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P. H. Adams, N. R. Keltner, C. T. Schafer, A. C. Skinrood

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

Printed July 1975

Sandia Laboratories
energy report

Issued by Sandia Laboratories, operated for the United States Energy Research and Development Administration by Sandia Corporation.

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Printed in the United States of America

Available From:

National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22151

Price: Printed Copy $4.00; Microfiche $2.25

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# TESTING A ONE MEGAWATT SOLAR RECEIVER IN AN ERDA RADIANT HEAT FACILITY

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## ABSTRACT

This ERDA-funded study investigated the feasibility of testing a Martin-Marietta designed one megawatt solar receiver in an ERDA Radiant Heat Facility located at Sandia Laboratories. It was concluded that tests utilizing quartz lamp arrays inside of the receiver or graphite heater arrays at the aperture could provide valuable compatibility and qualification data as well as provide data which will aid in interpretation of results to be obtained from tests at the Centre National de la Recherche (CNRS) solar furnace at Odeillo, France. It is proposed that three series of Radiant Heat Facility tests be conducted: (1) simulator tests; (2) pre-CNRS; and (3) post-CNRS. ERDA authorization to Martin-Marietta and Sandia Laboratories by August 1, 1975 will allow tests to be conducted on a schedule compatible with presently planned tests at CNRS.

# ACKNOWLEDGMENT

Guidance for this study was provided by G. Kaplan, ERDA Headquarters. Floyd A. Blake and Thomas R. Tracey, Martin-Marietta Corporation and Steve H. Bowmar, Jr., Georgia Institute of Technology made major contributions to the establishment of objectives, test configurations and schedules. Their assistance is gratefully acknowledged.

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# TESTING A ONE-MEGAWATT SOLAR RECEIVER IN AN ERDA RADIANT HEAT FACILITY

## SUMMARY

This ERDA-funded study indicated both the desirability and feasibility of testing Martin-Marietta's prototype one-megawatt solar receiver (Figure 1) in the ERDA Radiant Heat Facility at Sandia Laboratories. The radiant heat evaluation would be designed to supplement the testing program scheduled for the Centre National de la Recherche (CNRS) solar furnace test facility at Odeillo, France.* Results of this feasibility study indicate that valuable compatibility and qualification data would be obtained from a pre-CNRS series of radiant heat tests, and that post-CNRS tests could provide correlation between CNRS and radiant heat tests, aid in interpretation of the CNRS data, and provide information on the cyclic life of the receiver.

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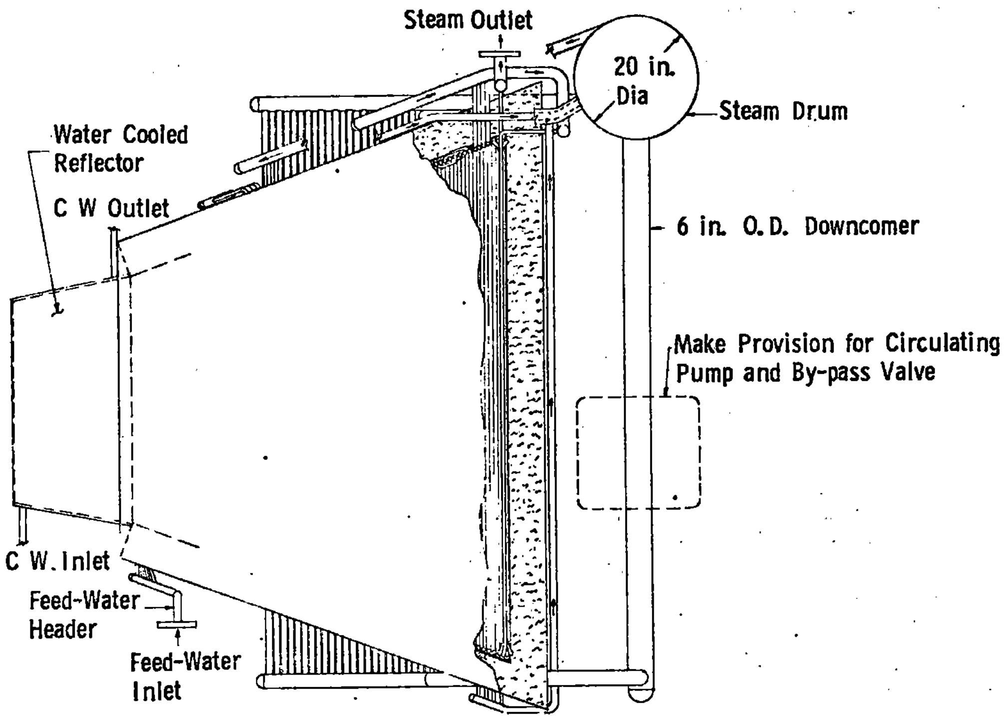
*Details of the CNRS test program are contained in a Martin-Marietta report, "Solar Power System and Component Research Program," January 1975, NSF/RANN/SE/AER75-07570.

EXPERIMENTAL CAVITY STEAM GENERATOR - SIDE ELEVATION



## 1 - 5 $MW_{TH}$ RECEIVER TECHNOLOGY - KEY SPECIFICATIONS

Scope: Component Development of Central Receivers for Solar Thermal Power Plants Based on Experimental Testing of Scaled-Down Units Capable of Operating with 1 and 5 $MW_{th}$ Concentrated Solar Energy.

1 $MW_{th}$ "Bench Model" Boiler/Superheater

| | |
|---|---|
| Input Capacity: | 1 $MW_{th}$ (3,413,000 Btu/hr) |
| Thermal Efficiency Goal: | 0.88 |
| Output Capacity: | 2225 lb of steam/hr |
| Steam Conditions: | $950°F_{min}$, 1250 psig ±50 |
| Feedwater (Condenser Discharge): | < 185°F, 0.3 - 17 psia |
| Enthalpy Gain: | 1350 Btu/lb |

Figure 1. Martin-Marietta Receiver Design

Based upon an analysis of instrumentation and equipment needs, the pre-CNRS radiant heat testing can be done on a schedule that is compatible with the planned tests at CNRS beginning in June 1976 if ERDA authorizes the radiant heat testing program by August 1, 1975.

## Proposed Test Program

The proposed radiant heat testing program consists of four phases:

- Feasibility testing
- Simulator testing
- Pre-CNRS testing
- Post-CNRS testing

The feasibility phase, which has been completed, was designed to select and evaluate specific testing apparatus to be used. The feasibility studies were necessary for two reasons. First, the radiant heater arrays had to be designed for the requirements for this particular test: a large area, relatively low to intermediate heat flux levels, and long-duration testing. The major concerns were minimizing the cost of the heater arrays. The second reason for the feasibility tests was to evaluate temperature and strain measurement techniques for use in the receiver environment.

The results of the various feasibility tests are included in the discussion of the test components in the section entitled, "Radiant Heat Test System."

The tentative schedule for the remaining three test phases is shown in Figure 2. This schedule was developed to allow Martin-Marietta to have their receiver and ancillary equipment ready for testing at CNRS by June 1, 1976. In order that the tests be conducted on this schedule, it is necessary that authorization for the pre-CNRS testing be received about August 1, 1975.

## Simulator Tests

The purpose of the simulator testing is to determine how closely the heat flux distributions created by the Radiant Heat Facility match the ones to be measured at CNRS. The comparison will be accomplished as follows.

During August-December 1975, Georgia Tech. will use a "receiver simulator" to obtain flux data at the CNRS test facility. This simulator is an instrumented mockup of the actual receiver that allows the flux levels to be measured on

FIGURE 2. SCHEDULE

| Date | Sandia | Martin-Marietta | Georgia Tech. |
|---|---|---|---|
| 8/1/75<br>Test Authorization | Start detailed design of heater arrays & test stand | Receive authorization to complete test support & cold flow checkout tests | Place hardware orders for receiver simulator (#2) |
| 10/1/75 | Place orders for heater arrays and test stand | | Start receiver simulator (#1) testing at CNRS |
| 12/1/75 | | Data available from simulator (#1) testing | |
| 2/1/76 | Start receiver simulator (#2) testing at Radiant Heat Facility | | |
| 3/1/76 | | Receiver & flow control system complete. Cold tests complete, ship to Albuquerque | |
| 3/15/76 | Start radiant heat tests of receiver (Series A) | | |
| 5/1/76 | Complete radiant heat tests of receiver (Series A) | Ship receiver and equipment to CNRS | |
| 6/1/76 | | Start test setup at CNRS | |
| 7/1/76 | | Begin solar tests at CNRS | |
| 10/1/76 | Define Series B tests in detail using data from CNRS tests | | |
| 12/1/76 | | Complete CNRS tests and ship receiver and equipment to Albuquerque | |
| 2/1/77 | Begin Series B tests | | |
| 7/1/77 | Complete Series B tests | | |

the wall sections of the receiver. It is proposed that a duplicate receiver simulator be used to measure the flux levels produced by the Radiant Heat Facility. In this manner, the radiant heater arrays can be designed so that the flux is tailored to the CNRS pattern as closely as possible.

## Pre-CNRS Test Series (Series A)

The series designated "A" in the schedule has the object of qualifying the receiver, auxiliary equipment and controls before the CNRS testing.

This series will begin with several low-level tests intended to check out the system. The levels will be gradually increased to approximately the CNRS levels. Start-up, temperature cycling, shut down, and up to 6-day-long checkout tests will be performed.

## Post-CNRS Test Series (Series B)

The series designated "B" has the object of correlating the CNRS test results with the data taken at the Radiant Heat Facility after the CNRS tests and providing engineering data. Engineering development tests will be conducted on the receiver to determine the effects of increased levels, radically non-uniform flux distributions, long-term tests, and thermal cycling.

Testing the one-megawatt receiver will provide a technology base for testing of 5 $MW_t$ receiver designs to be built by the Subsystem Research Experiment contractors funded by ERDA.

Detailed planning of the Series B tests will be done after data from the Series A receiver tests have been evaluated.

## Radiant Heat Test System

In utilizing the Radiant Heat Facility for this particular application, three basic test options were considered:

- Radiant heaters internal to the receiver
- Radiant heaters at the aperture of the receiver
- Exposure of individual sections of the receiver

The first option, shown in Figure 3, appears to be the best choice because the heat flux on the individual walls can be tailored to approximate CNRS fluxes by varying the design of the heaters and by controlling the electrical input power for each section. In addition, this design will simplify many of the preliminary checkout and startup tests because the heat fluxes on the individual sections of the receiver can be brought up at different times. For example, the heat flux

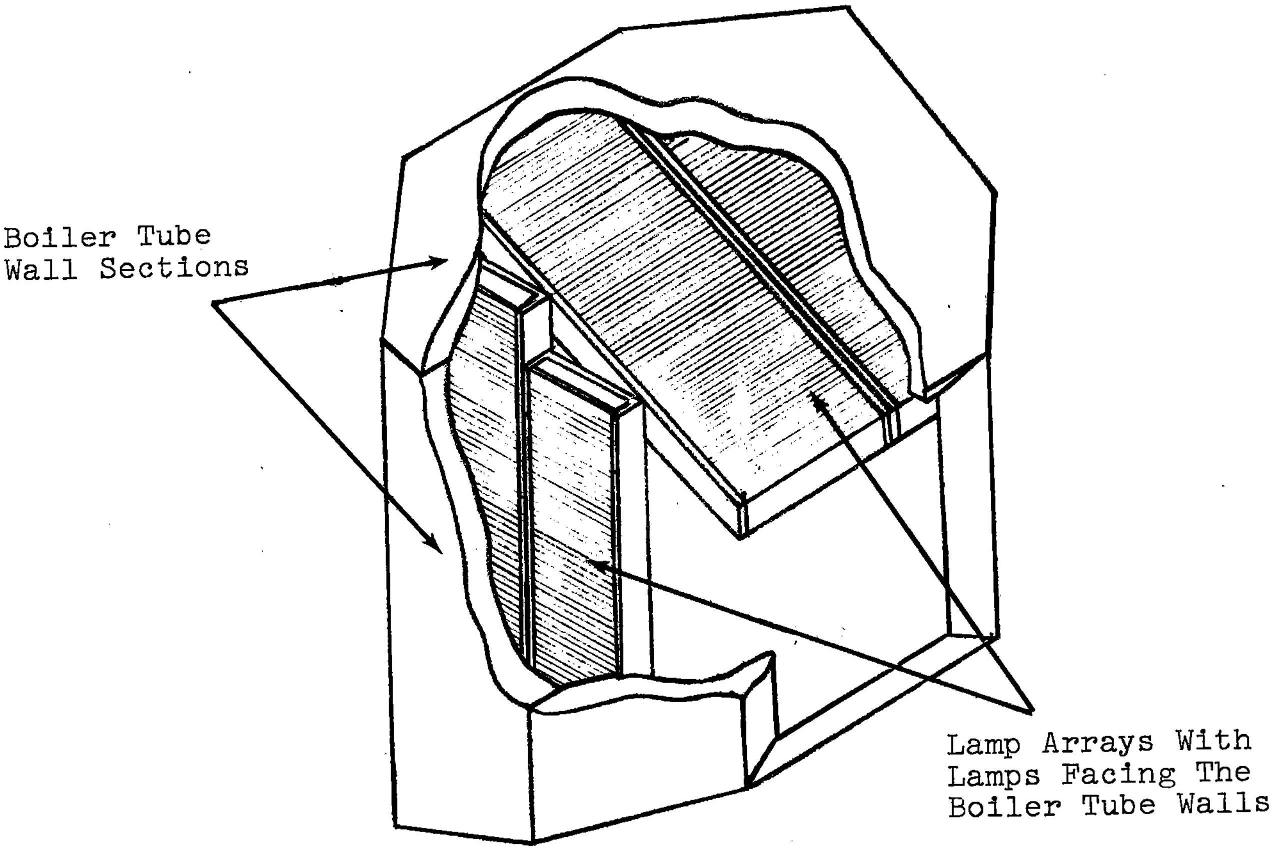
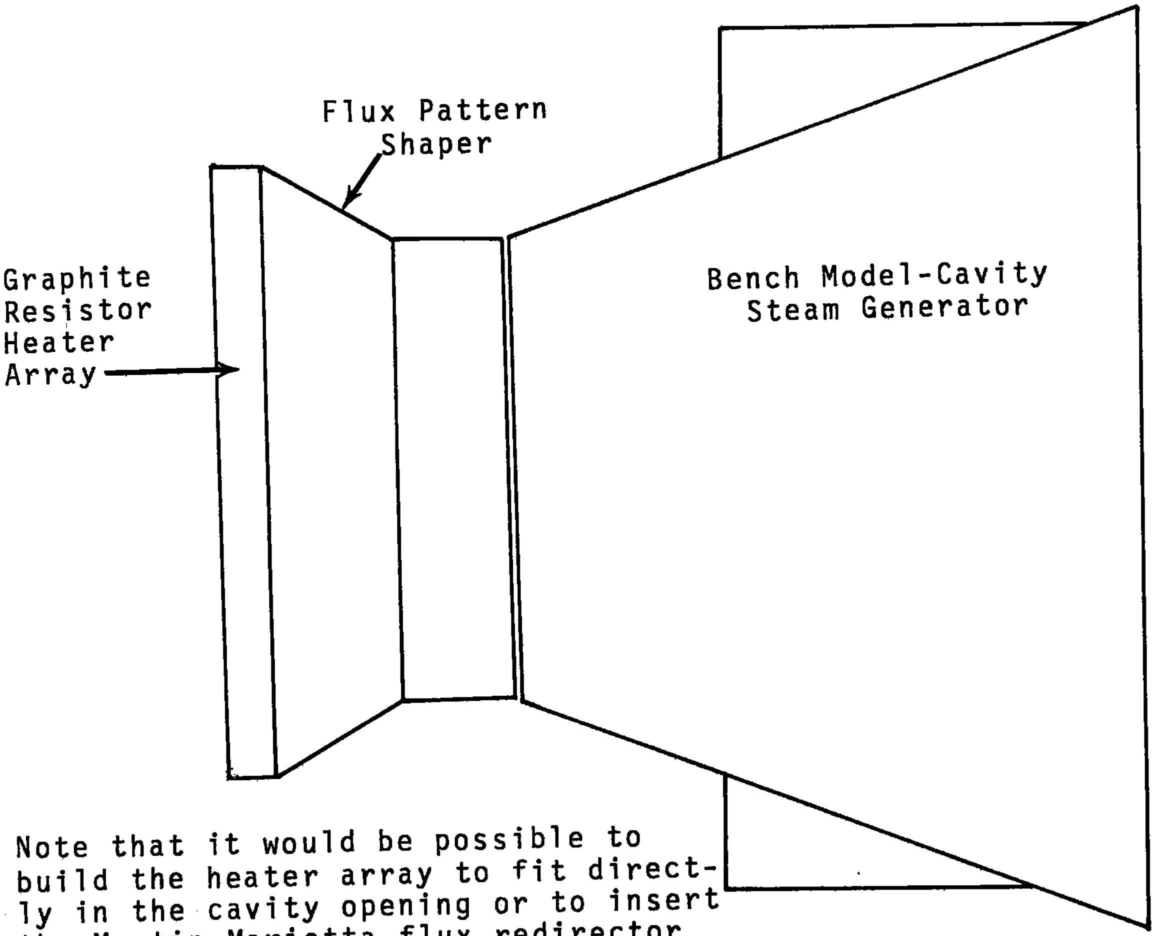


Figure 3. Possible Configuration for Lamp Arrays Built Inside the Boiler Assembly

on the superheater section can be held at near zero until steam flow is established. Required maximum flux levels will be approximately 15 W/cm$^2$. These flux levels can be provided by tungsten filament radiant heaters. The use of heater elements of this type is advantageous in that the receiver does not have to be sealed, and an inert atmosphere does not have to be maintained as would be required for use of graphite-resistive heater arrays. The main disadvantage of this option is its mechanical complexity; this leads to higher costs in designing, fabricating and assembling the heater arrays. For example, this option would require assembly and disassembly of the heaters inside the cavity at least three times during the testing sequence.

With regard to the other options, locating radiant panels at the aperture (Figure 4) could probably achieve the desired flux level on the receiver walls, but matching the distribution would make the design more difficult. The flux levels required for this option (100 to 250 watts per cm$^2$) would necessitate the use of graphite-resistive radiant heat arrays operated in an inert atmosphere; thus, the receiver would have to be sealed. In addition, directional control of the radiation might be required to match CNRS distribution. The simplified mechanical design of this type of heater and the fact that it would be assembled only once should make the overall cost of this option lower.



Note that it would be possible to build the heater array to fit directly in the cavity opening or to insert the Martin-Marietta flux redirector between the shaper and the cavity.

Figure 4. Possible Configuration for Radiant Heat Test of the Complete Steam Generator

Option 3, testing of individual receiver panels, is not attractive since the receiver is of welded construction and cannot be readily disassembled.

Test Configuration

In evaluating the above options, both the tungsten filament lamps and graphite resistor arrays were tested. A detailed description of the evaluation testing performed on both the graphite resistor arrays and a specialty lamp array is given on pages 26 through 31.

The proposed test configuration consists of flat panel lamp arrays of the type shown in Figure 5. These panels will be designed to cover the individual receiver faces as completely as possible. Seven power control channels will be utilized for the receiver testing in a heat flux feedback control mode. Figure 6 shows the nodal structure used by Martin-Marietta in their radiant transfer analysis of the receiver; Figure 7 shows the coverage of the receiver surfaces with the seven control channels or zones. Two channels will be utilized for the preheater surfaces, two channels for the boiler surfaces, and three channels for the superheater surfaces. The heat flux level in each control zone will be tailored to approximate the expected heat fluxes in the CNRS tests by:

- Controlling the voltage applied to the lamps;
- Varying the lamp spacing in the array;
- Using a combination of lamps with 100 W/in and 200 W/in power dissipation capabilities at rated voltage.

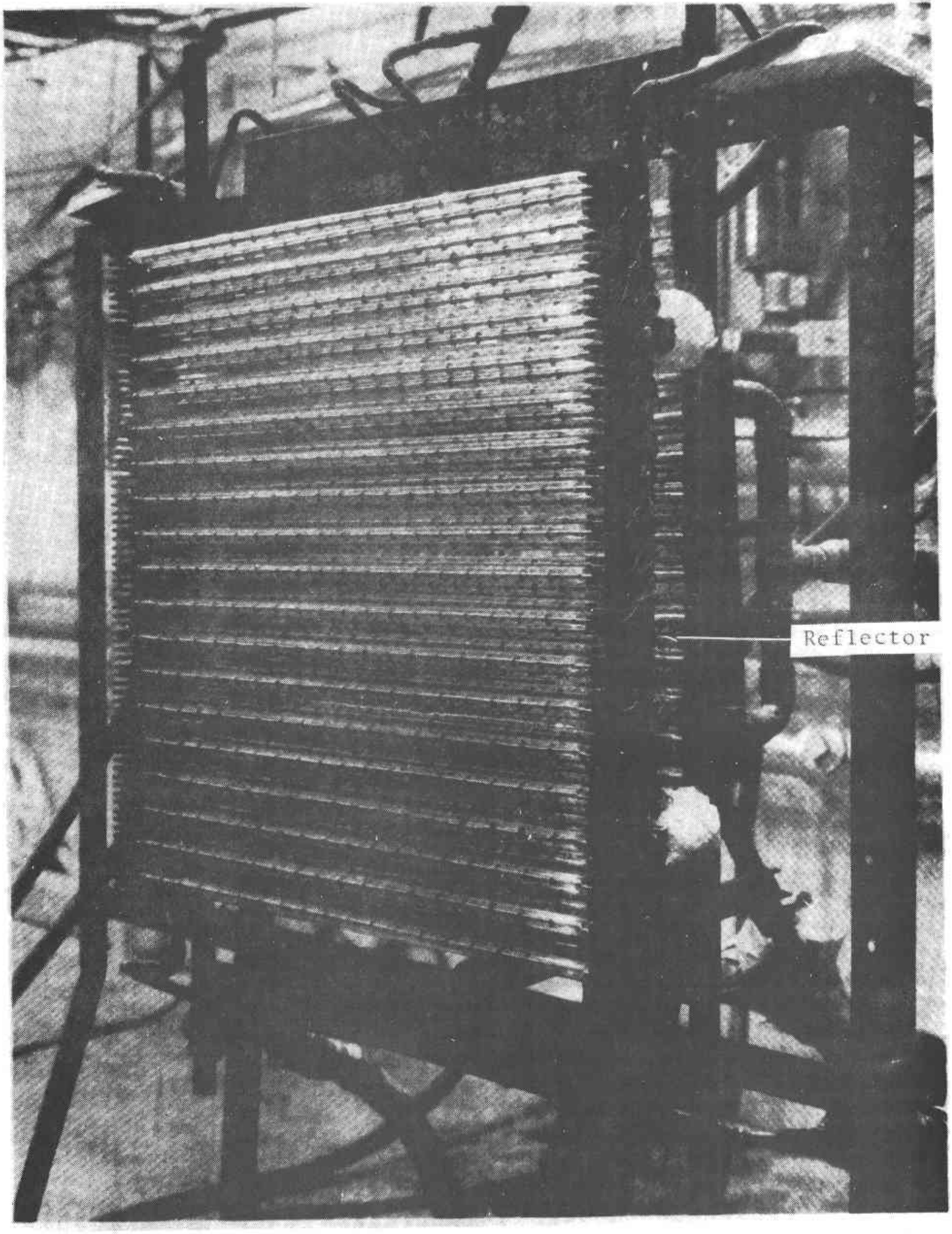


FIGURE 5. PLANAR QUARTZ LAMP HEATER ARRAY

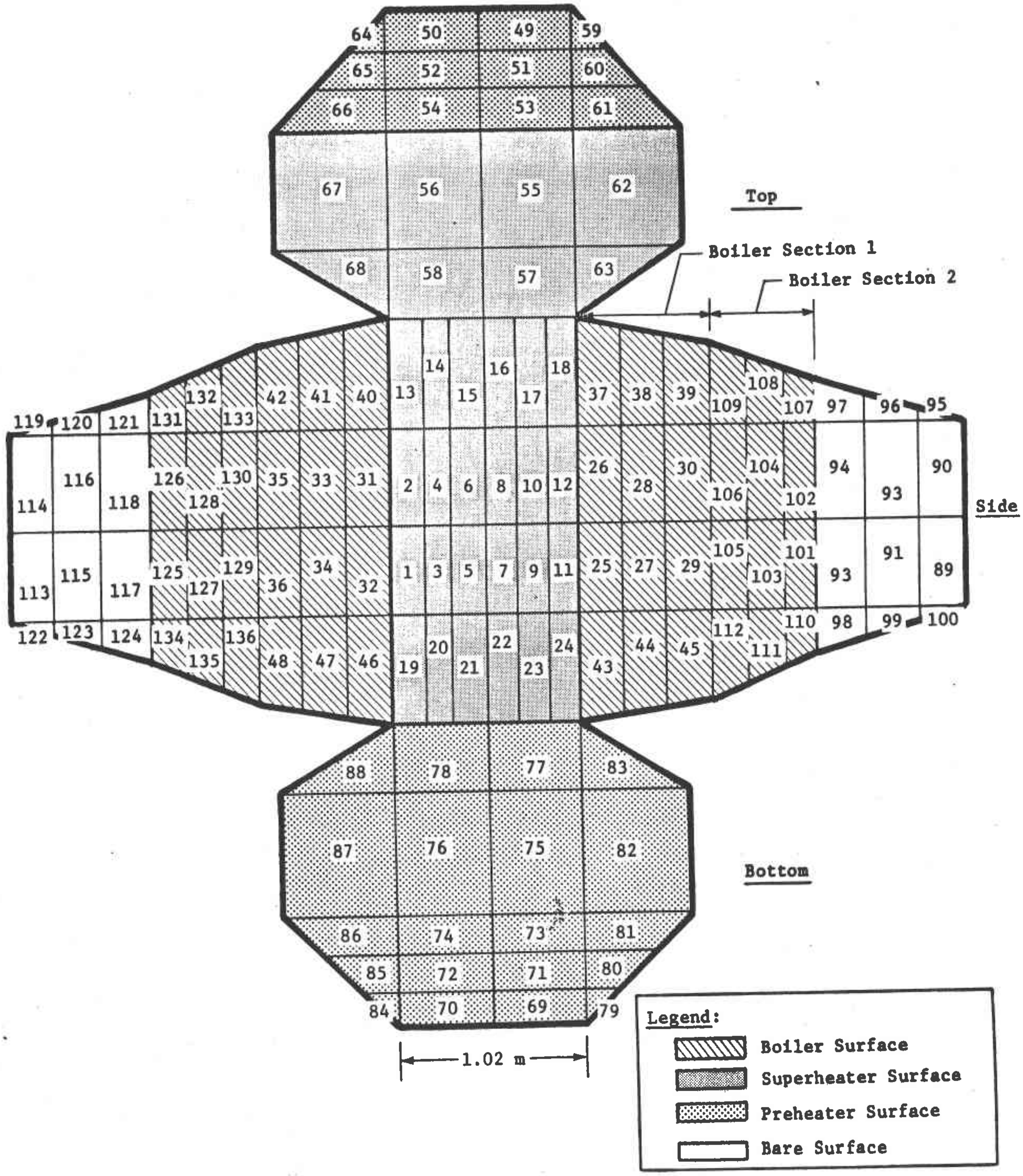


Figure 6. Cavity Surface Node Numbers (From Reference)

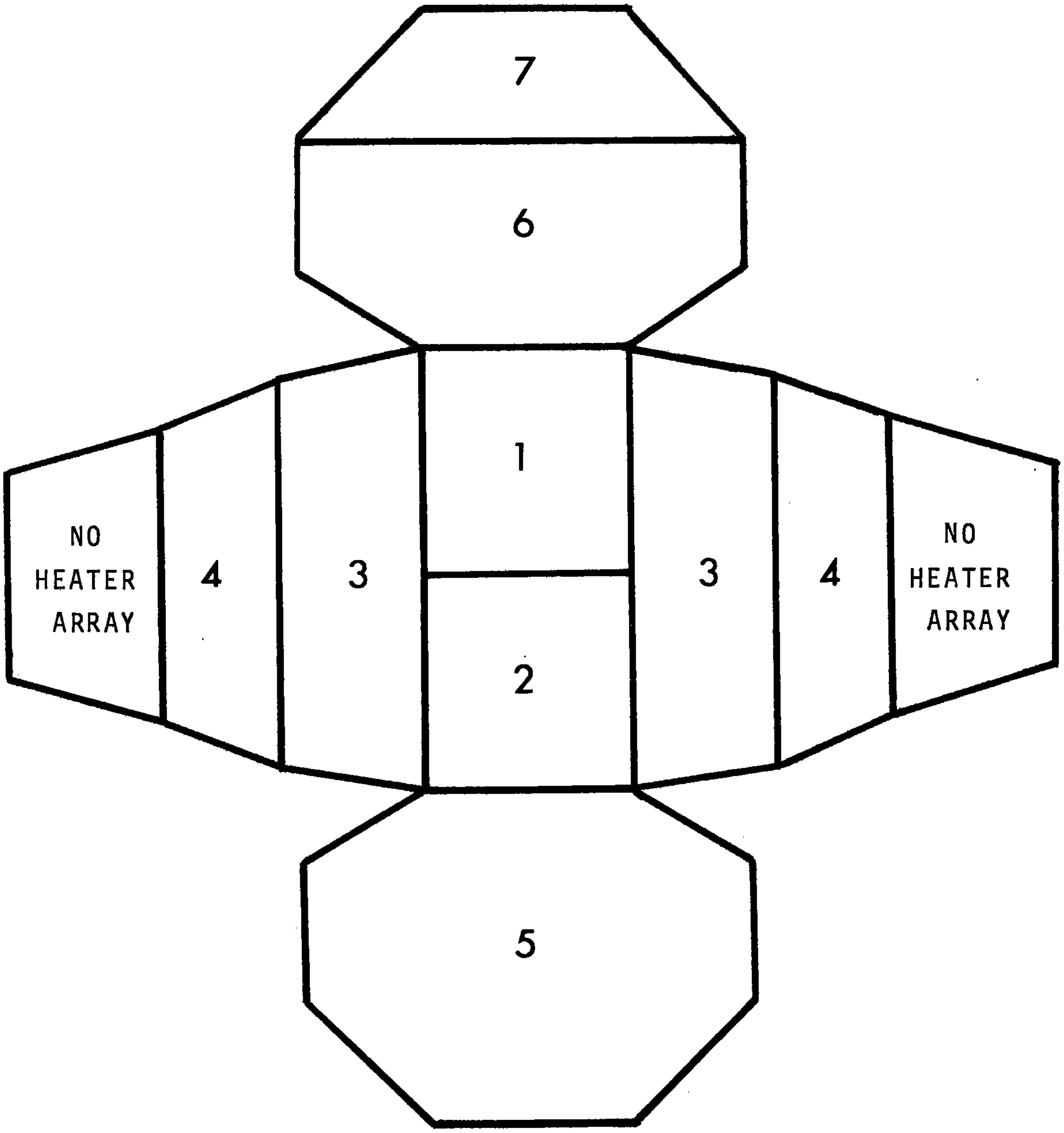


Figure 7. Control Channel Coverage of Receiver Surfaces

## Facility Studies

Lamp Array -- The lamp array tested to date is shown in Figure 8. The reflector is a 20-inch high by 31-inch wide by 3/8-inch thick polished aluminum plate. Tungsten filament lamps with a 25-inch lighted length and a power rating of 5000 W at 600 V are used in the array in a single row configuration with a 1/2-inch center-to-center spacing. The rear surface of the reflector is air cooled; the air flow is from holes in a serpentine copper coil arrangement or a muffin fan/plate arrangement (Figure 9).

The test runs for evaluating the heat flux capabilities of the array used a circular foil heat flux gage with no mounting shield to monitor incident heat flux. Temperature measurements were made at five locations on the rear surface of the reflector; Table I shows the results.

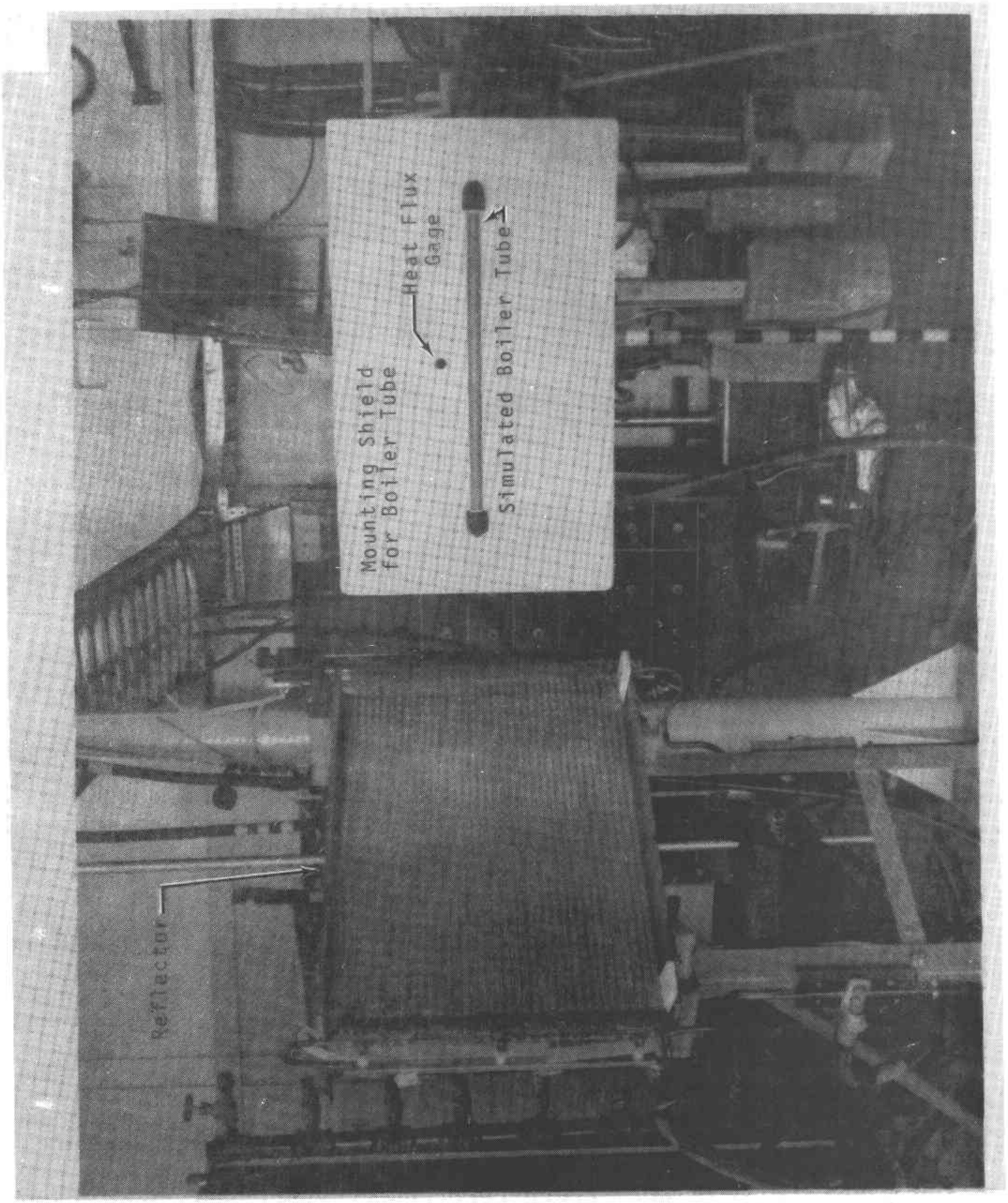


Figure 8. Flat Lamp Array and **Instrumented Boiler** Tube

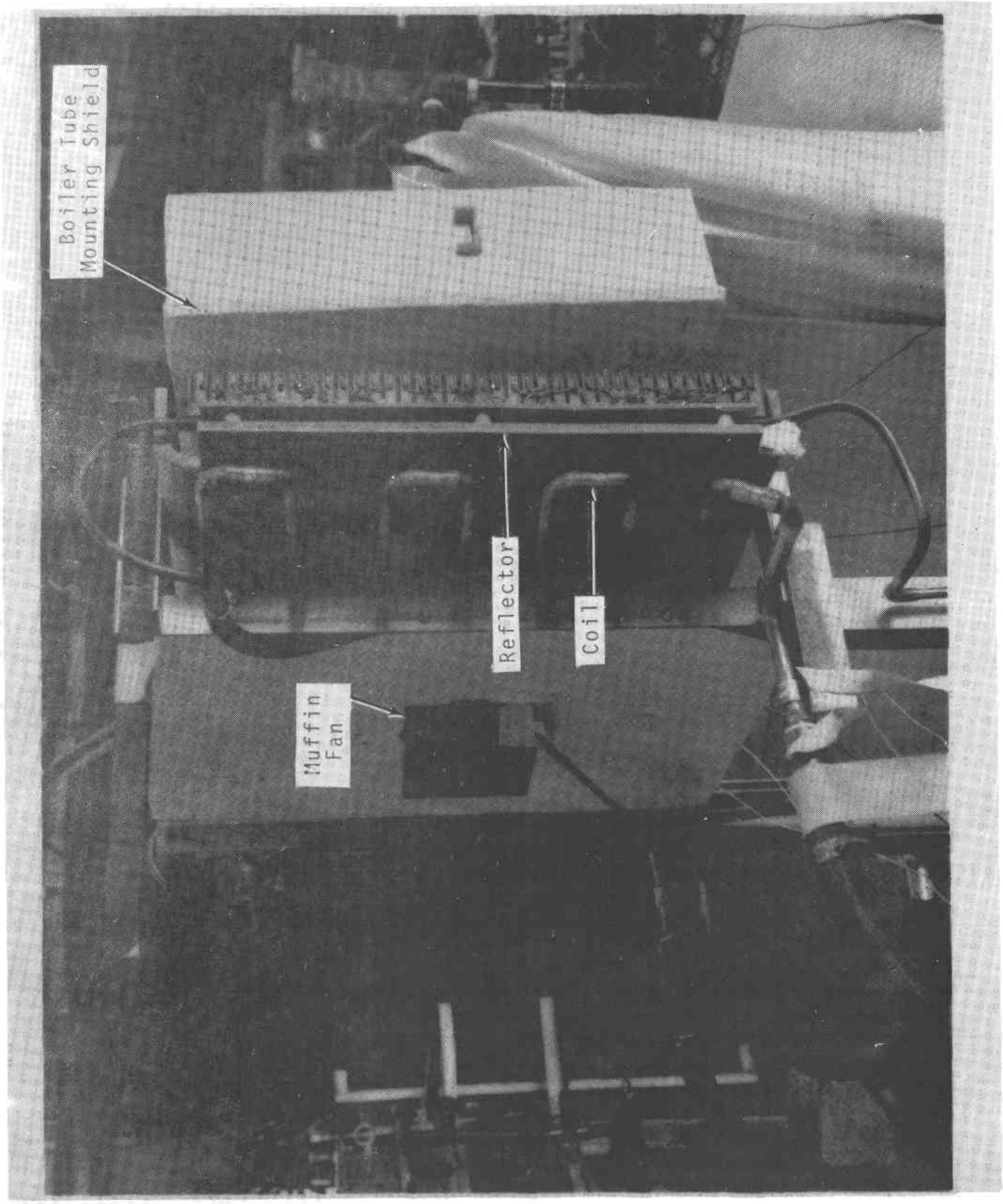


Figure 9. Configuration for Reflector Cooling and Instrumentation Tests

[illegible]

Table I

| Heat Flux BTU/FT$^2$-S | W/CM$^2$ | Voltage | Reflector Temperature (K) | Air Flow (CFM) | Air Supply |
|---|---|---|---|---|---|
| 4.5 | 5.1 | 80 | 388 | ~ 26 | Coil |
| 5.6 | 6.4 | 160 | 432 | ~ 26 | Coil |
| 7.9 | 8.9 | 200 | 518 | ~ 25 | Coil |
| 13.2 | 14.3 | 300 | 510 | ~ 57 | Coil |
| 21.9 | 24.9 | 400 | 625 | ~ 62 | Coil |
| 11.2 | 12.8 | - | ~500 | ~100 | Fan |

The results indicate that this lamp array could easily meet even the peak local heat flux requirement of 25 W/cm$^2$. Based upon these results, it may be possible to increase the lamp spacing from the 1/2-inch center-to-center used and thus decrease costs.

Air cooling of the reflectors should pose no problem. Blowers with somewhat higher static pressure capabilities than the muffin fan should be able to hold reflector temperatures to acceptable levels.

To evaluate heater performance under conditions similar to the receiver environment, several experiments were conducted with a steel plate facing the lamp array. The gap between the array and the plate was closed off with Refrasil® cloth to prevent convective cooling of the lamp envelopes. The plate temperature was raised to 810 K and held there for one hour. No degradation of the lamps or the reflector was noted.

## Other Radiant Heater Configurations Tested

Specialty Lamp Array -- A preliminary series of experiments were conducted to examine the feasibility of using specialty lamps to provide greater spatial variations in heat flux and possibly match the distributions expected in the CNRS tests. The setup utilized for these experiments is shown in Figure 10. The reflector is a polished aluminum truncated conical surface with a .7-rad half-angle curve.

Results of the preliminary runs are shown in Figure 11. The distribution for this design is very peaked and slightly below the peak flux listed in Martin-Marietta's report. Time did not allow a complete examination of this approach; however, the preliminary conclusions are that the heat flux capabilities are marginal for testing the bench model and that a significant amount of analysis would be required to design a complete array.

Graphite Resistor Arrays -- The experiments conducted with the graphite resistor array had a two-fold purpose:

- Determine the efficiency of converting the input electrical energy to thermal energy delivered to a water-cooled plate;
- Provide a preliminary determination of whether this type of array can provide sufficient heat flux capabilities to be utilized as an aperture heater (100 $W/cm^2$ or greater).

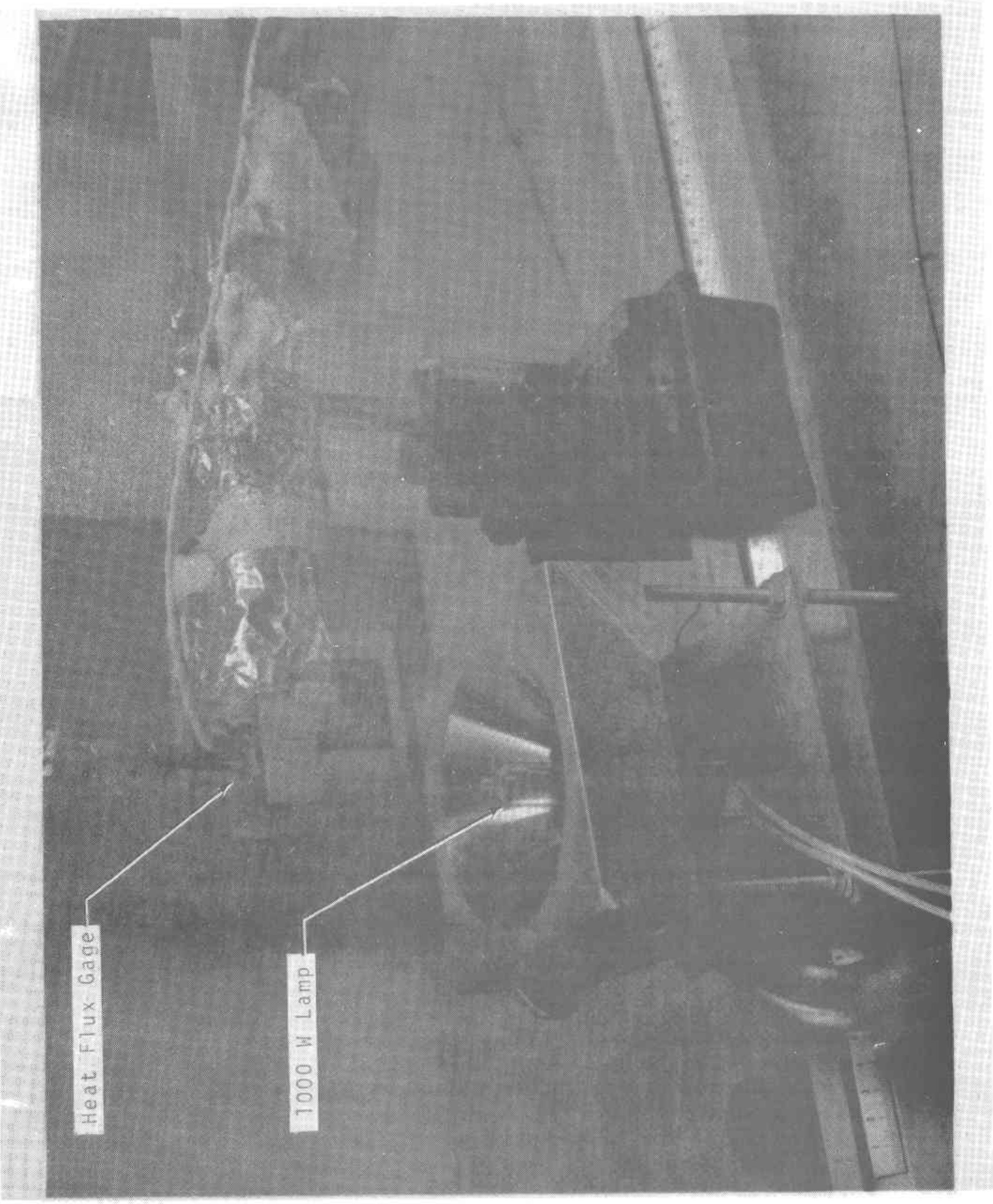


Figure 10. Specialty Lamp Test Setup

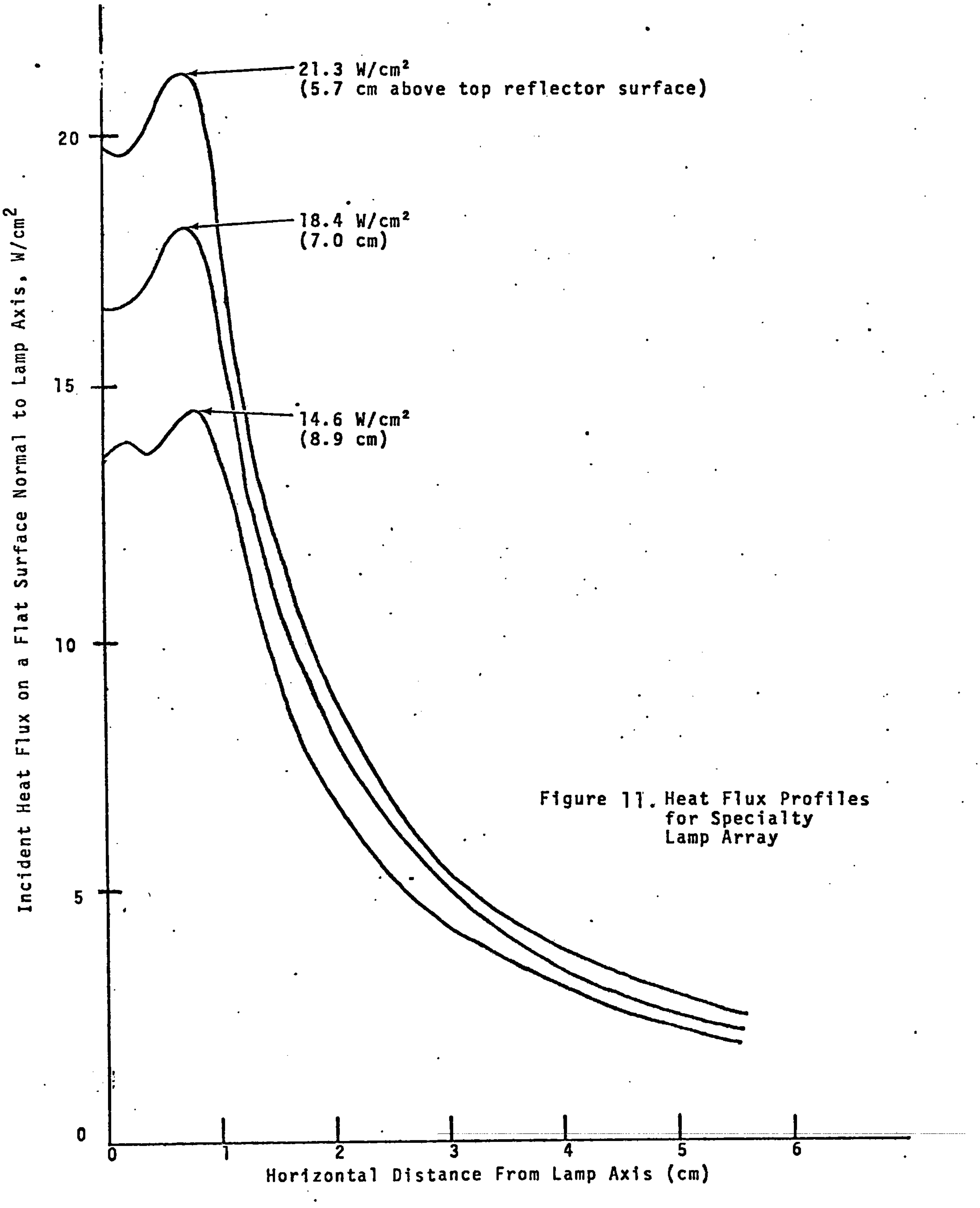


Figure 11. Heat Flux Profiles for Specialty Lamp Array

The setup utilized for these experiments is shown in Figure 12. Five sides of the box in which the graphite resistor was mounted were designed to be refractory surfaces; the sixth side was a water-cooled steel plate. Two designs were used for the refractory sides:

Insulated Design -- One-half-inch thick Fiberfrax® board lined with one-half inch of Microquartz® felt.

Radiation Shield Design -- The Fiberfrax board lined with three layers of Grafoil® which served as radiation shields.

The box was purged continuously with argon.

With the insulated design, the conversion efficiencies ranged from between 85 percent and 92 percent, with incident heat fluxes on the center of the cooled plate between 5.7 watts/cm$^2$ and 28 watts/cm$^2$.

For the radiation shield design, longer duration runs were conducted at 17 watts/cm$^2$ to determine efficiency and evaluate degradation of the resistor. Conversion efficiencies averaged 90 percent. There was significant degradation of the resistor during the first several runs. However, this degradation was traced to an air leak in the box; once this leak was plugged, there was no significant degradation on any subsequent runs, even at flux levels up to 68 watts/cm$^2$.

In the final experiments, the system was pushed to destruction of the steel plate, which occurred at a flux level

| Org. | Bldg. | Name | Rec'd by* | Org. | Bldg. | Name | Rec'd by* |
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*Recipient must initial on classified documents.

of 68 watts/$cm^2$ for a period of 25 minutes. No significant degradation of the resistor or the Grafoil lining occurred (Figure 13). The conversion efficiency was 85 percent; this low efficiency is attributed to radiation losses from the other surfaces of the box, most of which were cherry red.

From the results of these experiments, two conclusions have been drawn:

- Graphite resistance heaters can be utilized for long-term heating of the 1 MW and larger receivers at efficiencies of at least 90-95 percent. This higher efficiency results from scaling up of the heater area in relation to the area of the refractory surfaces in the actual design.
- An aperture heater operating at heat fluxes in excess of 100 W/$cm^2$ could be built using basically the same design as the Grafoil-lined box.

## Instrumentation

Two types of measurements will be required during the actual tests: temperature and strain. To evaluate methods for measuring the temperature and strain of the boiler tubes, measurements have been attempted on both the lighted and unlighted sides of a 3/4-inch O.D. steel pipe.

The temperature measurements were made with intrinsic thermocouples, sheathed thermocouples, and platinum resistance thermometers. Experimental results indicate that intrinsic thermocouples should be utilized for all of the tube

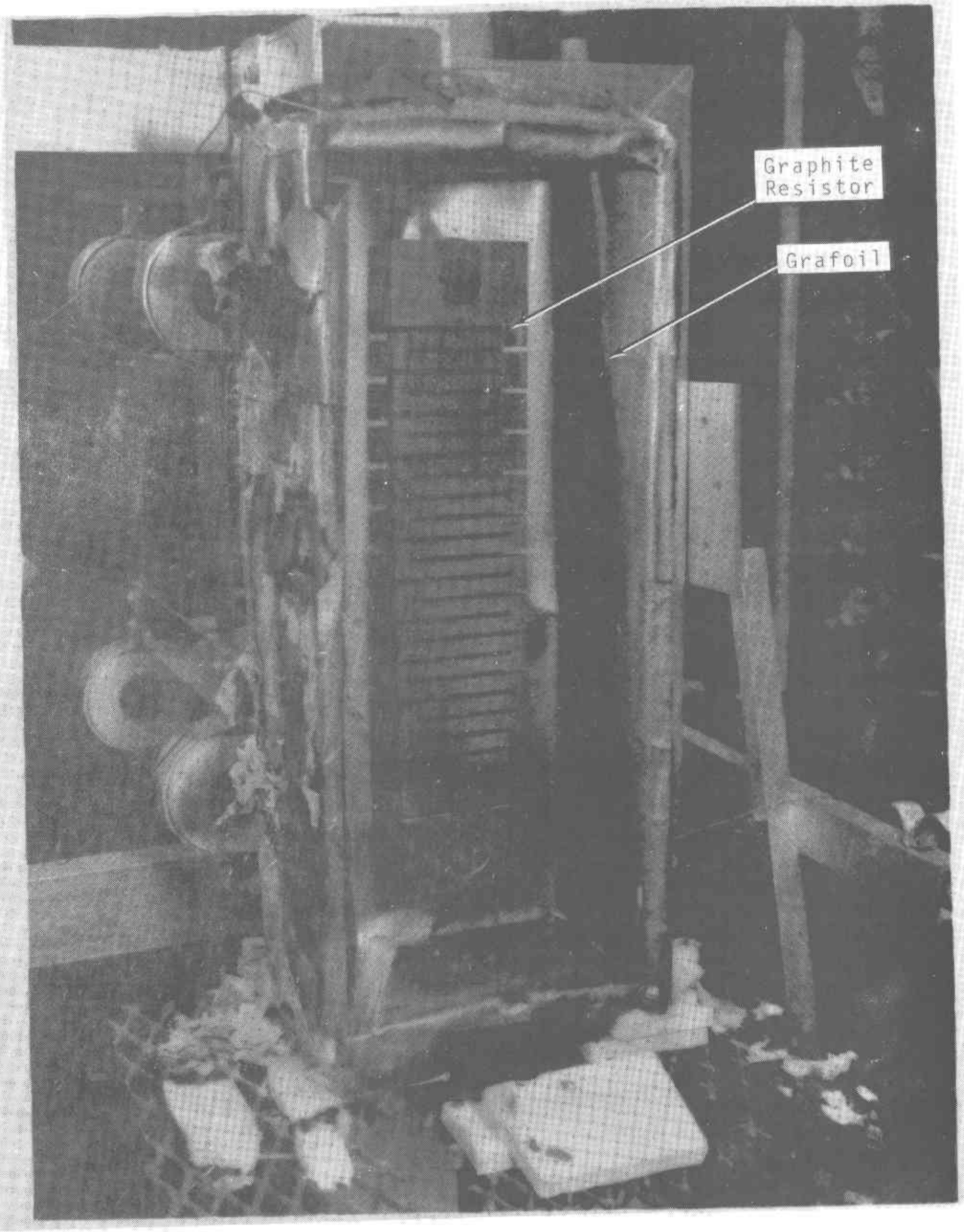

Figure 13. Interior of Graphite Resistor Setup at Completion of High Heat Flux Tests

temperature measurements. Metal sheathed or metal-armored thermocouple wire is recommended for durability.

The strain measurements were made with weldable strain gages and gages attached to the tube with flame-sprayed alumina. The weldable gages were:

- Ailtech SG423-4 -- a platinum-tungsten alloy gage with a dummy gage in the gage enclosure.
- Ailtech SG128 (SG125) -- a Karma alloy self-temperature-compensated gage.

The flame-spray attached gage was a BLH-HT-12115-8A-1 platinum/tungsten alloy gage.

Test results indicate that steady-state and transient measurements (with surface temperature rise rates of 50 K/min or less) can be made on the unlighted side of the tubes. The recommended gage is the Ailtech SG425 (an improved version of SG423-4) with a cost of $160 per channel. Strain measurements on the lighted side of the tubes may be extremely difficult. Serious heating problems were experienced with all gages tested. If lighted side measurements are determined to be absolutely necessary, investigations should be started immediately on a Boeing-designed capacitive strain gage manufactured by Hitec Corporation, Westford, Massachusetts. The cost per channel for these measurements might be $2500.

## Lead Times

Table II lists the projected lead times for major items in the test setup.

Table II

Projected Lead Times

| | |
|---|---|
| Structure and Reflectors | 6-8 weeks |
| Lamp Holders | 8-10 weeks |
| Lamps | 10-26 weeks |
| Air Cooling System | 10-12 weeks |
| Instrumentation | 6-8 weeks |
| Cables | 8-10 weeks |
| Graphite Resistors | 10-12 weeks |

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