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1-MW$_{th}$ BENCH MODEL SOLAR CAVITY RECEIVER STEAM GENERATOR BUILD AND TEST

Final Report

February 1978

Work Performed Under Contract No. EY-76-C-03-1068

Martin Marietta Corporation
Denver, Colorado

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1 MW_{th} BENCH MODEL SOLAR CAVITY RECEIVER STEAM GENERATOR PROGRAM

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FOREWORD

This report is submitted by Martin Marietta Corporation, Denver Division, in accordance with the Department of Energy Contract EY-76-C-03-1068 as a final report, Contractual Data Requirements List, Item No. 4.

This report will describe all the equipment as it presently exists and its capability. Thus this document can be used for possible future application of the equipment.

Previous tests will not be summarized in this report but results can be found as follows:

Radiant IR Test	-	Phase 2 Test Summary Report, 1 MW_{th} Bench Model Solar Cavity Receiver Steam Generator Build and Test, June 1976 MCR-76-133 (Issue 2).
Solar Test CNRS France	-	Phase 3 Test Summary Report, 1 MW_{th} Bench Model Solar Cavity Receiver Steam Generator Build and Test, June 1977 MCR-76-133 (Issue 3).

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FIGURES

I. INTRODUCTION

This report presents the final configuration of the 1 MW Thermal Bench Model Solar Cavity Receiver Steam Generator. The receiver was designed, built, and tested to provide an early demonstration of the feasibility of using solar energy to produce electricity with a conventional steam turbine generator. The receiver was fabricated by Martin Marietta Corporation at its Denver facility and was tested in the radiant heat test facility at Sandia Laboratories, Albuquerque and followed by solar testing at the Centre National De La Recherche Scientifique (CNRS) solar furnace in Odeillo, France. The program plan included subsequent testing at the Solar Thermal Test Facility (STTF) in Albuquerque. Modifications to the receiver have been made that will permit testing at STTF. These modifications included changes to the receiver and support equipment resulting from the operational experience gained in France, interface hardware to accomodate changes in relative location of the receiver and support equipment required at STTF and fabrication of an active cooling thermal protection shutter to protect the exterior of the receiver from the solar beam that is larger than the aperture.

II. SUMMARY

The primary program objective was to demonstrate the feasibility of conversion of solar energy into steam suitable for turbine electrical generation. The design steam pressure (1250 psig) and temperature ($960^{\circ}F$) are comparable to present power plants. Final solar energy demonstration testing of the unit was done in the CNRS facility in Odiello, France. This facility was the largest solar facility in the world at the time of the test.

The receiver design is a cavity configuration. The internal tube surfaces are divided into boiler, superheater, and preheater sections. The general design selected for the system was a typical commercial boiler design of a steam drum with natural circulation. The receiver was designed and built to Section 1 of the ASME boiler code. All materials and processes also conformed to ASME specifications. The system was designed and built to be used in the CNRS facility.

Other team members involved in the program were:

- Centre National De La Recherche Scientifique of France for the use of the CNRS Facility.
- Engineering Experiment Station, Georgia Institute of Technology, for the water quality control, the interface with the French test facility, and the stress analysis and measurement of the receiver.

- o Sandia Radiant Heat Facility at Albuquerque, New Mexico for the IR simulation of phase 2 of the program.

A summary of the major phases of the test programs is presented below.

Functional Test

Functional tests were performed to verify the pneumatic and electrical systems and to verify pump operation and flow prior to test in the radiant heat facility. No heating was performed during this phase. Thest tests were performed at MMC, Denver facility March 1976.

Radiation Heat Test

Infrared heating was used to simulate the solar heating by placing banks of quartz lamps next to all the tube surfaces. Tests were performed at full pressure and temperature. A maximum power of 620 KW was achieved in an energy distribution similar to that expected at CNRS. The test accomplished checkout of the system, resolution of minor operation problems, and training of operating personnel. Operational times were as follows:

Total operating time	165 hours
Time at full pressure	90 hours
Time at full superheat	32 hours

See reference 3 for detailed report on this phase of the test program. These tests were performed April and May 1976.

Solar Test at CNRS France

The 1 MW Thermal Bench Model Cavity Receiver and its support equipment was shipped to France, installed and checked out during the period of May and June 1976.

During July and August tests were performed totaling 32 steam generating days, 104.3 hours at rated pressure, 71.4 hours at rated superheat, including 14 "official days" consisting of a minimum of 4 hours at rated pressure plus a minimum of 2 hours at rated temperature. Although local weather conditions, and the experimental nature of the program, made the tests somewhat erratic, superheat was maintained for over 78 percent, and rated pressure for over 91 percent, of available daily solar exposure time during long test runs.

The tests demonstrated quick startups and rapid recovery from passing clouds. Boiler temperatures suitable for "hot" morning startup of a full scale system were demonstrated by the use of aperture insulation supplemented by the use of an electrical heater.

An overall thermal efficiency of 86 ± 4 percent at designated conditions comprised of a cavity efficiency of 92 ± 2 percent, the latter is the efficiency of converting this absorbed energy into steam.

Results of stresses determined from the strain gages in the cavity showed that all measured stresses were less than the ASME Boiler Code allowables. It is therefore concluded that the bench model receiver is structurally sound for continuous steady state operation and for operation cycles. Cyclic operation is limited by fatigue considerations and was not a part of this program.

Functional Test of Thermal Protection

Functional tests have been performed on the thermal protection system that was designed for use in the Solar Thermal Test Facility in Albuquerque, New Mexico. These tests verified the pneumatic and electrical systems, the pump operation and the coolant flow of the thermal protection system. No heating was performed.

III. SYSTEM DESCRIPTION AND CAPABILITIES

Overall Design

The solar receiver system was designed to absorb and convert 1 megawatt of solar energy into superheat steam. The steam conditions selected were 1250 psig, and 960°F. The receiver was designed for the solar flux beam in the CNRS test facility in France. The system also includes the support equipment to control the receiver and condense the steam in order to maintain a closed loop water system. The major pieces of equipment are as follows:

Receiver

Equipment Module

Control Panel

Water Quality Module

Thermal Protection System

The system schematic shown in Figure 1 whows all the test equipment and includes the major data collection and control points of pressure, temperature and flow.

The receiver and equipment module were built in accordance with ASME boiler code specifications. Accordingly, the feedwater heater and sump conform to Code U-Section H (Unfired pressure Vessels) ASME certification. The remainder of the equipment module was built per applicable ANSI specifications. The

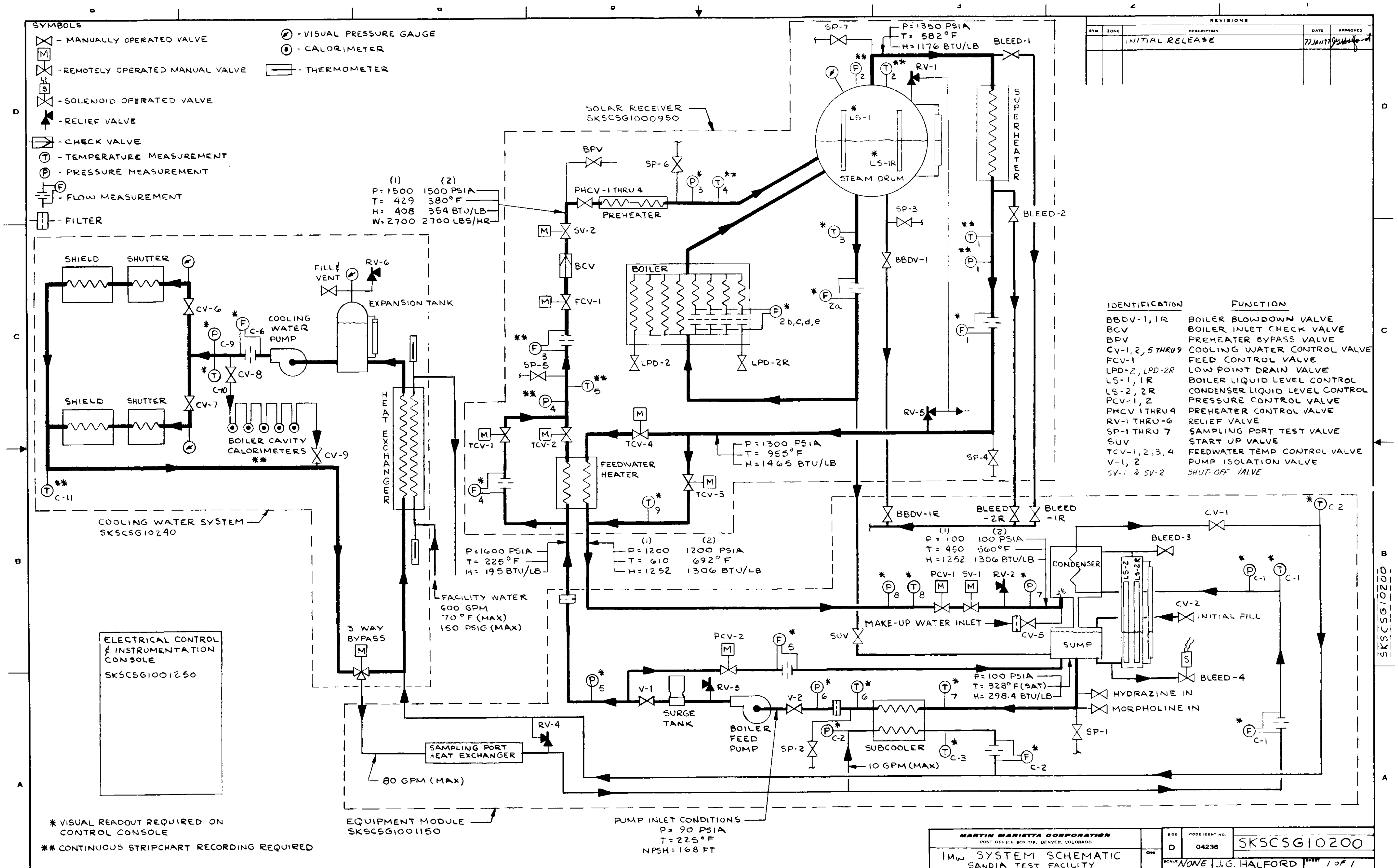

FIGURE 1 SOLAR RECEIVER SYSTEM SCHEMATIC

receiver itself has a Section I (Fired Pressure Vessel) ASME certification.

Receiver

The receiver is an adaptation of conventional boiler technology to solar power. It consists of a natural circulation boiler section, steam drum, preheater, superheater, safety relief valves and control valves. A heat exchanger extracts heat from the superheated steam and adds it to the feedwater simular to the regenerative feedwater heating process via steam extracted from a turbine. The solar-peculiar feature of the receiver is its geometry, consisting of a cavity with an aperture, as shown in Figure 2. Highly concentrated solar energy is admitted through the aperture, and absorbed by the preheater, boiler, and superheater sections mounted inside the cavity. The cavity is well insulated to minimize heat losses.

The system is designed to generate 2700 lbs/hr of superheated steam at 1250 psi and 950^{o}F with a solar input into the cavity of 1 MW. The steam outlet pressure and temperature are the primary controlled variables during operation. The pressure is controlled by the pressure control valve PCV-1 (Figure 1) which restricts the steam flow to the condenser in a controlled fashion to maintain the desired drum pressure at a given heat input. The temperature is controlled by the use of a Refrasil curtain which can be raised or lowered to partially block the incident radiation on the rear

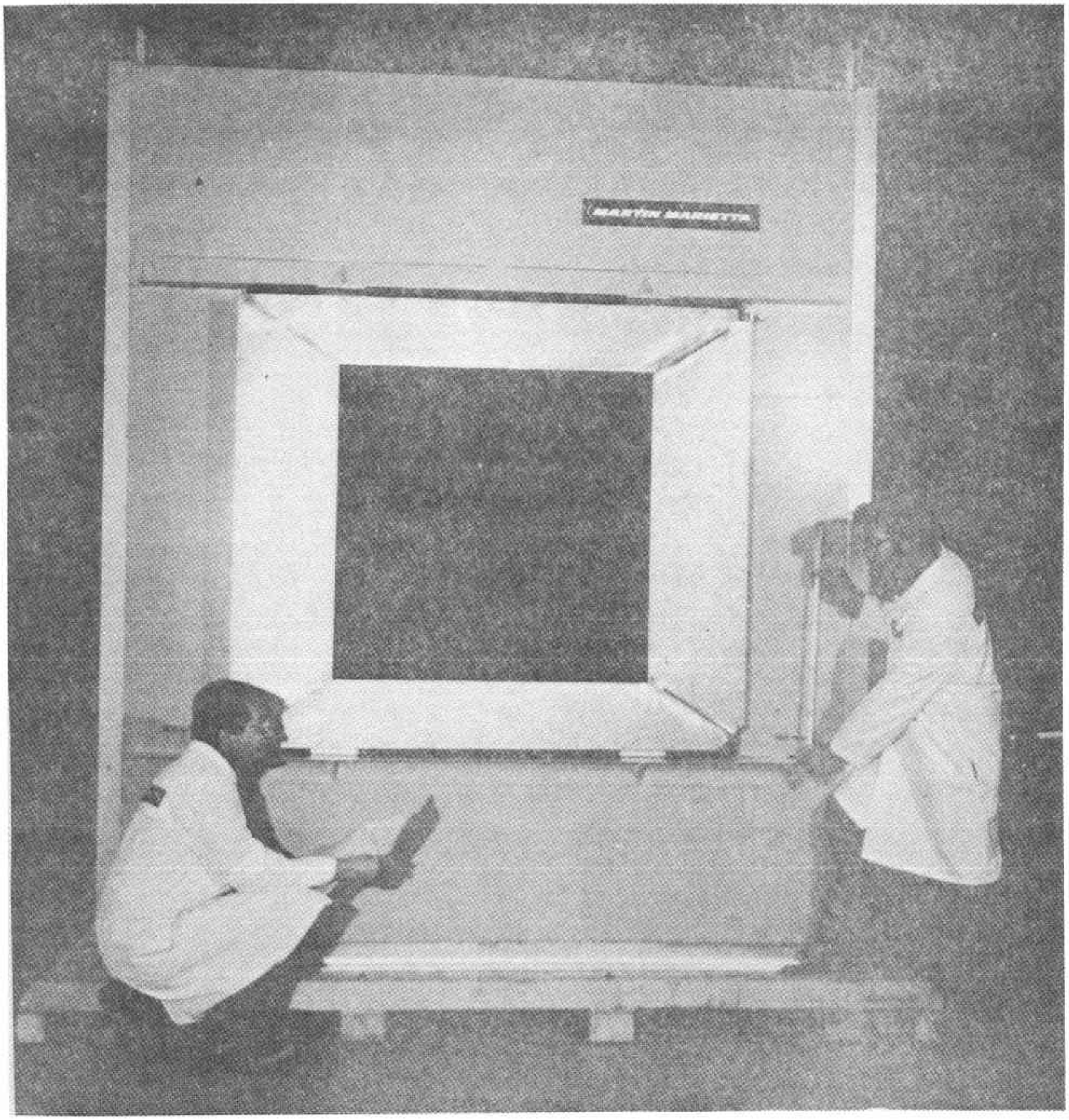

Figure 2 1 MW_e Solar Receiver Cavity with Aperture superheater. Drum (and sump) level was maintained by controlling the upstream pressure P5 to the heat exchanger by varying the bypass flow from the sump outlet to the condenser via the flow control valve FCV-1 (Figure 1).

The external dimension of the receiver is approximately 8 feet square, 10 feet high and weighs 18,000 pounds. The inside cavity dimension is approximately 6 feet cubed. Figure 3 shows the present configuration of the receiver with an insulated movable door on the front of the receiver. Figure 4 shows the back of the receiver with the steam drum heat exchanger and control valves. Figures 5 and 6 show the receiver tubes during construction.

The heat transfer surfaces of the receiver are shown in Figure 7 in a "folded flat" condition. The maximum absorbed flux into the boiler tubes is 150,000 Btu/Hr-Ft^2 and into the superheat tube is 100,000 Btu/Hr-Ft^2. When the surfaces are exposed to a greater flux level than they can safety absorb the tube surface must be coated with a low absorbing paint. The coating pattern necessary to test the receiver in the FTTS facility is shown in Figure 8. The usage of the receiver in another solar field would require analysis to achieve the coating pattern necessary for correct operation.

A heat exchanger on the back of the receiver is designed to reduce the steam outlet temperatures from 960^{o}F to less than

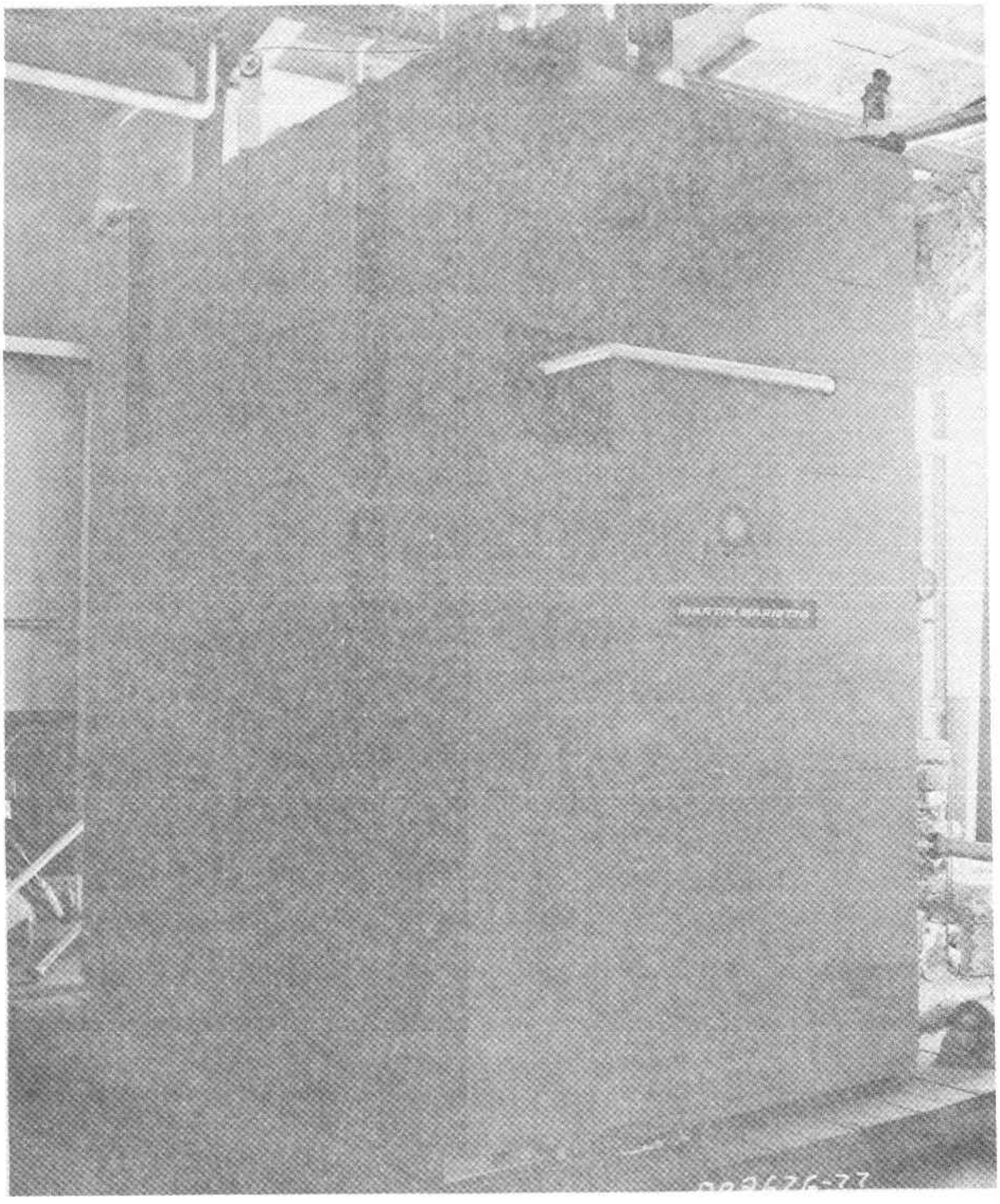

FIGURE 3 1 MWe RECEIVER CONFIGURATION

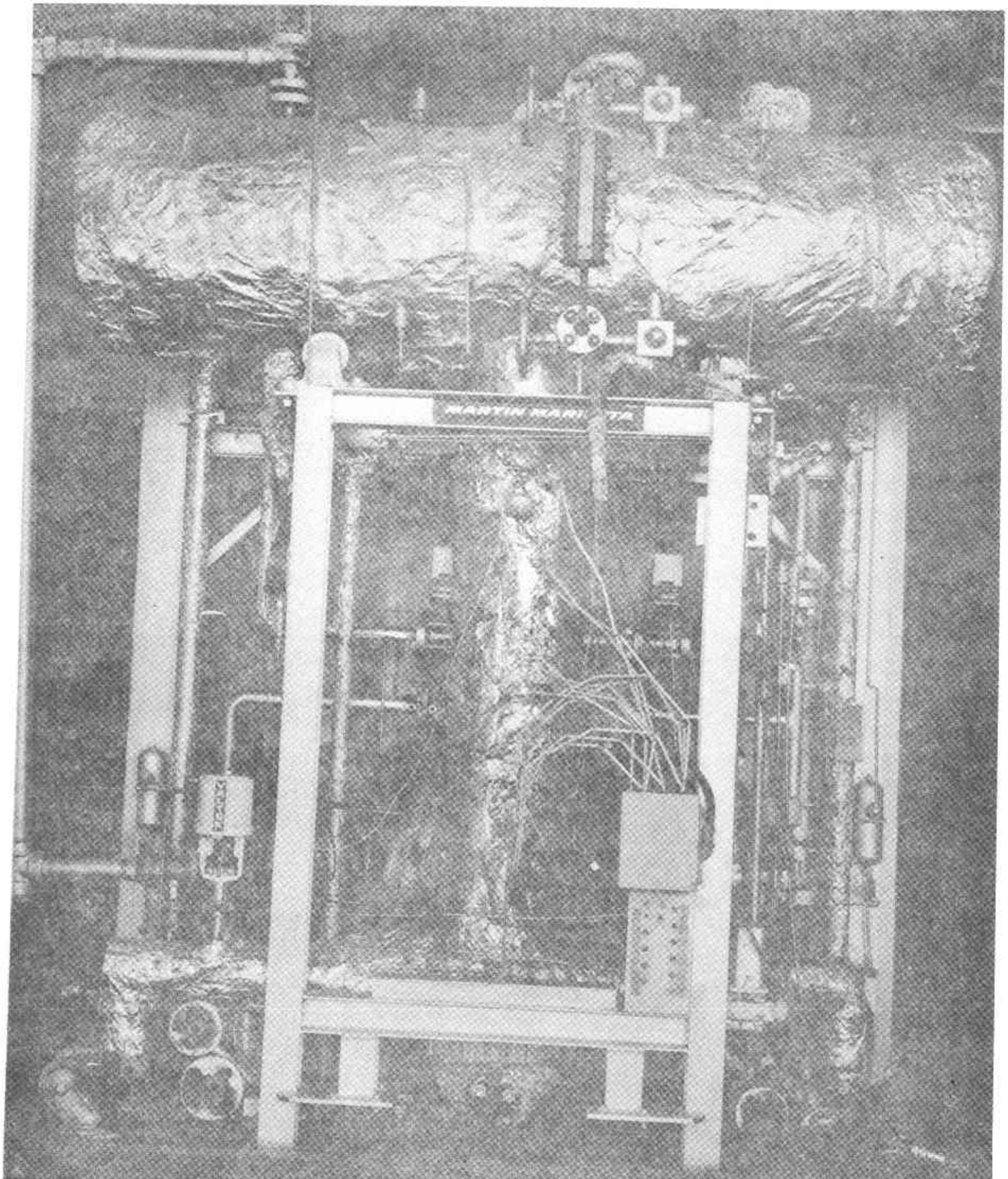

FIGURE 4 1 MWe RECEIVER REAR VIEW

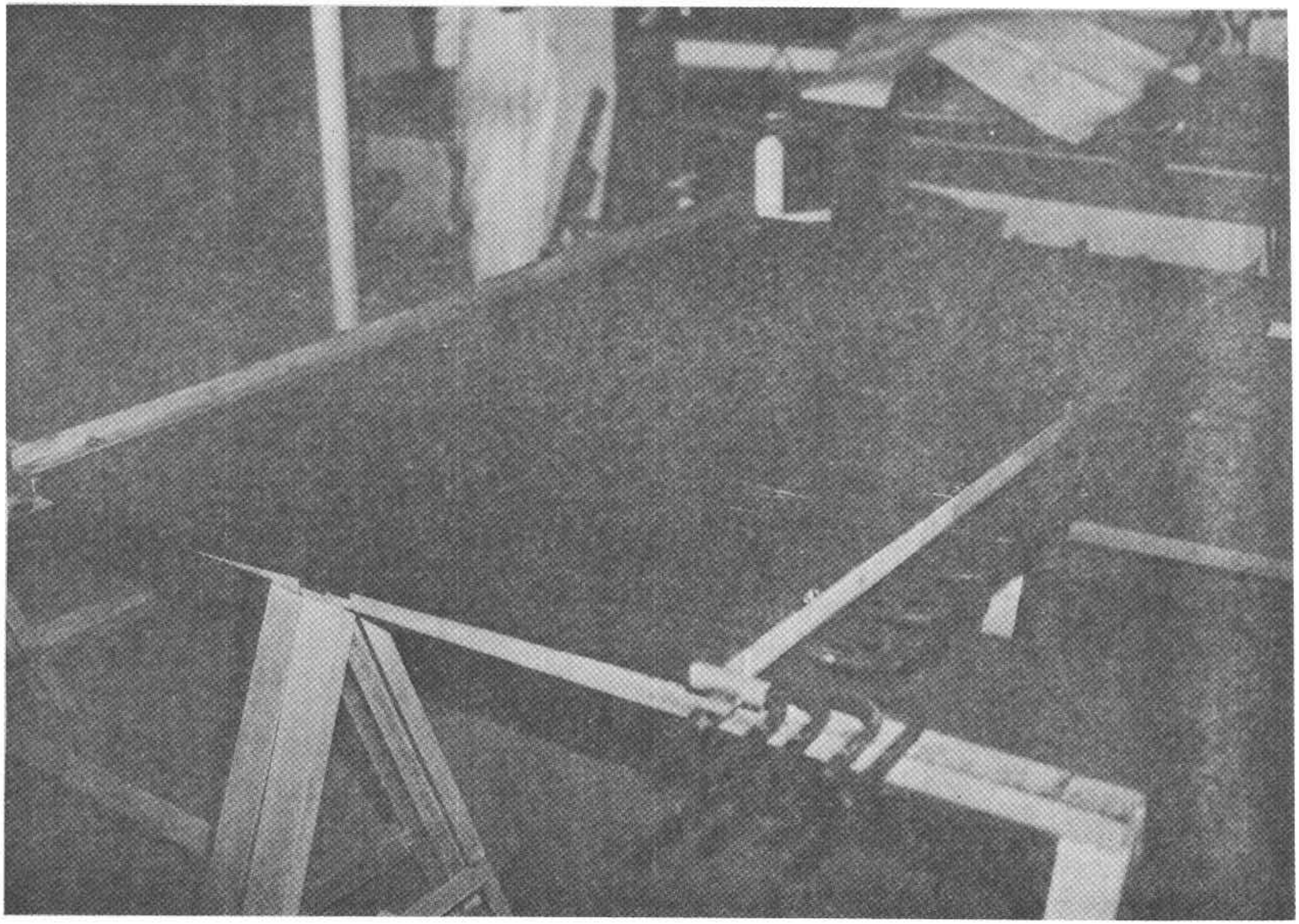

FIGURE 5 1 MWe RECEIVER TUBES

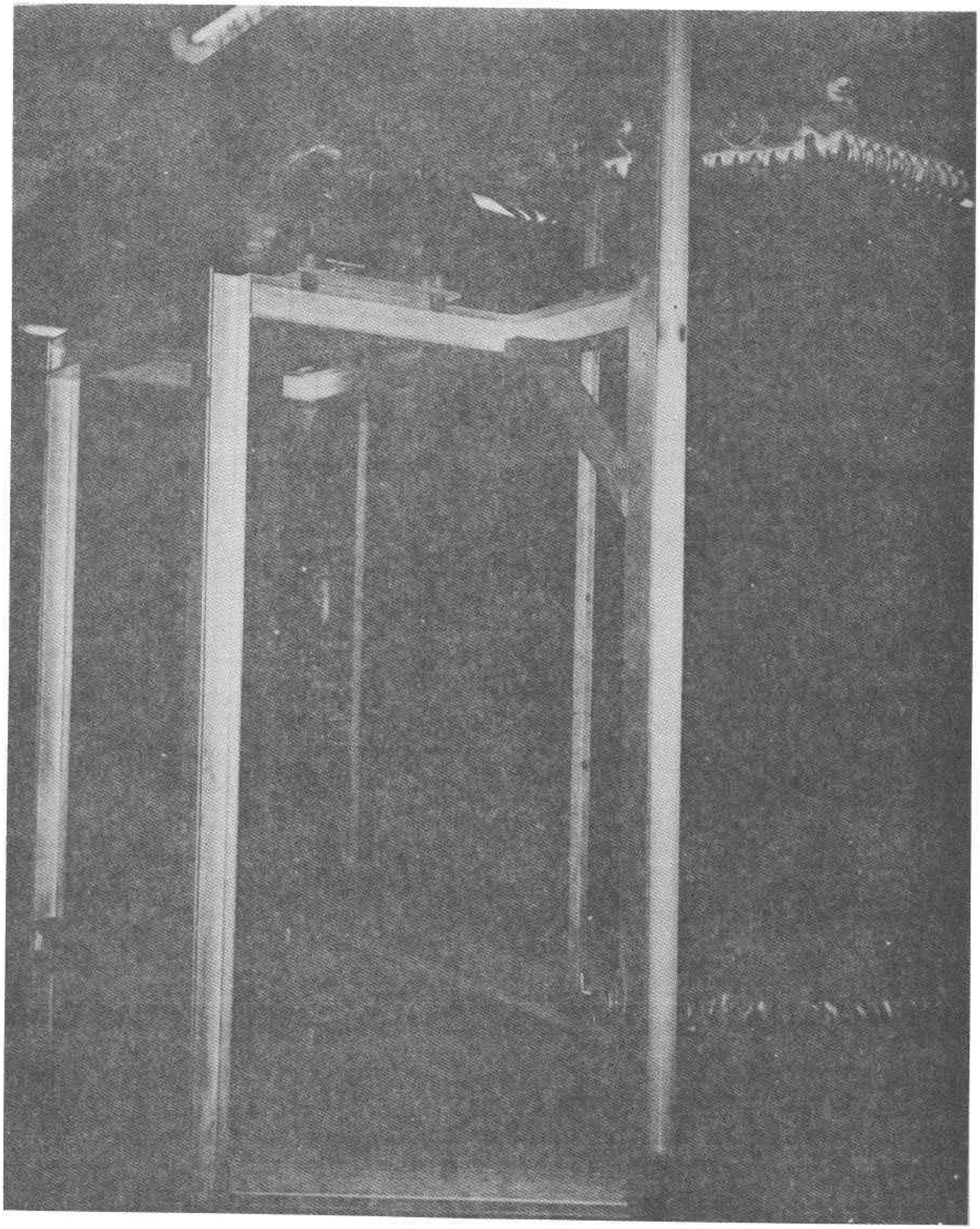

FIGURE 6 1 MWe RECEIVER TUBES

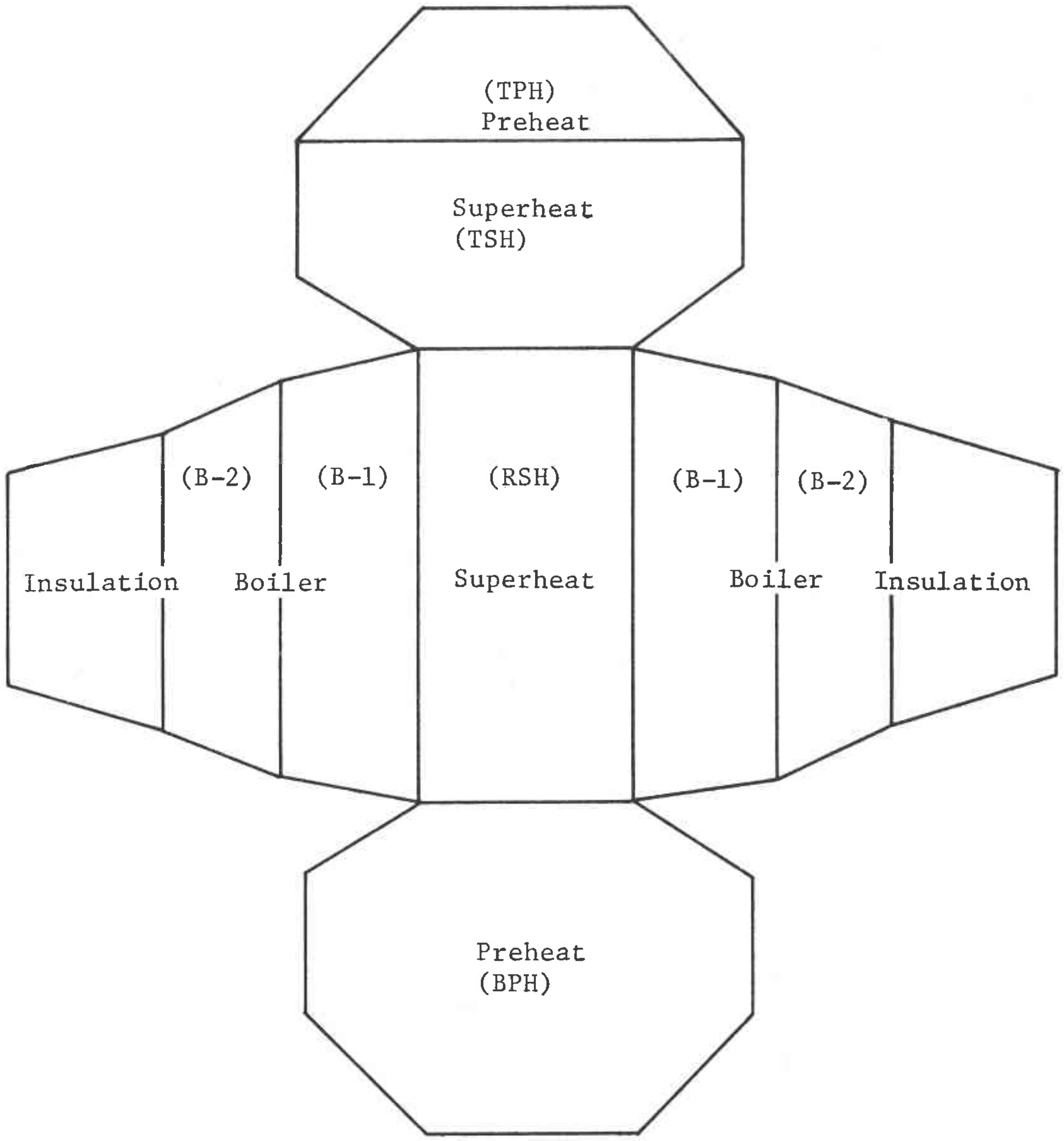

Figure 7 Location of Heat Transfer Surfaces

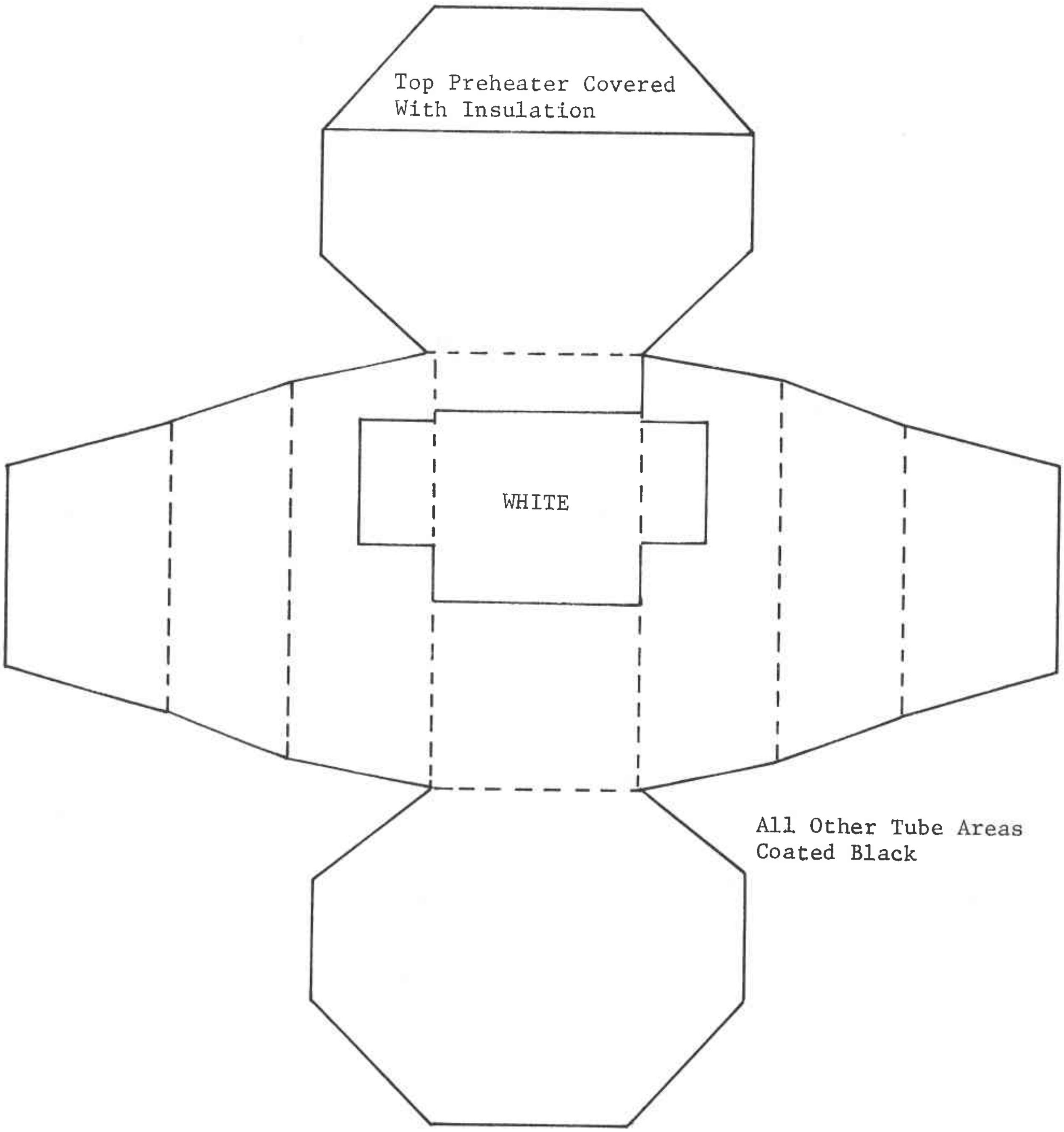

Figure 8
Internal Cavity Coating Pattern Requirements for 1 MW Input

700^{o}F. This allows the steam to be compatible with other equipment on the equipment module.

Equipment Module

The equipment module contains the feedwater pump, a condenser with sump tank, a subcooler (to control pump inlet temperatures), and the majority of the control valves of the subsystem. Figures 9 and 10 show views of the equipment module. Figure 9 is a photograph of the equipment module assembled with the receiver for a cold checkout test. At present the interconnecting pipes are configured for test in the STTS facility.

The unit is 5 feet by 9 feet and 6 feet high. It weighs 3000 pounds. The capability of the equipment module is to condense 3240 pounds of steam per hour. The maximum steam conditions is for 700^{o}F and 125 psig. Thus the pressure of the steam from the receiver is reduced by throttling and the temperature is reduced by the heat exchanger on the back of the receiver.

The limitation of each item on the equipment module is listed below:

Pump:	Flowrate	3240 pounds/hr
	Maximum temperature	250^{o}F
	Maximum outlet pressure	1600 psig
Subcooler:	(To cool pump inlet water)	
	Flowrate	3240 pounds/hr
	Maximum inlet temperature	350^{o}F
	Outlet temperature	225^{o}F
	Maximum pressure	150 psig

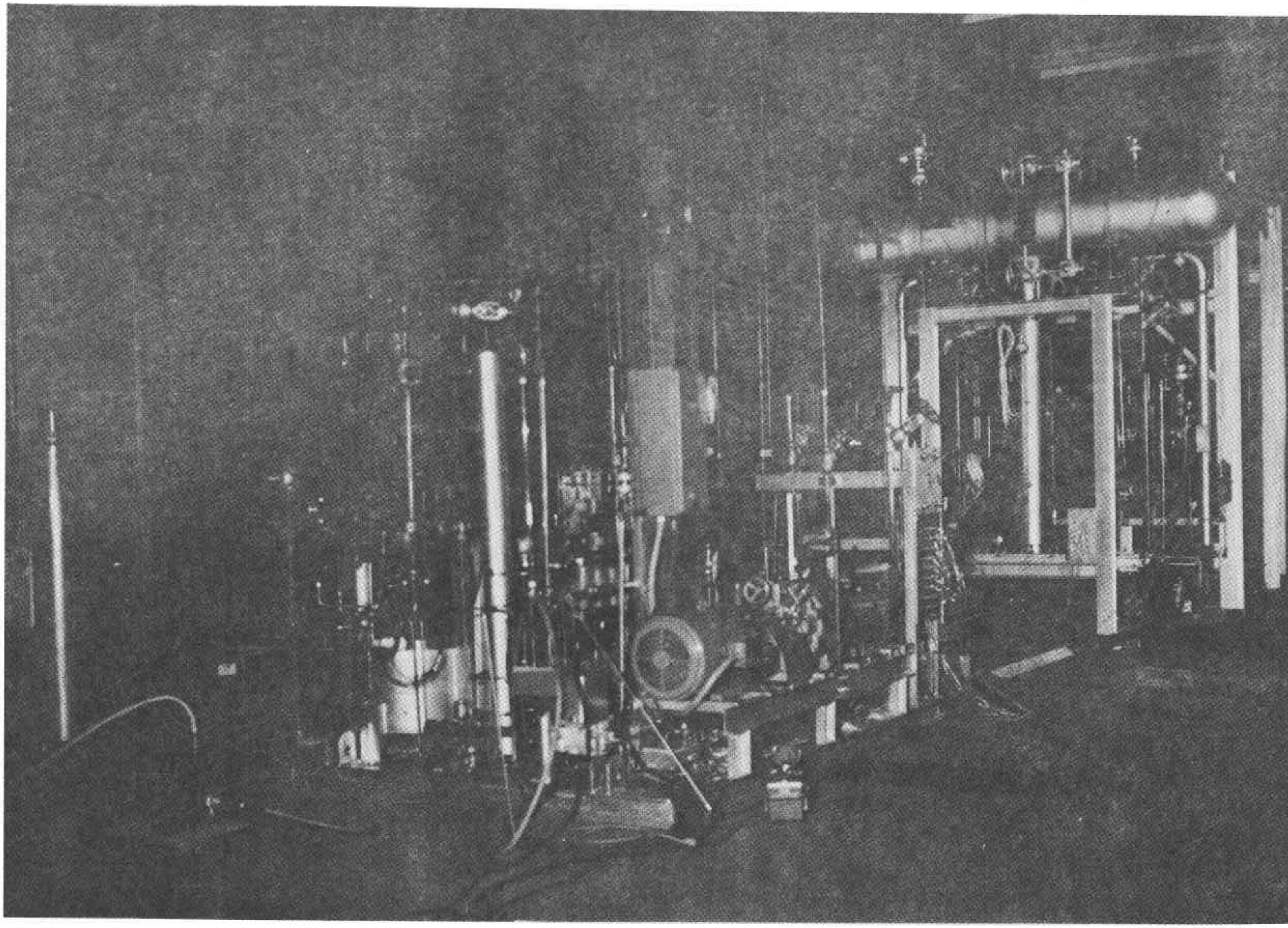

FIGURE 9 RECEIVER EQUIPMENT MODULE

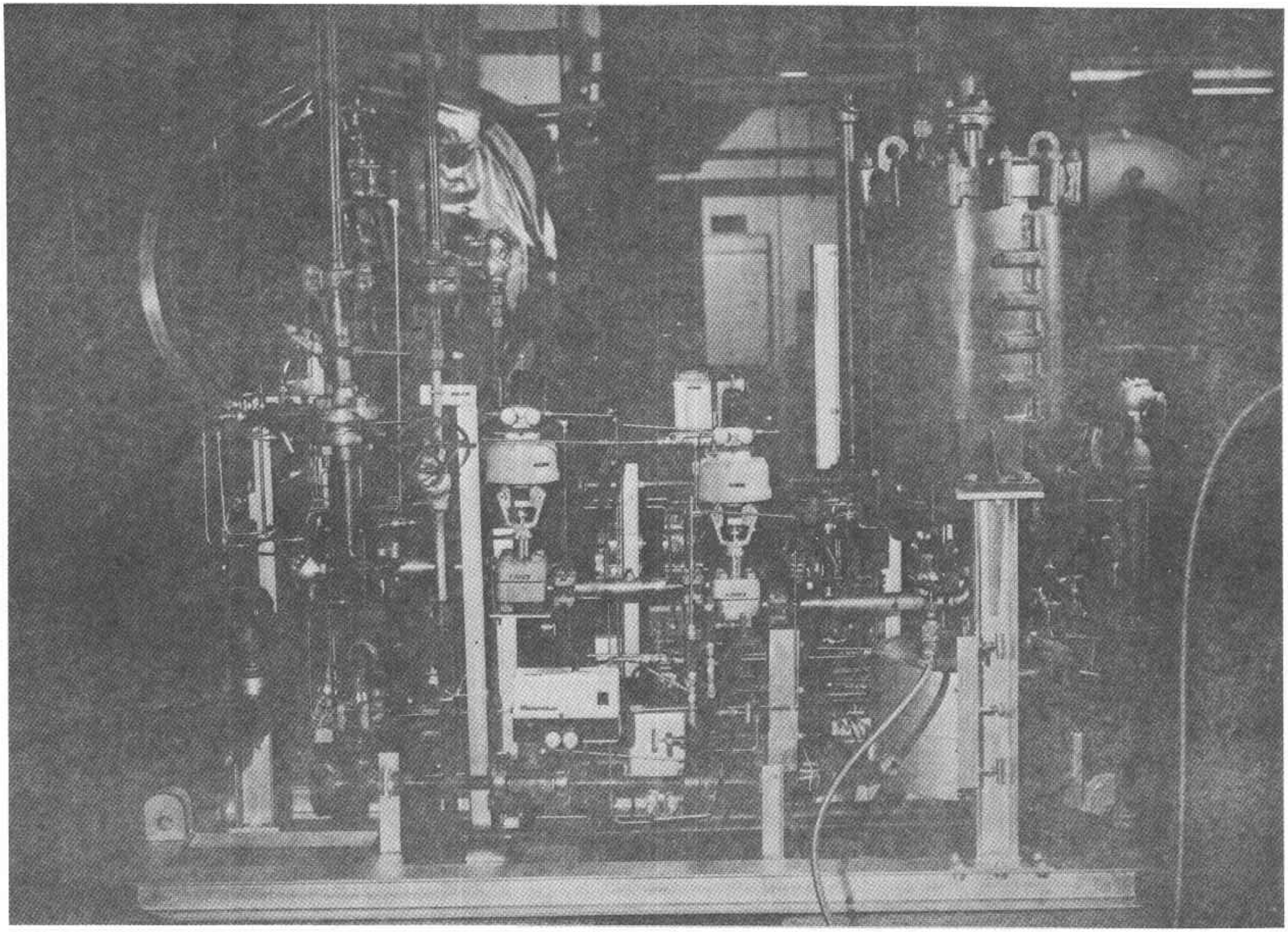

FIGURE 10 RECEIVER EQUIPMENT MODULE

Condenser:	Flowrate	3240 pounds/hr
	Maximum temperatuer	250°F
	Maximum pressure	125 psig

Control Console

Figure 11 shows the control console which controls all the equipment except the water quality module.

The control console contains all controls for setting the receiver system pressures, flow rates and liquid levels. It contains four recording charts for selected temperature, pressures, and flow rates. Controls are also provided for the thermal protection system and includes flow and pressure indicators. The console is equipped with emergency shut down controls. Position light and alarm bell provide for safe operating of all systems.

Control signals are both electrical and pneumatic.

Pneumatic controls are 3-15 psig air pressure.

The control console is 2 X 6 feet and 6 feet high. It weighs 800 pounds.

Water Quality Module

This unit was designed and built by Engineering Experiment Station Georgia Institute of Technology under a separate ERDA contract, E(40-1)4921.

This module was used to take water samples from selected points of the system loop. It also pumped hydrazine, morphline, and make up water into the water/steam. The water chemistry of the steam system was closely controlled to prevent corrosion and scale buildup.

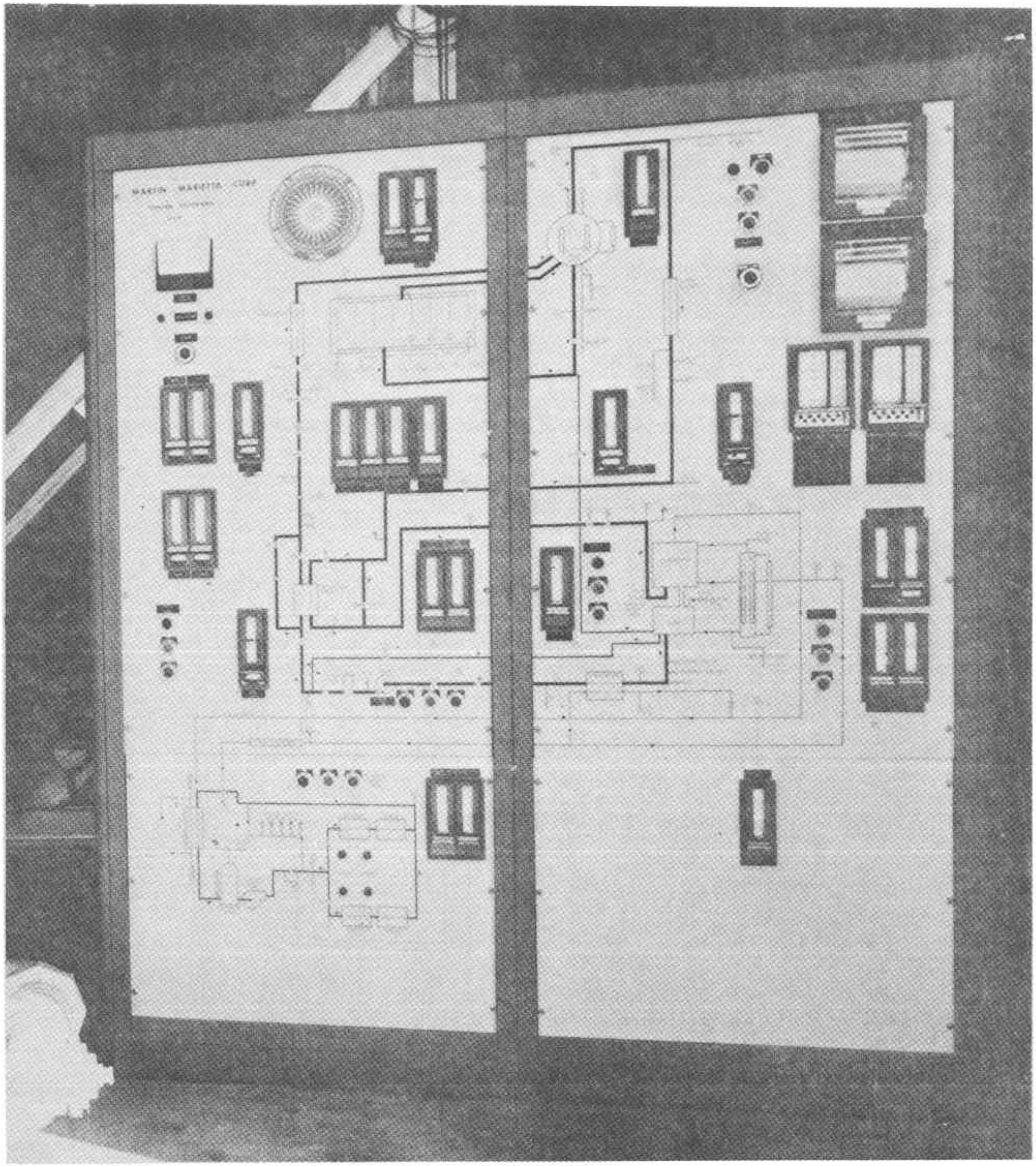

FIGURE 11 CONTROL CONSOLE

Figure 12 shows the water quality module which is approximately 3 X 5 feet and 4 feet high. It weighs 500 pounds.

Thermal Protection System

Testing of the receiver in the FTTS facility in Albuquerque requires the front of the receiver to be protected from the solar beam which is larger than the 40 inch square aperture of the receiver. This Thermal Protection System (TPS) is shown in Figures 13 and 14. The system includes the total collant loop system consisting of the following components:

Structure with attached coolant panels.

Pump and motor

Control valve

Surge tank

Facility heat exchanger

Connecting lines

The structure with coolant panels shown in Figure 13 is designed to support the receiver and be tilted at a 20 degree angle to better align the receiver with the solar beam at the STTF. The horizontal coolant panels at the top and bottom are fixed to the structure. The panels at the middle are movable so they can be pulled to the sides thus extablishing an opening for the receiver of approximately 40 inches square. The movable panels are pneumatically operated and can be opened or closed in less than 1 second. The front of

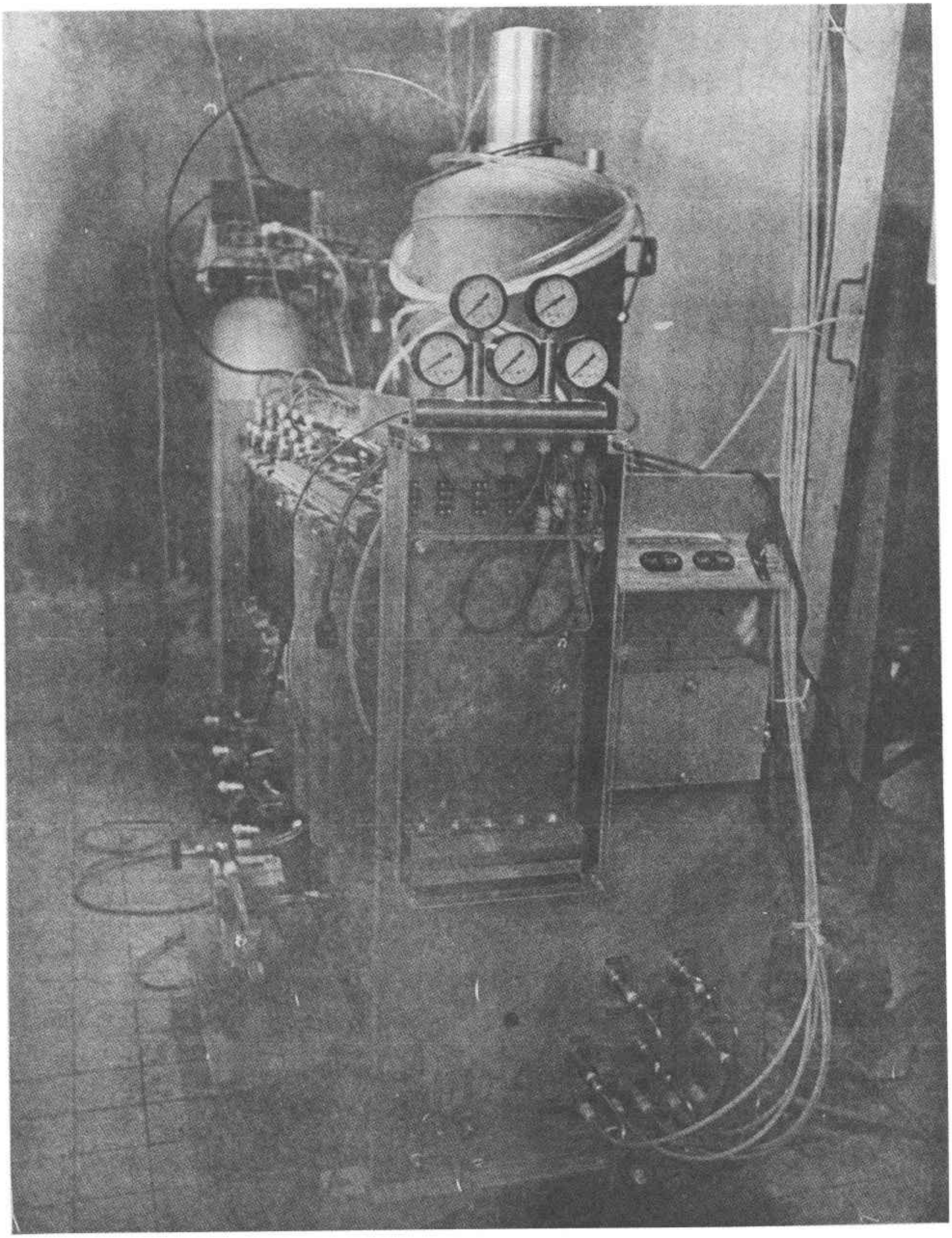

FIGURE 12 WATER QUALITY MODULE

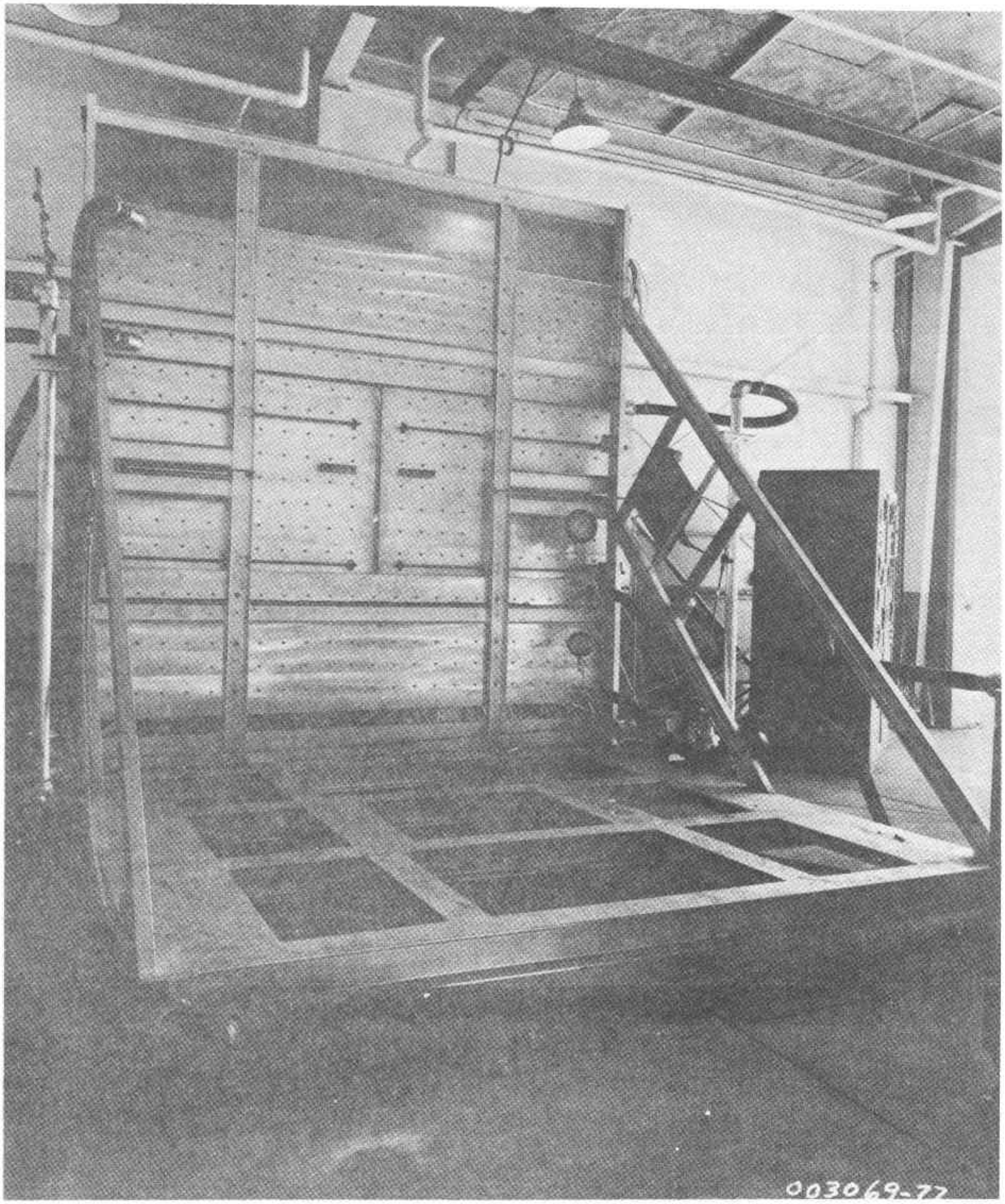

FIGURE 13 THERMAL PROTECTION SYSTEM

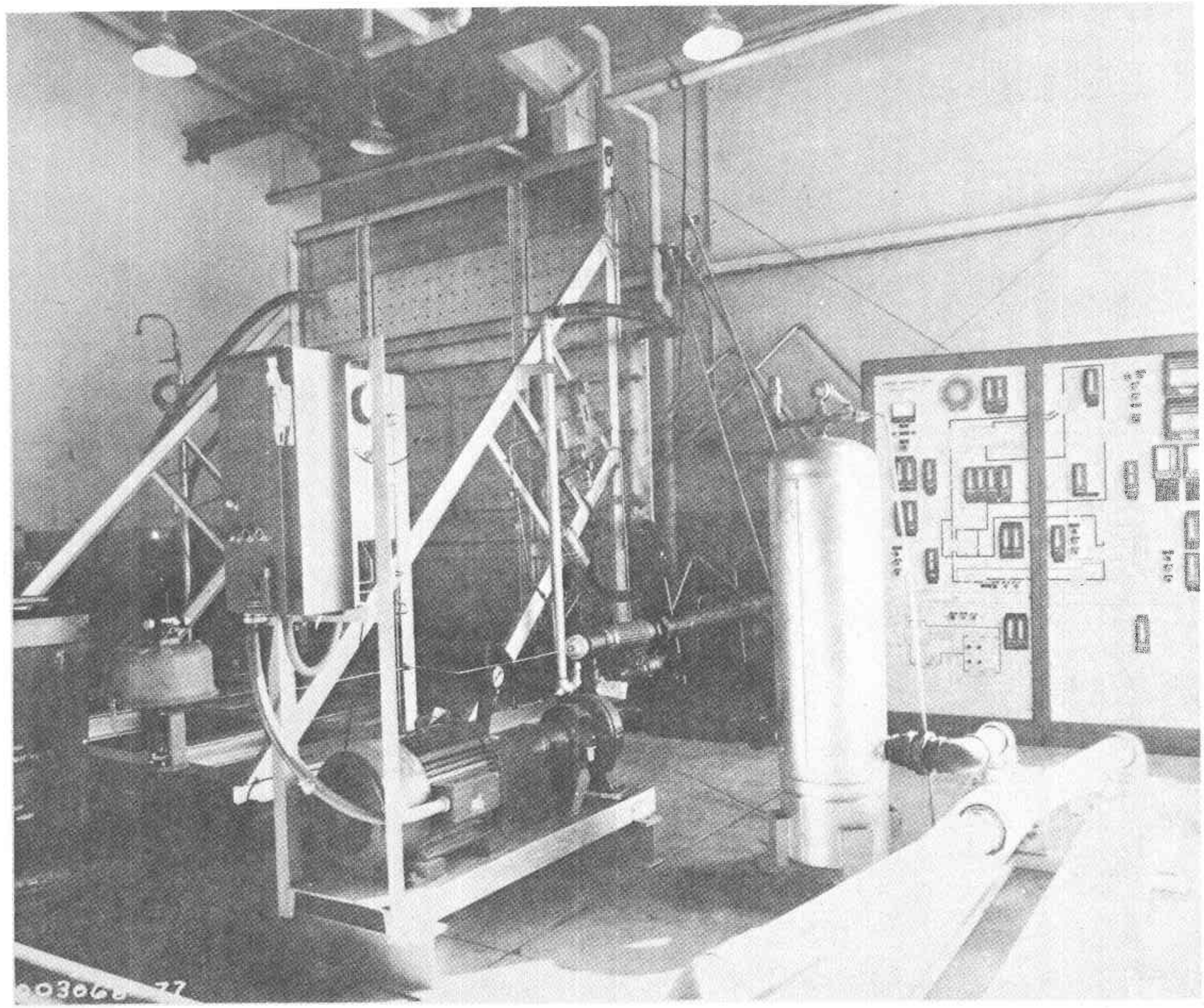

FIGURE 14 THERMAL PROTECTION SYSTEM

the panels need to be painted prior to usage to reflect the majority on incident solar energy. The TPS is designed for a continuous total incident flux of 7.8×10^6 Btu/Hr and a maximum continuous flux of 8.1×10^5 But/Hr-Ft^2.

IV. CONCLUSIONS AND RECOMMENDATIONS

1. The program demonstrated the feasibility of large-scale conversion of solar energy into the generation of superheated steam at pressures and temperatures suitable for efficient turbo-electric power generation. This demonstration was accomplished by maximum utilization of conventional boiler technology, the principal solar-peculiar features of the 1 MW Thermal Receiver being limited to its cavity configuration and a novel method of superheat control (via Refrasil curtain).
2. The excellent thermal performance of the test article has demonstrated the potential for economic operation of the Cavity Receiver concept. Both the cavity efficiency and the boiler efficiency exceeded 90 percent, with potential further improvements indicated by the data. Equally significant are the high solar utilization factors realized during long test runs, with rated pressures maintained over 91 percent, and rated superheat over 78 percent of available daily insolation.

   No excessive thermal stresses have been measured during steady state operation, nor during the rapid transients associated with quick startup, cloud transients, and the step-wise heating of tubes characteristic of heliostat operation. These rapid transients are a key to efficient utilization of available insolation.

4. Present configuration of the receiver and associated equipment is ready to be used in the STTF facility after painting and solar mapping. It is also possible to be used in other facilities with additional analysis.

5. Life testing has been outside the scope of this program. It is recommended that investigations of fatigue strength of aolar-receiver tubing and boiler drums, and of life-cycles of supporting equipment, be included in future research in this area. It is recommended that an element test of tubes with one side radiant heating be performed to determine fatigue limitations.

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