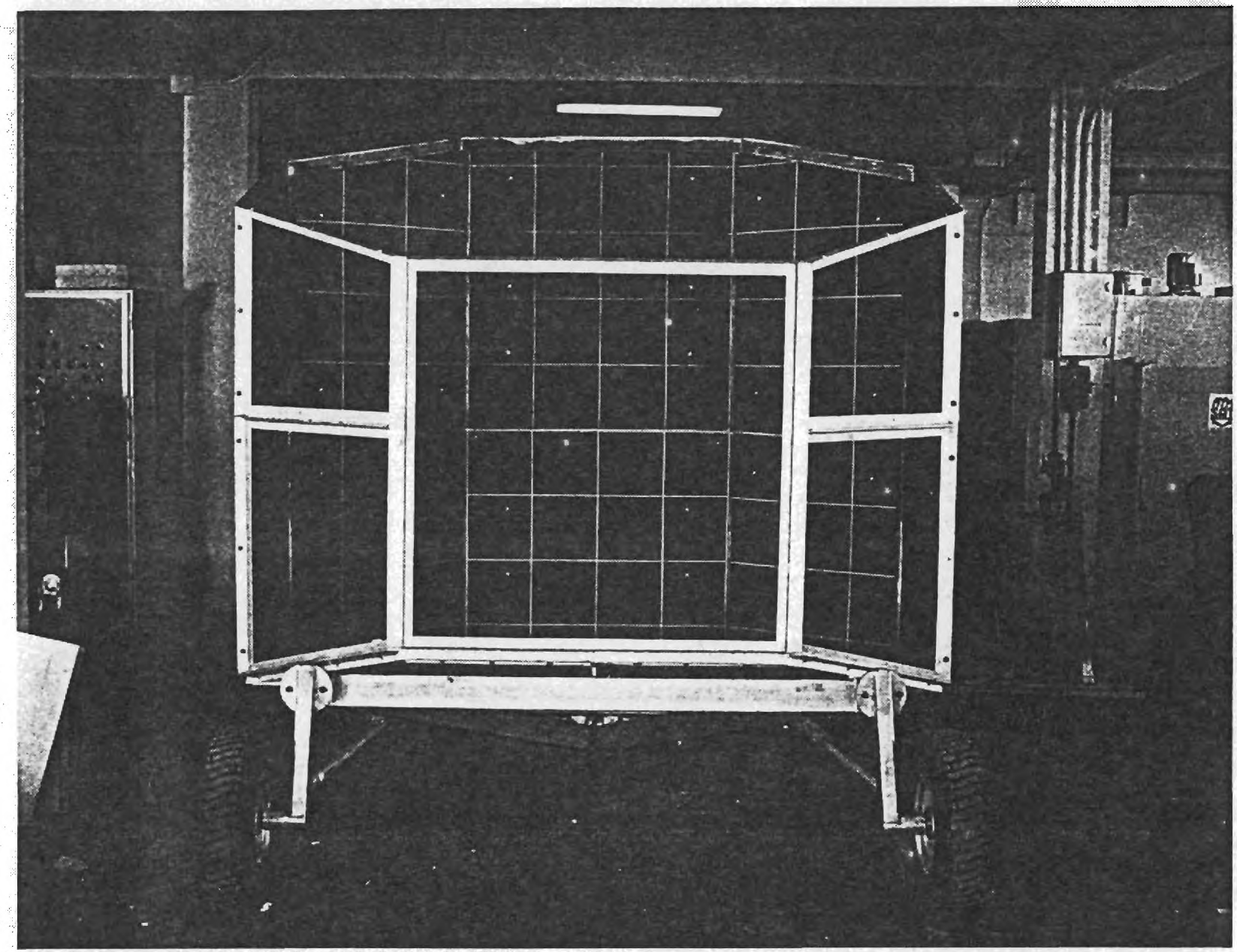


Figure 9. Dummy Cavity Receiver - Top and Front Panels Removed.

III. THERMAL AND PRESSURE STRESS ANALYSIS

A. Calculated Stresses

One important aspect of the Martin Marietta-Georgia Tech program was to study the thermal stresses that were predicted to occur in the asymmetrically heated tubes during the cyclic operations of solar boilers. Georgia Tech studied such stresses both analytically and experimentally.

The first step was to develop several heat transfer/thermal stress analysis computer codes to calculate thermal stresses in asymmetrically heated tubes. These programs were used to certify the acceptability of the bench model receiver boiler and superheater tubes, in accordance with the criteria of Sections I and VIII of the ASME Boiler Code.*

B. Measured Stresses

These computer models were used together with the empirical characterization of the cavity radiation to help select those points on the receiver where it would be most instructive and most critical to observe the stresses. Before the Phase II hot checkout at Sandia Labs Radiant Heat Facility, twenty-seven high temperature electrical resistance strain gages** and their accompanying thermocouples were attached to the boiler. These gages were all uniaxial and most were placed on the back sides of the tubes in order to be shielded from the direct radiation. The computer codes helped provide the extrapolation from observed stress on the back side of the boiler tubes to the probable stress on the front surface.

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*ASME Boiler and Pressure Vessel Code, Division 2, 1971 Edition, The American Society of Mechanical Engineers, New York, N. Y.

** Purchased from AILTECH Co., City of Industry, California.

The Phase II hot checkout of the bench model receiver was conducted at the Sandia Labs Radiant Heat facility from April 5 to April 29, 1976. The radiation environment to be expected at CNRS was simulated by arrays of quartz lamps within the cavity. During these tests, thermal and pressure stress data were collected at one minute intervals. The range of stresses measured was well within that allowed by the ASME Boiler Code. The data and the detailed results were reported in Quarterly Report No. 4, Solar Power System and Component Research, Project No. A-1734-001 and were also forwarded to Martin Marietta.

The same gages and thermocouples were used to monitor stresses during the Phase III tests at the CNRS Solar Furnace from June 25 through August 11, 1976. These results are described in Semi-Annual Report No. 1 (Quarterly Reports 5 and 6), Solar Power System and Component Research, Project A-1734-001. During the tests, all strain gages and thermocouples were continuously monitored, and scanned and recorded at 10 minute intervals. The data were fed off line to a Hewlett Packard 9820A calculator which was programmed to plot the data on a 9862A Plotter. The output represented the strain corrected for apparent strain caused by temperature. Zero strain values were established for each gage before the first solar test, but later redetermined to correct for changes probably caused by strain relieving after the shipment to France.

Design stress calculations for the bench model receiver were made using assumptions which represented "worst case" conditions. The stresses determined from strain measurements during the Phase III tests were lower than the calculated stresses and verified the basic conservatism of the

approach. It must be recognized, however, that the design was based on the assumption of a relatively short service life. Long life under cyclic operational conditions was not considered in detail. Therefore, specific structural problems associated with long life have not been identified.

Long term structural problems which may exist in the design of solar receivers can best be identified by the accumulation of operational experience with prototype design. During the Phase III testing of the bench model receiver, nothing was revealed which would indicate specific problems associated with the solar environment. Therefore, it is felt that future structural problems in solar receivers can be solved by good conventional design practice. The one area which does need clarification is that of materials properties and behavior at the higher design temperatures.

Thus, it is felt that structural analysis and the monitoring and evaluation of structural behavior during tests should be an integral part of all future solar receiver development.

C. Modifications for Future Tests

Throughout the solar tests in France, the data collection system functioned properly and yielded valuable information. Nevertheless, experience with this system underscored two general limitations: The first was its failure to display reduced data in real time. Such a capability is necessary to insure the safe operation of all equipment and to understand better the stimulus-response relationship of the boiler components.

Another shortcoming of the data collection system was the limited quantity and frequency of data that could be sampled. The measurements gave a general picture of the strain within some receiver components, but were not

sufficiently detailed to allow the prediction of the fatigue life associated with them. This very desirable analysis can be undertaken if detailed stress cycle and stress amplitude data can be collected.

These limitations of the data collection system could be overcome with an on-line computer. In preparation for the Phase IV tests, Georgia Tech adapted a computerized data acquisition system to support the program. The system consists of a 16-K word PDP 8/a* minicomputer, 104 channels of multiplexed A-to-D, a graphics terminal to allow real time display of data, two disk-type mass storage devices, a hard copy terminal, 40 channels of strain gage bridge completion circuitry and 52 channels of thermocouple signal conditioning circuitry. The system is shown schematically in Figure 10 and pictorially in Figure 11. The system is owned by Georgia Tech.

Input to the system would be in the form of analog electrical signals from strain gages, thermocouples, and possibly several pneumatic to voltage transducers. The digitized raw data was to be stored on magnetic disk so that further analysis such as fatigue studies could be performed off line. The data was to be simultaneously converted to engineering units and displayed on the video terminal. Specifically, the video display terminal would plot such parameters as temperature and strain as a function of real time. Four channels could be viewed simultaneously on the screen. Figure 12 presents a sample display of temperature as a function of time for four thermocouples in an oven which was rapidly heated and then allowed to cool.

Under normal conditions, the video display could be refreshed with four new data channels every N seconds, where N is specified by the operator. This "page-up" process could be stopped at any time to allow the operator to

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*Digital Equipment Corporation, Maynard, Mass.

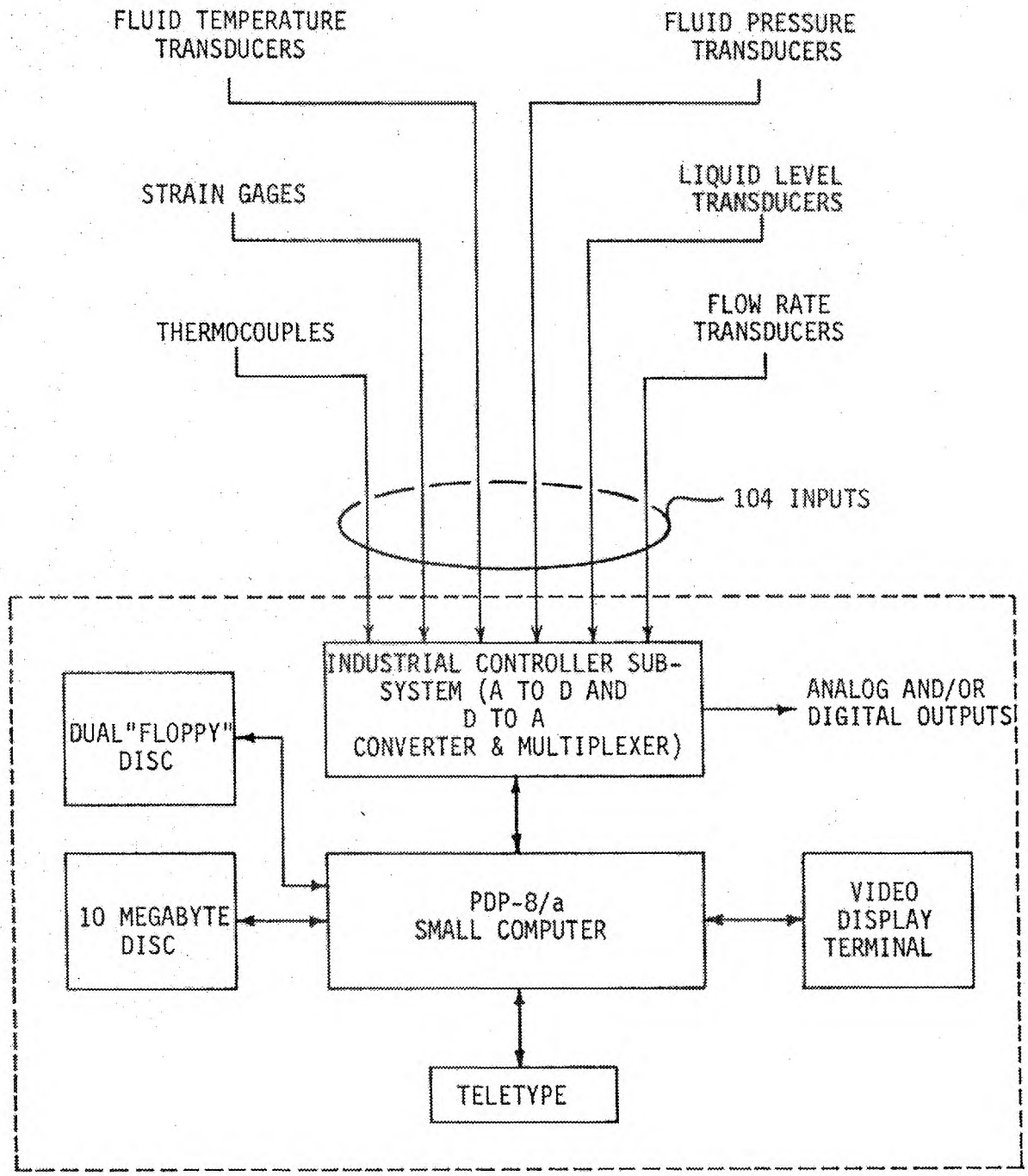

Figure 10. Schematic Diagram of Computerized Data Acquisition System.

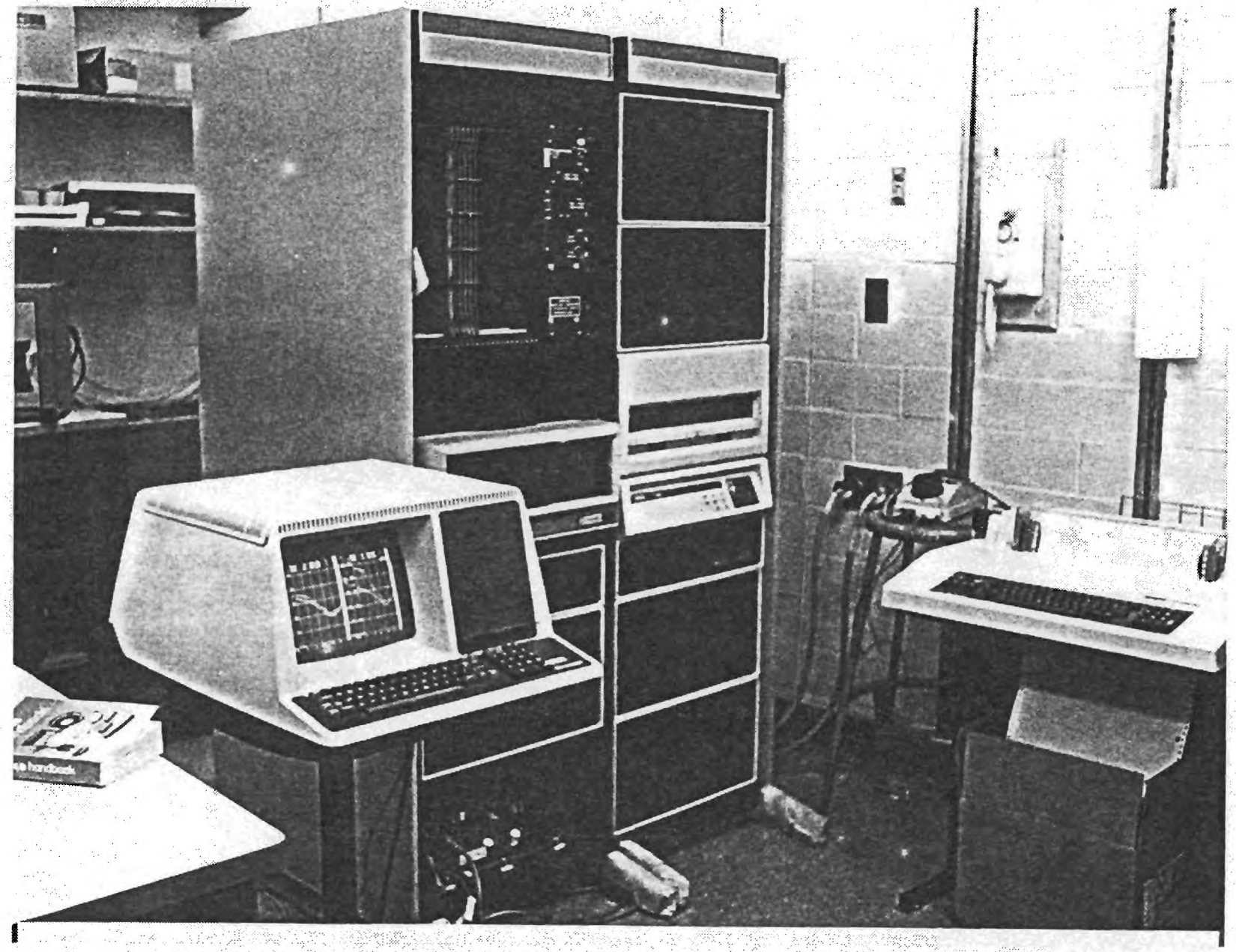

Figure 11. Georgia Tech Computerized Data Acquisition System to be Used in the Phase IV Bench Model Solar Tests.

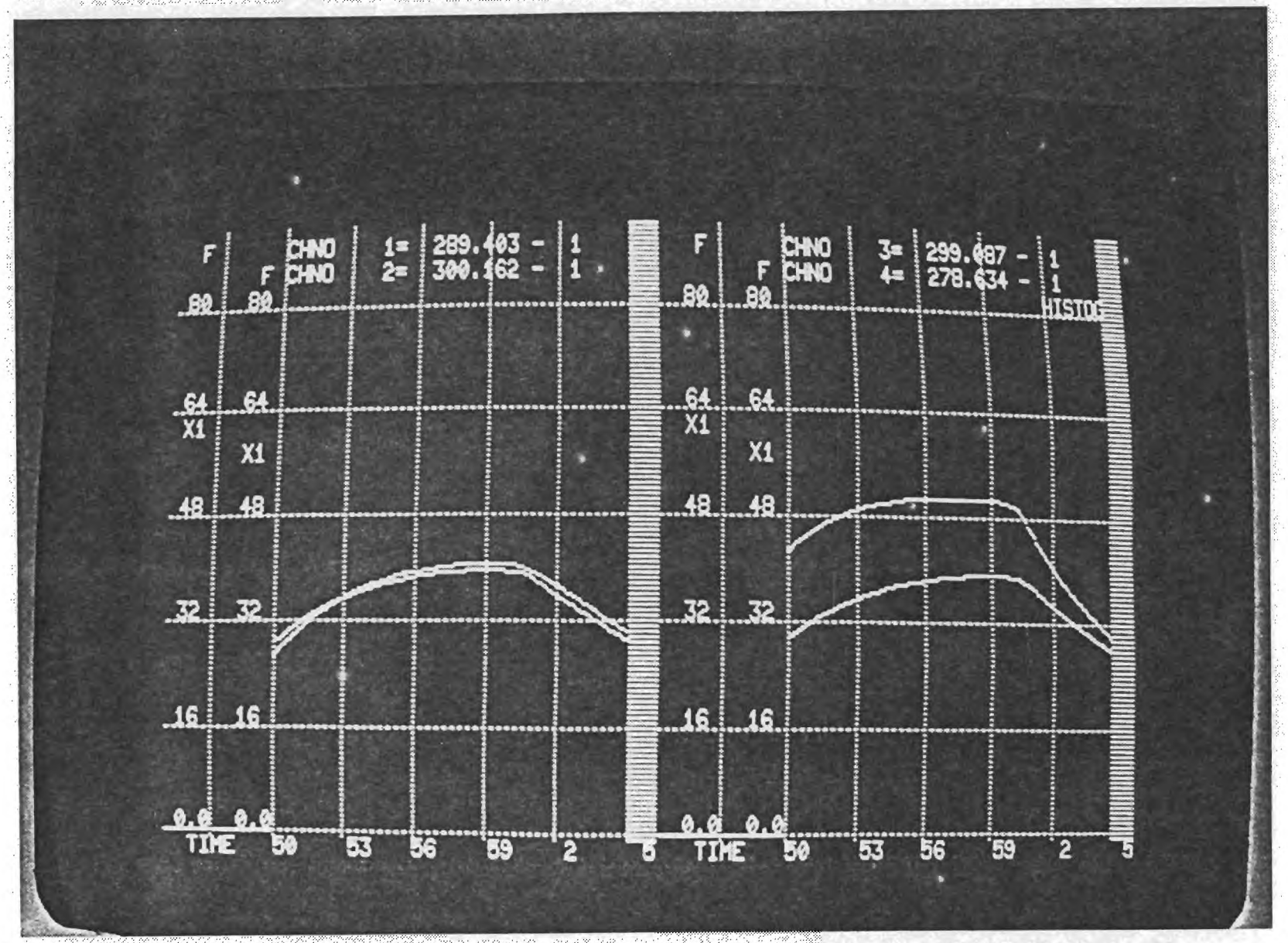

Figure 12. Sample Display of Data on Video Terminal. Graphs Show Time Dependence of Temperature for Four Thermocouples in an Oven That Has Been Rapidly Heated and Then Allowed to Cool.

view in more detail any given channel. The frozen image would then be updated every N seconds. Hard copies of the image could be produced at any time.

The provision for more data channels would allow the placement of strain gages in twenty new locations. The installation of these new strain gages would provide data for a more detailed analysis of the strain and stress distribution in the receiver. In previous strain measurements of boiler and superheater tubes, only longitudinal strains on tube back surfaces were determined. These measurements were used in conjunction with an analytical stress analysis to estimate the entire stress distribution in the tube. Because several parameters influence the stress distribution, this approach may not be adequate when only back-surface longitudinal strains are measured. Thus, both circumferential and front-surface gages were to be added in support of any future test phases. The front surface gages were to be placed in areas where they would have a high probability of surviving the indirect solar heat flux.

IV. WATER CHEMISTRY PROGRAM

Georgia Tech had complete responsibility in the bench model receiver program for all water-side surface chemistry. The cleaning and maintenance of the quality of water side surface is important to equipment and personnel safety, for, in any high pressure boiler, the presence of impurities in the low parts-per-million (or even parts-per-billion) range can rapidly lead to corrosion and scale formation.

A. Make-Up Water Delivery System

The water chemistry system designed for the bench model receiver had to deliver high quality make-up water, mechanically deaerate it, and chemically treat it. The make-up water system for the Phase II and III tests is depicted in Figure 13, and pictured in Figures 14 and 15. The major components are the commercially supplied deionized water reservoir, the cartridge-type polishing demineralizer, a specific conductivity cell to monitor the quality of the make-up water and a high pressure pump to deliver the water into the boiler system. Also shown are the ports for delivery of hydrazine to scavenge residual dissolved oxygen from the feedwater and morpholine to maintain the system pH in a range which minimizes corrosion.

B. Sampling Points

Within the boiler loop, Georgia Tech specified the penetration points such as water and steam sampling ports, chemical feed lines, a make-up water line, a vent for noncondensable gases and various system drains. All sampling points are depicted in Figure 16. The water and steam collected at these points was condensed, cooled, reduced in pressure and subjected to

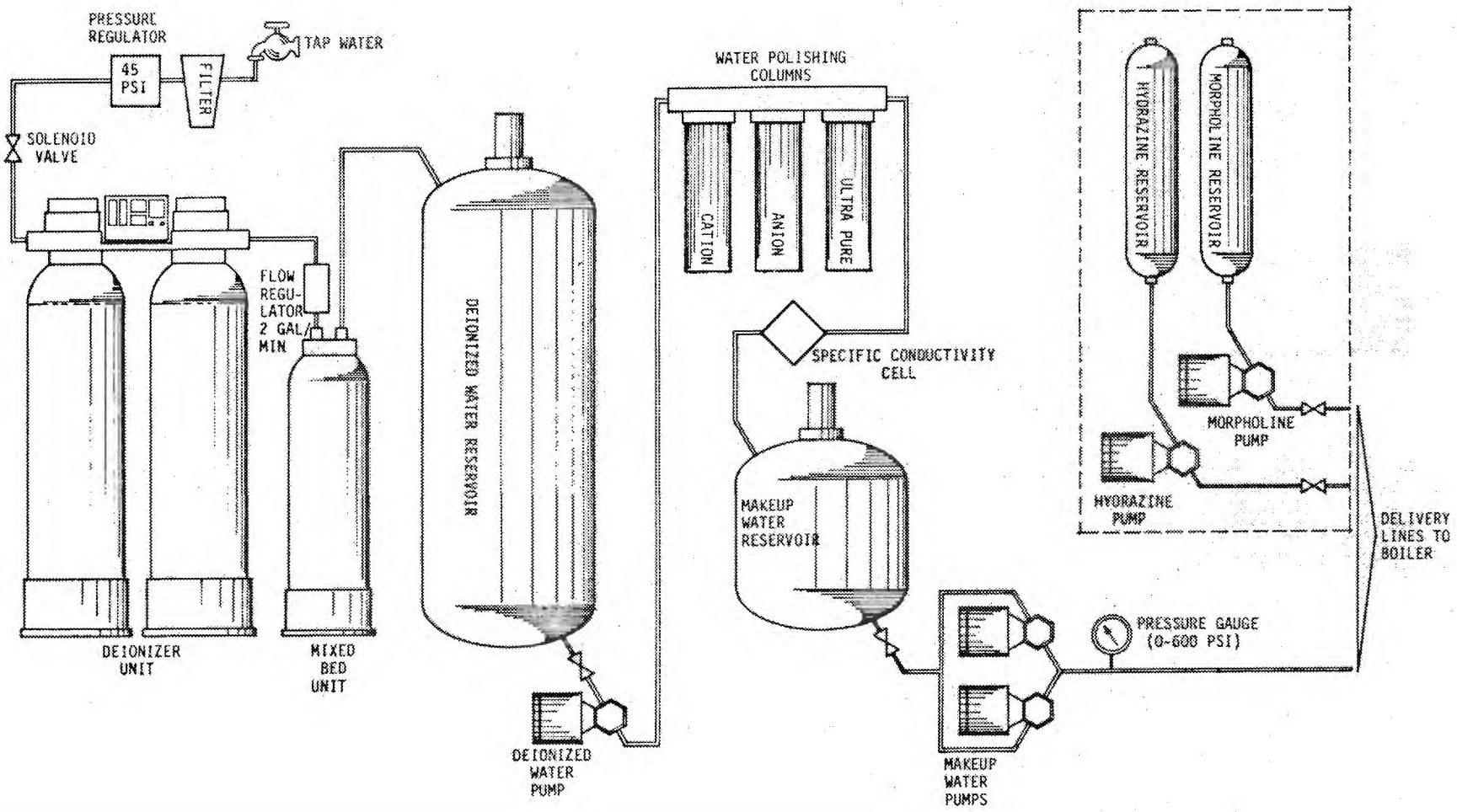

Figure 13. Simplified Schematic of Water Quality Module and Demineralizer Unit.

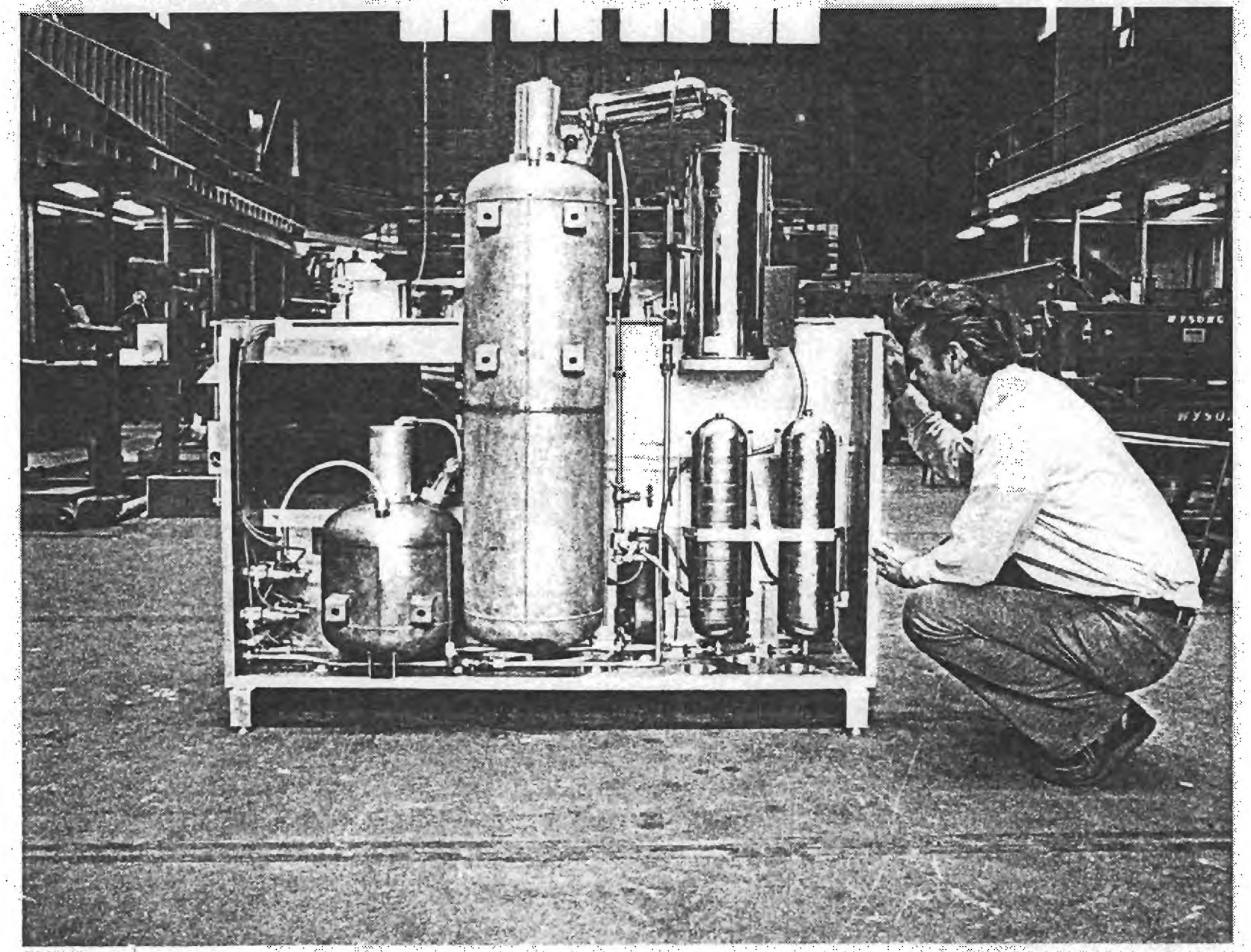

Figure 14. Front View of Water Quality Module.

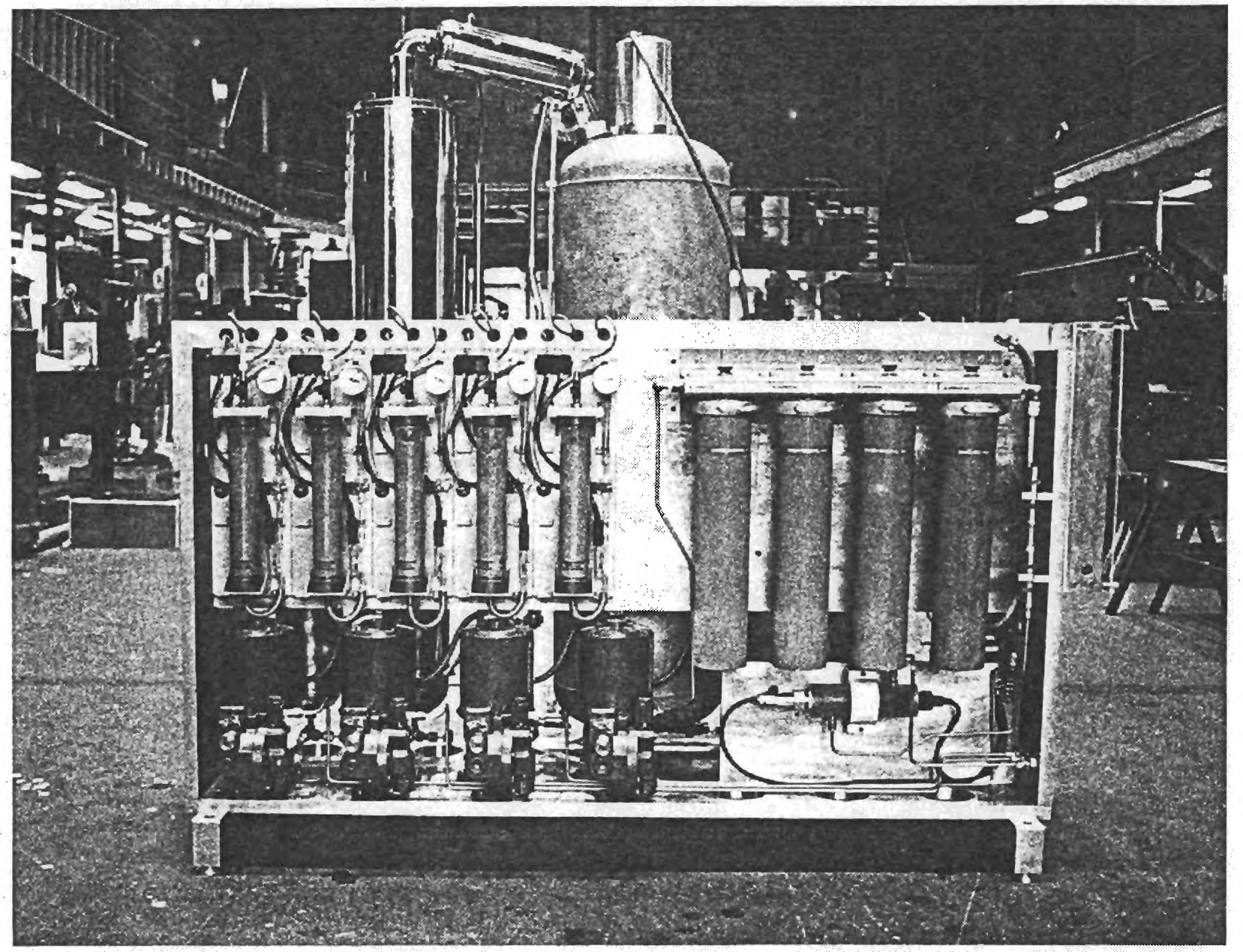

Figure 15. Rear View of Water Quality Module.

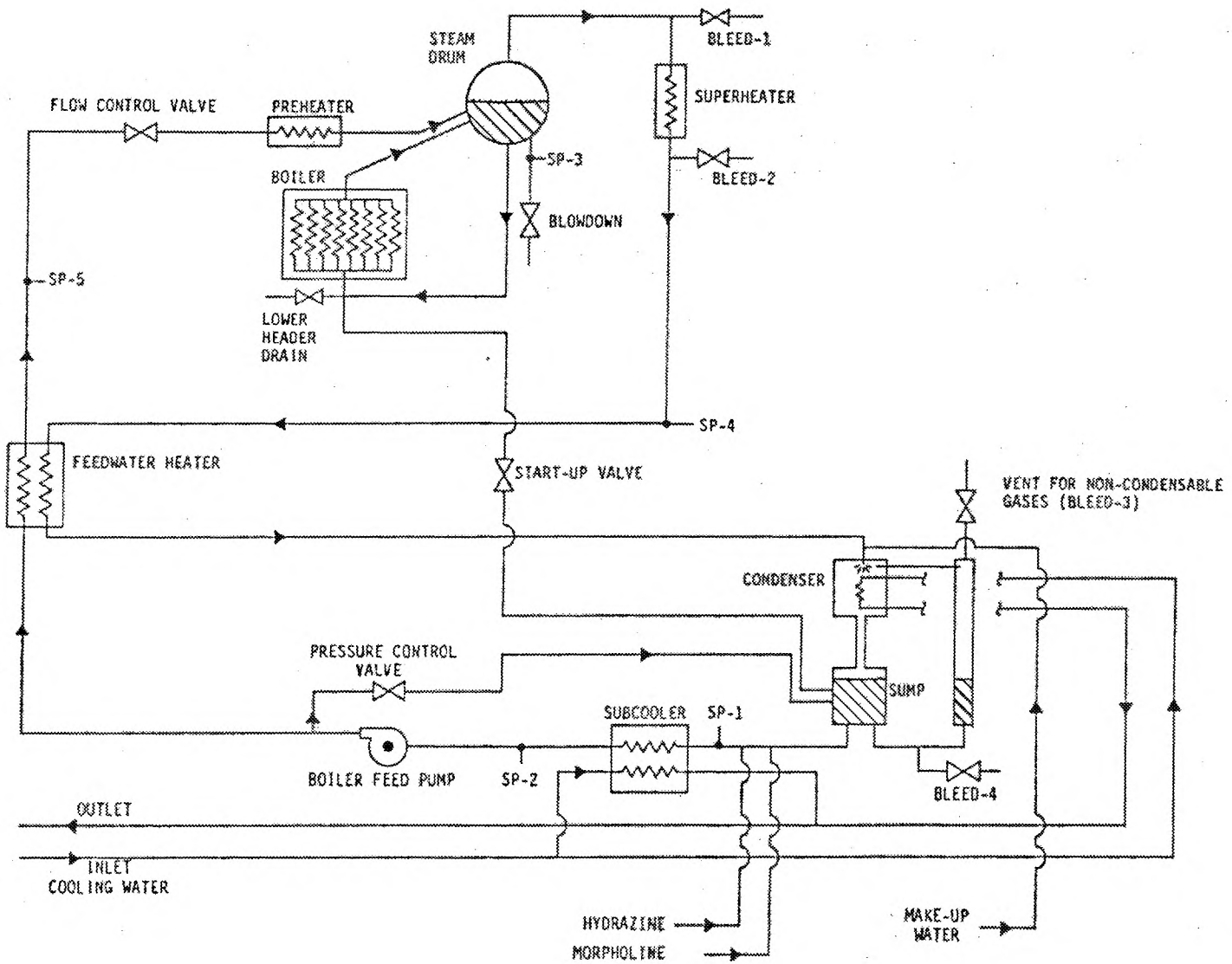

Figure 16. Simplified Schematic of Bench Model Boiler System Showing Sampling Points, Chemical Feeds, and Mechanical Deaeration Features.

continuous electrical conductivity measurement and chemical analysis. Chemical variables were determined at a laboratory bench adjacent to the water quality module. Properties measured at this bench were the alkalinity, hardness, pH, and concentrations of dissolved oxygen, phosphate, morpholine, hydrazine, ammonia, copper, silica and chloride. The allowed range of these variables is listed in Semi-Annual Report No. 1, Solar Power System and Component Research, Project No. A-1734-001.

C. Initial Cleaning of the Receiver

The receiver was cleaned during the Phase I cold flow tests. First, the components of the equipment were flushed with water and compressed air prior to final assembly. The completed unit was then purged with high pressure gas and flushed with high pressure water.

During the Phase II Sandia tests the boiler system received: (1) an alkaline boilout to remove traces of oil and grease which might cause foaming in the steam drum and hence promote carry-over of solids into the superheater, and (2) a number of rinse and flush cycles with demineralized water to remove the boilout solution.

The experience with this water chemistry program in each phase was valuable in making design modifications for the next phase. In the Phase II hot checkout the system's use of make-up water was greater than anticipated, so plans for Phase III corrected accordingly. Unfortunately, the collection of basic water chemistry data for cyclic operation was hampered during Phase II by the lack of long term stable operation of the boiler at Sandia Labs.

D. Modifications for Future Tests

During the Phase III tests in France, all parts of the system functioned satisfactorily except for the deaeration system. As a consequence, this portion of the system has been redesigned in preparation for possible future tests at the US/STTF. The system was further improved by the addition of several new sampling points and the automation of the make-up water delivery system.

The make-up water delivered to the boiler during the tests in France had a satisfactorily low concentration of dissolved solids, but an unsatisfactorily high oxygen content. The original design called for mechanical deaeration of the make-up water by spraying it into the condenser concentric with the incoming steam, and providing a vent on the condenser for the removal of noncondensable gases. Further deaeration of the feedwater was to have been provided by the addition of oxygen-scavenging hydrazine.

Unfortunately, the effectiveness of both of these techniques was hampered by circumstances imposed by the thermal testing program. First of all, the vent necessary for the mechanical deaeration had to be closed during start-up when the steam flow rate to the condenser was small, and during the collection of receiver efficiency data when it was important to minimize parasitic heat loss. Under these frequently prevailing conditions, make-up water could not be added since it could not be deoxygenated. Water sampling for chemical analysis thus had to be curtailed for long periods of time during many of the test days. These operating conditions severely hampered the collection of basic water chemistry data for cyclic operation.

Secondly, the utility of hydrazine as an oxygen scavenger was limited by the failure of the feedwater to remain long enough in the temperature

range where hydrazine is most effective. Below a temperature of 350° F, hydrazine does not scavenge well; above 450° F it decomposes rapidly to troublesome ammonia. Unfortunately, peculiarities of the receiver hardware arrangement prevented the use of the preheater and feedwater heater during the Phase III tests. Thus, the feedwater temperature rose quickly from 300° to 580° F as it entered the boiler's steam drum. Any further testing would require appropriate changes to the boiler to assure that the feedwater is regularly preheated.

The Phase III restrictions on the addition of make-up water can only be removed by a system that deaerates the make-up water before its addition to the feedwater system. The method chosen for deaeration was vacuum degasification. An integrated system based on this technique is diagrammed in Figure 17. Some of the components necessary to convert the previous system to this new design were obtained before the Phase IV tests were indefinitely postponed. Other modifications were recommended for the existing program. One was the addition of such automatic features as liquid level controls and differential pressure sensors to the water quality module. A second was the addition of two sampling points - one between the preheater and steam drum and one between the drum and superheater inlet as shown in Figure 18. A third modification was the installation of a selective sampling system.

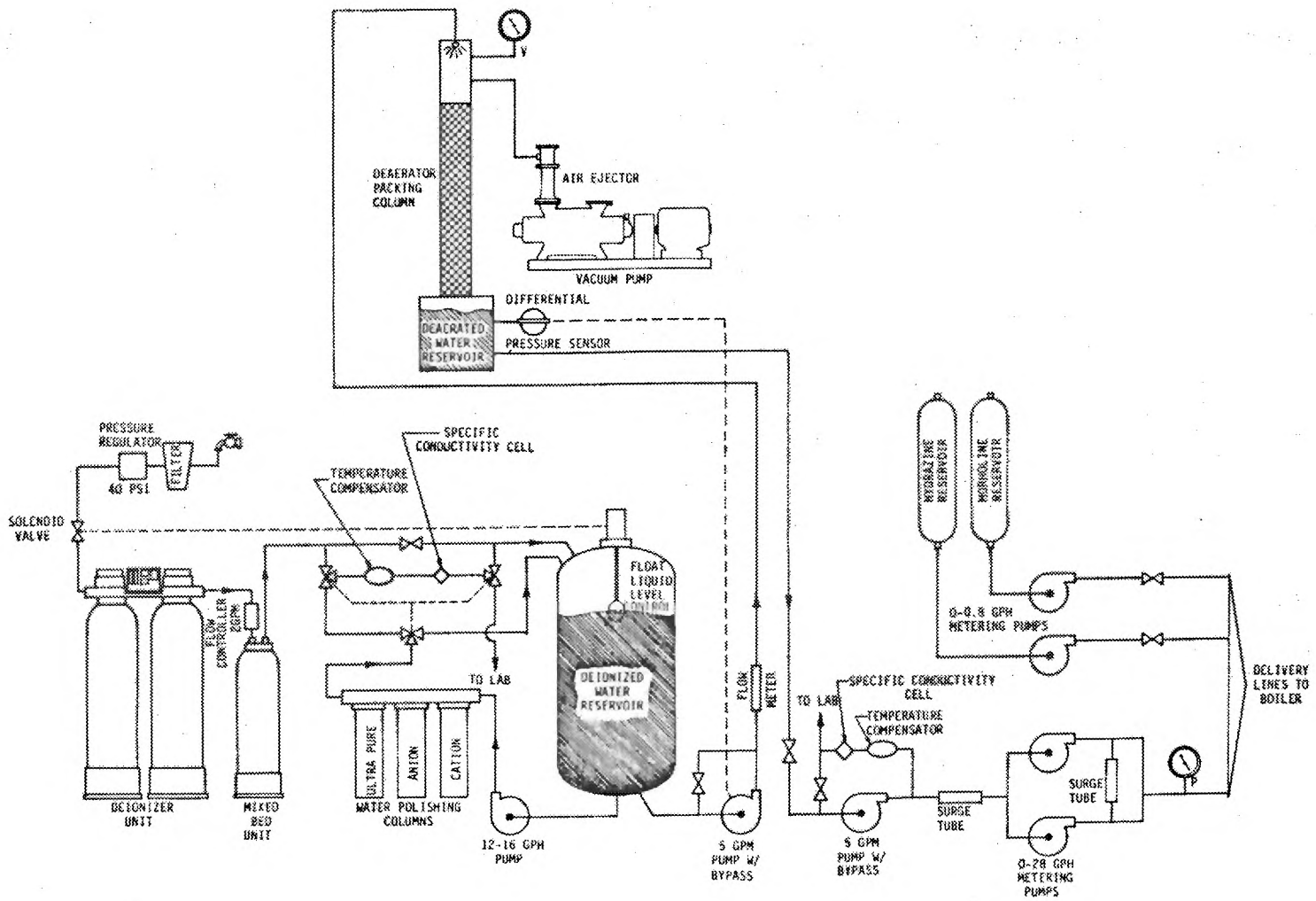

Figure 17. Modified Design for Makeup Water Delivery System.

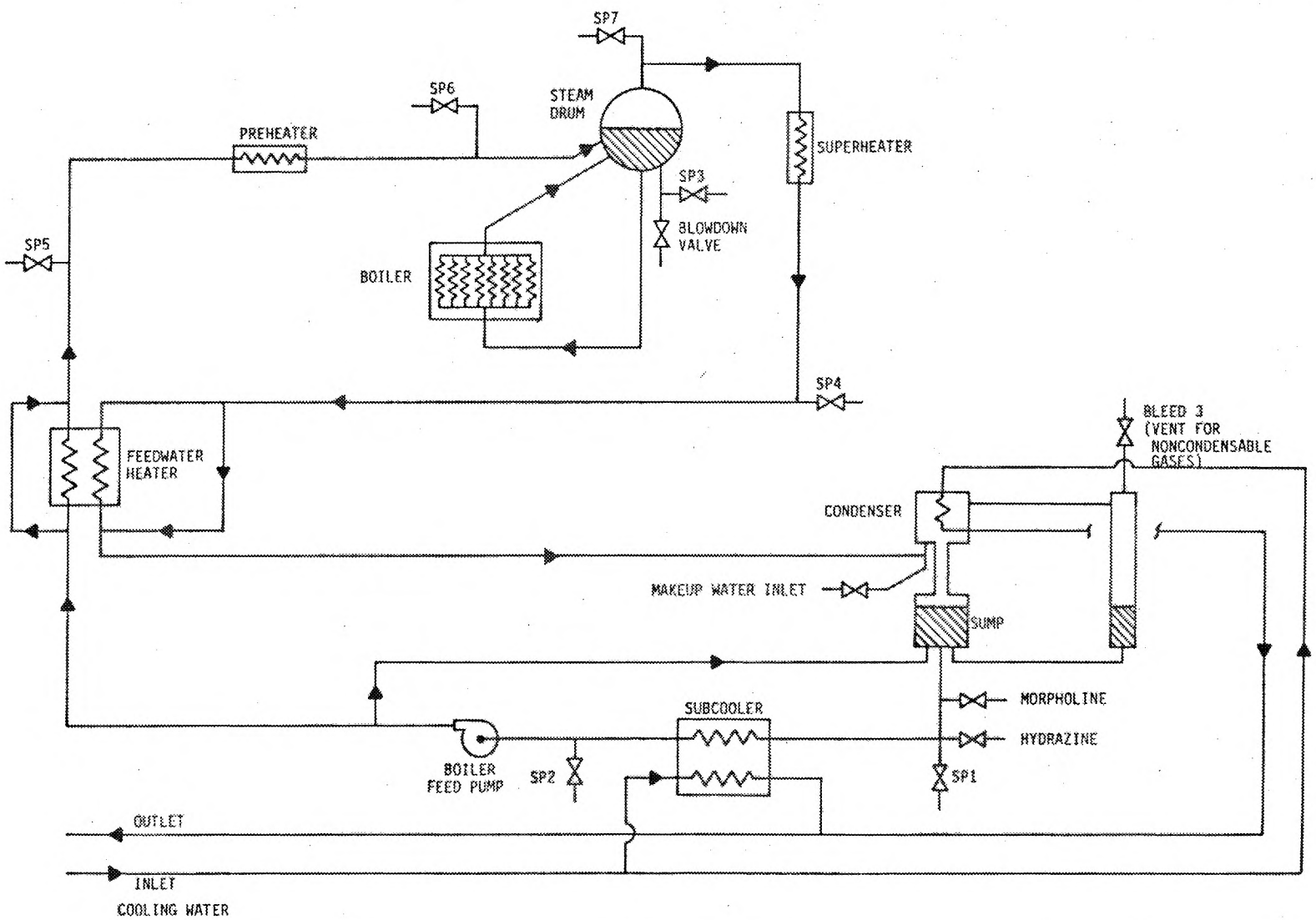

Figure 18. Location of New Sampling Points - SP6 and SP7 - in Boiler Loop.

V. CONCLUSIONS

Georgia Tech collaborated with Martin Marietta Corporation in a variety of ways during the three-phase testing program of the 1 MW Bench Model Receiver. During the Phase I cold flow tests, it conducted an initial cleaning of the water-side surfaces of the receiver. In preparation for the next two hot phases, Georgia Tech undertook thermal and pressure stress analyses to verify the boiler design and to predict experiment stresses to be measured. To ensure proper interfacing with the Phase III solar test at CNRS, Georgia Tech constructed a flux redirector, built a dummy receiver cavity and used them both in a preliminary characterization of the thermal flux environment at the French facility.

During the Phase II hot checkout at Sandia, Georgia Tech conducted an alkaline boilout and final cleaning of the receiver, and acquired initial operating experience with the water chemistry monitoring and maintenance program. Georgia Tech also planned the placement of thermocouples and strain gages, and collected thermal and pressure stress data during these tests to assist in developing expectations for the thermal behavior of the receiver during the solar tests.

Throughout the Phase III tests at the CNRS Solar Furnace in France, Georgia Tech continued to be responsible both for monitoring the thermal and pressure stresses of the boiler and for maintaining the water chemistry program.

The smooth operation of the bench model receiver during the Phase III tests indicated that the entire program had culminated in valuable experience in the operation of a solar receiver. This experience may benefit all future experimenters.

One lesson that resulted from the early phases of the program was the importance of thorough prior study of both the receiver and the solar facility. In particular, the smooth interfacing of the 1 MW bench model receiver and the CNRS Solar Furnace rewarded Georgia Tech for its careful planning.

Another valuable experience was the analysis of the thermal stresses of a particular boiler design. The computer codes developed by Georgia Tech for the bench model receiver, when compared to the experimental data, were found to be appropriately conservative. The measurement program for the collection of temperature and thermal stress data was reasonably successful as well in that they verified that the receiver was behaving very much as expected. However, it was recommended that future measurements of thermal stresses be improved by real time collection and display of data; by greater numbers of sensors and higher frequency of sampling; and by the use of circumferential as well as longitudinal strain gages, placed on some front surfaces as well as back surfaces.

The water chemistry design also proved largely successful as originally designed, with one major exception: The deaeration system depended on mechanical deaeration together with scavanging of oxygen by hydrazine. This design conflicted with some peculiarities of both the receiver hardware and the testing procedures. It is recommended that future water chemistry programs deaerate the make-up water before it is added to the feedwater. The importance of multiple sampling ports, frequent collection of samples and prompt chemical analysis is stressed.

As stated before, the Phase III tests of the 1 MW bench model receiver did not reveal any problems with thermal and pressure stresses. However, the program was a short term one and could not manifest the behavior of thermal stresses under long term cyclic operations. It is recommended that further testing and measurements of thermal stresses be undertaken both on a longer time period and at a higher design temperature.