CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM

Review and Summary of Available Test Facilities

MASTER

THE AEROSPACE CORPORATION

DISTRIBUTION OF THIS DOCUMENT UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM

REVIEW AND SUMMARY
OF
AVAILABLE TEST FACILITIES

Prepared for:
THE NATIONAL SCIENCE FOUNDATION
Washington, D. C.

January 1975

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Prepared by:
ENERGY AND RESOURCES DIVISION
THE AEROSPACE CORPORATION
El Segundo, California

Telephone: (213) 648-6407

Contract No. NSF-C933
Task Order No. 1

MASTER

TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	3
2.0 TEST OBJECTIVES	4
2.1 Receiver	4
2.2 Collector	11
2.3 Thermal Storage	11
3.0 AVAILABLE FACILITIES	12
3.1 Receiver	12
3.1.1 CNRS Solar Furnace, Odiello, France	18
3.1.2 U. S. Army Solar Furnace, White Sands, N. M.. . . .	22
3.1.3 Arnold Engineering Dev. Center, Tenn.	25
3.1.4 NASA Lewis Solar Simulator, Cleveland	26
3.1.5 JPL, Pasadena, Calif.	27
3.1.6 Aerothermal Test Facility, G. E., Phila. Pa.. . . .	28
3.1.7 Radiant Heat Facility, Sandia Labs, Albuquerque, N. M.. . . .	31
3.1.8 "Heat Facility," NASA, Edwards AFB, Calif.. . . .	42
3.1.9 Radiant Heat Facility, Flight Dynamics Lab, Wright-Patterson AFB, Ohio.	47
3.1.10 Radiant Heat Facility, McDonnell Douglas Aircraft, St. Louis	51
3.1.11 NASA, J. S. C. Houston, Texas	57
3.1.12 Rockwell International, Downey, Ca.	58
3.2 Collector	59
3.2.1 Optical Evaluation Facility, Sandia Labs, Livermore, California	60
3.2.2 Optical Evaluation Facility, NASA Lewis Research Center	63
3.2.3 Naval Weapons Center, China Lake, California	64
3.3 Thermal Storage	66
3.3.1 Sandia Laboratories, Livermore, California	67

1.0 INTRODUCTION

The National Science Foundation is undertaking the development of a Central Receiver Solar Thermal Power System for the conversion of solar radiation into thermal energy and then to electrical power by conventional methods. The next phase of this program will involve the efforts of several contractors or contractor teams, each preparing a preliminary design for a 10 MWe Proof-of-Concept Experiment (POCE) Pilot Plant. The preliminary designs will evolve largely from a series of subsystem research tests which are intended to verify, by actual hardware operation and evaluation, the design concepts and analyses. The data and results of those engineering and development tests are essential to provide the proper basis for, and confidence in, the preliminary designs of the POCE Pilot Plant. The POCE Pilot Plant Preliminary Design will be technically and logically related to the proper design and construction of anticipated commercial Central Receiver Solar Thermal Power Systems. The research experiment hardware and testing procedures must simulate the system operational conditions in order to properly verify the performance expectations derived from the analyses, as well as the conceptual and developmental design efforts. Of the three subsystems included in the Subsystem Research Experiments (Collector, Receiver, and Thermal Storage) the Receiver Subsystem seems to pose the greatest problems concerning availability of adequate test facilities for conducting meaningful tests. The emphasis in this report will be concerning those facilities for the receiver subsystem experiments. Even though concerted efforts have been made to identify those facilities, both government and industrial, which could be of use in conducting such tests, no claim can be made that the coverage is complete and that all existing facilities have been included. It is believed that the more important government facilities and the better known or available industrial facilities have been included. It is also believed that they are representative of existing facilities and will provide a reasonable check list for initial screening by prospective program participants.

The test facility descriptions were provided by personnel at each of the various test facilities. Some editing was made to the facility descriptions in the compilation of this report. The National Science Foundation and The Aerospace Corporation wish to thank each of the contributors for the effort required for the preparation of this document. These individuals are identified in the appropriate sections of the text.

2.0 TEST OBJECTIVES

2.1 Receiver

The objectives of the Receiver Subsystem Research Experiments are to provide the research and test data necessary to demonstrate and verify the technical and economical feasibility of achieving solutions for the high risk technological issues of the Receiver Subsystem. Since the identification of a receiver design is the major objective of these tests, it is not possible to identify specific configurations beyond that of these basic concepts: (1) enclosed tube, or cavity receiver, and (2) exposed tube receiver. Either receiver concept employs thermal cycles such as indicated in Figures 1, 2, and 3. Whatever facilities are employed in the testing of the specific receiver configurations, the essential design data and verification results must be determined. Each receiver configuration will require specific and unique test procedures, instrumentation and facilities to satisfy the test objectives.

The test hardware, as a model or module of the prototype concept, must provide adequate similitude of the operational conditions in each of the areas of concern: size, flows, dynamic response, etc., while the test facilities must provide controlled and reproducible inputs to the test hardware.

The primary requirements for the test facility are to provide steam generator interfaces which will normally exist in the central receiver system and to provide necessary data taking and reduction facilities to make the test results meaningful. The principal interfaces are the radiant heat source and fluid interfaces. In many instances, these interfaces will be dictated by the particular design of the steam generator. Consequently, test facilities must have sufficient flexibility to accommodate various steam generator designs as well as dynamic modes to simulate the transients of plant operations. The radiant heat source requirements will be dictated by the trade-offs between the receiver and the particular design of the collector assembly. Since neither the collector nor the receiver (steam generator) have been designed, test facility requirements are discussed below in general terms.

The following discussions are not intended to be tutorial in nature, but are presented to indicate the general facility requirements for conducting engineering and development tests for the receiver concepts. The specific values are illustrative only and are not intended to specify design values.

Steam Cycle Consideration. The steam cycle which will be used in the central receiver will probably be some derivative of the Rankine Cycle. Although the exact nature of the cycle is still unknown and the temperature and pressure values a matter of speculation, some general comments can be made. Figure 1 shows the basic Rankine steam power plant cycle. The major components are the steam generator, the steam turbine, the condenser, and the fluid pump. The cycle is shown on a temperature-entropy

diagram. In this particular cycle, compressed liquid is introduced to the steam generator at state point 1 (p approx. 1250 psia, T approx. 110 F) and exits the generator at state point 4 (p approx. 1250 psia, T approx. 950 F). The test facility must be able to provide water to the generator at state point 2 and accept it back at state point 4. There are several options for providing water at the necessary conditions: (1) water at state point 6 can be pumped to state point 1 where it is introduced to the generator; superheated steam at 4 can then be dumped into the atmosphere or into a cooling pond (the primary concern in this approach is providing necessary make-up water at sufficient purity); (2) a second approach would be to use a high pressure condenser where steam at state point 4 will be cooled along the 4-3-2-1 curve; this is basically reversing the boiler process; the advantage of this method is that the working fluid is reused, and that the pumping power will be reduced because once the system is charged only a circulation pump will be necessary.

Figure 2 shows a Rankine cycle with one reheat. The steam generator interface is more complicated because fluid from the high pressure turbine at 5 is reheated to 6. The turbine process from 4 to 5 and from 6 to 7 are work extraction processes where the pressure, temperature, and energy content are reduced at nearly constant entropy. Simulation of this process is most difficult without a turbine. A throttling process followed by a cooling process can be used to get the fluid from 4 to 5. Also, an auxiliary boiler could be used to provide steam at state point 5.

Other features which are generally seen in a steam power plant are additional reheats and feed-water heaters. The basic rationale for using reheats and feedwater heaters are that they improve cycle efficiency. It is not expected that the test steam generators will have many reheat cycles. Feed water heating would be considered part of the steam generator.

Both cycles considered above are subcritical cycles. A third potential cycle is the supercritical cycle shown in Figure 3. The main feature with this cycle is that the pressure is in the order of 3500 psia and the inlet and outlet temperature are approximately 110 and 850 F, respectively.

Based upon the above discussion, power cycle interfaces were developed to serve as a basis for comparison of existing facilities. These baseline cooling system requirements are outlined in Table I. The thermal heat load for the steam generator was assumed to be 5 MW. Consequently, for steady state testing, the cooling system must be capable of rejecting 5 MWth. The working fluid (water) flow rate through the steam generator will be in the order of 1.46 Kg/sec (23 gpm) for the cycle shown in Figure 1. Inlet fluid to the steam generator must be conditioned to approximately 43 C and 85 ATMOS. The inlet fluid (1.46 Kg/sec of 43 C and 85 ATMOS water) can be from a closed cycle system or an open cycle. The type of system selected will have an impact on items such as the pump components and the cooling system and the selection of a water supply. If a

Figure 1. Simple Rankine Cycle

Figure 2. Rankine Cycle with Reheat

Figure 3. Supercritical Rankine Cycle

Table I. System Cooling Requirements

o Heat Load	5 MW	15 mil. Btu/hr
o Working Fluid Flowrate	1.46 kg/sec	11600 lb/hr (23 gpm)
o Fluid Inlet Conditions to Generator (Primary)		
- Temperature	43 C	110 F
- Pressure	85 ATMOS	1250 psia
o Fluid Outlet Conditions from Generator (Primary)		
- Temperature	510 C	950 F
- Pressure	85 ATMOS	1250 psia
o Fluid Inlet Conditions to Generator (Secondary)		
- Temperature		500 F
- Pressure		200 psia
o Fluid Inlet Conditions to Generator (Tertiary)		
- Temperature		575 F
- Pressure		1250 psia

supercritical cycle is to be tested, the pump must be able to provide water at supercritical pressure.

Superheated steam outlet conditions will be in the order of 510 C and 85 ATMOS. If a closed cycle system is used, the system must be able to condition this fluid to the primary inlet conditions of the steam generator. This will require rejecting approximately 5 MW and reduce the temperature to 43 C while maintaining the pressure at 85 ATMOS. If an open cycle is used, the superheated steam can be dumped (i.e., into a cooling pond).

The availability of secondary and tertiary inlet fluid is desirable. Secondary fluid conditions may be 200 psia and 500 F which essentially corresponds to the low pressure inlet fluid to the steam generator in the reheat cycle (Figure 2). The tertiary condition is probably the saturated steam condition (S) in Figure 1. This flexibility would be useful to perform tests on the steam generator superheater.

Radiant Energy Source. The radiant energy source (Table II) should be in the order of at least 5 MW thermal. The maximum energy flux on the steam generator should be at least 1 MW/sq. meter in order to simulate the incident energy from a collector system. The system must be able to sustain energy/flux levels for periods sufficient to establish steady state operations. The irradiated area (beam) must be of sufficient size to cover the steam generator heating surfaces. It is estimated that a beam of approximately 5 sq. meters may be necessary.

There are radiant energy requirements which are yet undefined. These include a requirement to be able to provide a uniform incident flux across the entire test area to within $\pm$ TBD. Additionally, there will be a requirement to vary the flux level from zero to the maximum level in a continuous manner. The rate of change of the intensity will be dictated by considerations such as the simulation of cloud movement across the collector field. An additional requirement is to be able to control discrete sections of the beam independently of each other. This will enable heating of various sections of the steam generator independently of the other sections.

The heat load should be programmable. This will allow the development of heat load tapes and will obviate "turning knobs" during the test. The system must be calibrated so that heat fluxes are known at both the test facility/steam generator interface and directly at the tube surface.

Instrumentation. It is believed that at this point in the program, one must provide as much instrumentation (Table III) as possible. The steam generator contractor must provide all instrumentation physically attached to his test article. The test facility must be able to process the data from the contractor's measuring instruments, and also measure and process data defining the test facility performance during test.

The instrumentation will consist of items such as pressure gauges, thermistors, flow meters, radiometers, and strain gauges.

Table II. Radiant Energy Source

o Minimum Energy Level	5 MW
o Maximum Intensity (at least)	1 MW/sq. m.
o Beam Size (Approximately)	5 sq. m.
o Beam Flux Characteristics	
- Uniformity	±TBD
- Variability	0 to at least 1 MW/sq m
- Rate of Change	TBD W/sq m - sec
- Number of Discrete Uniform Controllable Subsections Within Beam	TBD
o Requirement for Programmed Control of Individual Subsections	Yes
o Calibration Requirement	
- Flux at Generator Surface	
- Flux at Generator Interface	

Table III. Instrumentation

o Pressure Gages	0 to 15000 psia
o Thermistors	32 to 1200 F
o Flow Meters	0 to 12000 lb/hr
Compressed Water	
Steam	
o Calorimeters	
Steam Quality	
o Radiometers	
Heat Leak	
Radiant Energy	
o Strain Gages	
High Temperature	
o Recorders	approximately 1000 channels
Digital	
Strip	
Gage	
Stored Tape	
o Water Purity Measurement	
o Programmed Heat Load	
o Process Plant Type Water Flow Control System	
o Constant Head Variable Speed Pump	
o Inlet and Outlet Flow Control Based on Temperature	

Also test equipment such as steam quality calorimeters and water purity monitoring apparatus will be necessary. Data should be displayed in digital read-outs, strip charts, and gauges; the data should also be stored on tape. A measurement capability in the order of 1000 channels may be necessary.

Control System. The primary control requirements are the provision to program the heat load, and to control water flow rates to simulate various exit fluid temperature and pressure combinations which are required to simulate actual operational conditions, both steady state and transient.

2.2 Collector

The objective of the Collector Subsystem Research Experiments is to assure that the collector subsystem equipments can be produced, installed, and operated in a cost effective manner. The subsystem will consist of many reflective units (heliostats), each capable of continuously directing the reflected rays of the sun to the absorptive sections of the receiver. These units will consist of three basic components: (1) reflective surface(s), (2) supporting structure and mount, and (3) control loop and drive mechanism. The specific design features of the subsystem are intimately correlated with those of the receiver and an effective design balance between these two subsystems is required for any optimization of the Central Receiver POCE Preliminary Design. Since there seem to be no significant technological developments (except perhaps material lifetimes) required to accomplish a collector subsystem design, the testing objective, as stated above, is one of cost effectiveness for the total system design. Therefore, there seems to be little need for exotic or highly specialized optical laboratory test facilities, or original and exhaustive procedures, beyond that necessary to establish compliance with those specifications derived from receiver/collector compatibility. Each of the possible receiver configurations will impose particular specifications on the collector configuration such as: reflected image size, flux distribution, pointing and tracking accuracies, etc. An interface of concern can be expected between the reflective surface(s) and the supporting structure which may produce variable image distortions due to temperature, inertia, sag, wind, etc.

2.3 Thermal Storage

The objectives of the Thermal Storage Subsystem Research Experiments are similar to those for the Receiver Subsystem (Section 2.1). The Thermal Storage Subsystem should provide an efficient economical method to smooth out system transients and extend the power plant operation into periods of reduced insolation. The Thermal Storage Subsystem configuration will be directly influenced by the receiver output characteristics as well as the requirement for sustaining energy flow to the turbine generator during periods of inadequate receiver output. Whereas the energy source for the receiver tests is radiant heat, the energy source for the Thermal Storage test model or module should simulate the output of the receiver (see Figures 1, 2, and 3).

3.0 FACILITY REVIEW

3.1 Receiver

The facilities which have been identified as potentially providing some useful capability for the receiver model or module tests for the Central Receiver Project may be classified in three categories: (1) Solar Furnaces, (2) Solar Simulators; and (3) High Flux Radiant Heat Facilities.

(1) Solar furnaces concentrate the sun's radiant energy into relatively small test volumes and produce very high temperatures (at least 4000 degrees K) at the center of the test volume.

There are two solar furnaces which have been identified for use in the NSF test program, one in Southern France and one at White Sands Missile Range in New Mexico. The basic capabilities of these facilities are summarized in Table IV with more detailed information contained in Sections 3.1.1 and 3.1.2. The Solar Furnaces were developed and designed to produce a very high solar flux in a limited test volume. The French facility has a rated capacity of 1 MWth and is being adapted to test early concepts of a cavity receiver. The White Sands Furnace has a capacity of approximately 35 KWth and is limited to small area material and component testing.

(2) Solar Simulators are designed and used to simulate the solar spectral radiation with concentrations much lower than that required for receiver module testing. There are many of these facilities varying from modest capabilities, size, and power, to large units which provide space simulated conditions for the study of thermal responses of entire large space vehicles. Even though these larger facilities have high power capabilities (i.e., some greater than 7 MW), the flux levels of incident radiation on test surfaces is significantly below that required for operational tests of receiver modules or models. Some use of these facilities may be made at these lower flux levels to verify materials for surface absorption and reflectivity. By use of optical collectors or concentrators, high flux levels can be attained over relatively small areas. In this respect, these facilities suffer the same limitation as the solar furnace at White Sands. Table V summarizes some of the capabilities of a few solar simulation facilities. Additional information may be found in Sections 3.1.3 through 3.1.6.

(3) Radiant heat facilities have been developed to produce high temperatures to simulate various environments of nuclear bursts, re-entry heating, fires, etc., and to study their effects on materials, components, and fuel assemblies. These high flux values and high temperatures are achieved with quartz lamp banks for flux levels up to approximately 100 Btu/sq ft-sec (113 W/sq cm) and with graphite radiant heaters approaching 500 Btu/sq ft-sec. Match of the radiated energy is in the I.R. and does not simulate the solar spectrum. However, there seems little hope, short of the POCE pilot plant or a special solar thermal test facility, of matching the solar spectrum at the high energy levels required to demonstrate the feasibility of receiver

Table IV. Solar Furnaces

Dimensions: Feet (Meters)	CNRS IMW Odeillo-Font Romeu France	U.S. Army Nuclear Weapon Effects Lab. White Sands Missile Range New Mexico (35 KW)
<u>Heliostats</u>		
Number of Heliostats	63	1
Size of Heliostats	19.7 × 24.6 (6 × 7.5)	36 × 40 (11 × 12.2)
Number of Mirrors per Heliostat	180	356
Mirror Size	1.64 × 1.64 (0.5 × 0.5)	2.03 × 2.03 (0.62 × 0.62)
Number of Heliostat Mirrors	11,340	356
Total Heliostat Mirror Area	30,515 (2,835)	1,472 (137)
<u>Concentrator</u>		
Configuration	Parabolic	Spherical
Size	131 × 177 (40 × 54)	28 × 28 (8.5 × 8.5)
Focal Length	59 (18)	35.7 (10.9)
Number of Mirrors	9,500	180
Mirror Size	17.7 × 17.7 (0.45 × 0.45)	90 @ 24.4 × 24.4 (0.62 × 0.62) 90 @ 25.2 × 26 (0.64 × 0.66)
Mirror Configuration	Flat panes bent by mechanical constraint to minimize image size	Spherical
Total Mirror Area	20,707 (1,923)	781 (72.6)
<u>Flux Distribution</u> (See Fig. 4)		
Normal to Optical Axis at Focal Plane, Distance from Optical Axis	1600 W/cm ² @ ~1 cm 1200 W/cm ² @ ~6 cm 800 W/cm ² @ ~10 cm 400 W/cm ² @ ~15 cm 160 W/cm ² @ ~23 cm	400 W/cm ² @ ~ >1 cm 200 W/cm ² @ ~ <5 cm 100 W/cm ² @ ~ <6 cm 50 W/cm ² @ ~ <65 mm
Along Optical Axis, Distance from Focal Plane	1600 W/cm ² @ ~1 cm 1200 W/cm ² @ ~ >10 cm 800 W/cm ² @ ~ <14 cm 400 W/cm ² @ ~ >21 cm	400 W/cm ² @ ~4 cm 200 W/cm ² @ ~13 cm 100 W/cm ² @ ~22 cm 50 W/cm ² @ ~27 cm
<u>System Cooling</u>		
<u>Instrumentation</u>		
Data Handling		
<u>Contact</u> *	Mr. J.D. Walton, Jr. (404) 894-3661	Mr. Marvin Squires (915) 678-1161
<u>References</u>	Solar Energy, 1973, Vol 15, pp 57-66, "High Temperature Solar Energy," Engineering Experiment Station, Georgia Institute of Technology	"Experimenter's Guide" for the Nuclear Weapons Effects Laboratory at White Sands Missile Range, Section 10, Solar Energy, Vol 1, No. 2, 3, 1957, pp 16-22 Visit 19 November 1974

* The individual listed provided most of the information listed and is not necessarily associated directly with the ownership or operation of the facility.

Figure 4. Image Contours in Horizontal Plane

Table V. Solar Simulators

Table V. Solar Simulators

	Arnold Engineering Development Center		NASA-Lewis Research Center		JPL Pasadena	G. E. Valley Forge Space Center Aerothermal Test Facility
			Solar Simulator	Thermal Simulator		
Power	800 KWe 50 channels @ 15 KW	140 KWe	450 KW D.C. arc lamps 50 KW output	~ 7 MWe	1.11 MWe	740 KWe
Type	T-3 quartz	7 - 20 KW Xenon arc	Arc lamps	1 KW Tungsten lamps	37 - 30 KW Xenon lamps	148 - 5 KW Xenon arc
Test Area		Aerospace Chamber 8 ft dia. x 8 ft high	Up to 450 ft ²	16 ft dia. x 57 ft	20 in dia.	Up to 15 ft dia.
Flux Levels	1-2 Suns	~ 20 Suns	1 Sun @ 450 ft ² ~ 1000 suns @ 18 in dia.	~ 2 W/cm ²	~ 11 suns @ 20 in dia.	~ 30 suns @ 16 in dia. ~ 100 suns @ 8 in dia.
Instrumentation Data Channels						800 for Thermocouples
Water Flow Available						
Contact	Mr. David Anderson (Aero Inc.) (615) 455-2661 x7741		Mr. Harvey Bloomfield Mr. Roy Pickrell (216) 433-4000 x 6733		Mr. H. Norman Riise (213) 354-2049	Mr. R. G. Shoulberg (215) 962-4008
Reference	"Test Highlights" AEDC August 1974 "Test Facilities Handbook" AEDC May 1974		NASA TMX-68042 "400 Kilowatt Argon Arc Lamp for Solar Simulation"			G. E. Valley Forge "Environmental Simulation and Test Capabilities"

designs. Therefore, these large radiant heat facilities seem to offer a compromise of capabilities for testing the large components or modules of the proposed receivers. Table VI summarizes characteristics of the radiant heat facilities identified in this report. Additional information may be found in Sections 3.1.7 through 3.1.10.

Table VI. Radiant Heat Facilities

	Sandia Laboratories Albuquerque, New Mexico	NASA Flight Research Center Edwards, California	USAF Flight Dynamics Lab. Wright Patterson AFB Dayton, Ohio	McDonnell Aircraft Co. St. Louis, Missouri	NASA J.S.C. Houston, Texas	Rockwell International Downey, California (NASA J.S.C. Owned)
Power						
Total Input:						
Steady State	5 MWe	2.3 MWe (Analog Controller) 5 MWe (day) Digital Contr. 20 MWe (night)	23 MWe	7.5 MWe	5 MWe	5 MWe
Peak Transient	20 MWe for 40 sec (transformer limited)	"Significant overload can be tolerated for short periods"	50 MWe for 5 min	34.5 MWe for 60 sec (transformer limited)	?	?
Total Delivered to Test Area	?	?	?	4.5 MWth	?	?
Radiator Type(s)	T-3 Quartz Lamps Graphite radiant	T-3 Quartz Lamps	Quartz Lamps Graphite radiant	T-3 Quartz Lamps Graphite radiant	T-3 Quartz Lamps Graphite radiant	T-3 Quartz Lamps Graphite radiant (no permanent heater arrays, flexible make-up)
Maximum Flux Density at Test (Steady State)	>100 W/cm ² (Quartz) >400 W/cm ² (Graphite)	>100 W/cm ² (Quartz)	>100 W/cm ²	~100 W/cm ² (Quartz) >500 W/cm ² (Graphite)		
Maximum Test Area (Beam size) (@ 100 W/cm ²)	Power limited, "test items up to 17' high can be accommodated"	Power limited, test area 150' x 120' x 40' high (10' x 10' have been used)	?	"Up to 32 ft ² " (power limited)	~50 ft ² , i.e., 6' x 8'	
Flux Distribution Control						
Number of Beam Subsections	8 channels of 3 phase Ignitron Tube Controllers	24 with Analog Controllers (Ignitron power regulators) 512 with Digital Controllers (Solid State SCR)	Grid Flux Control 80 channels of 580 KVA each Ignitron Power Controllers	3 channels of "E" Ignitron 54 channels of "B" Ignitron 57 Total-Separate Control	22 heater channels	36 stationary channels of 400 Amp @ 480 volts
Flux Uniformity/Subsection	?	?	?	?	?	?
Flux Variability/Subsection	?	Zero to maximum values	?	Zero to maximum per heater	?	?
Flux Rate of Variation/ Subsection	For T-3 Quartz Lamps: to 75% radiation in 2-3 sec on: to 10% radiation in 2-3 sec off	?	?	Configuration dependent ~500 W/cm ² per sec (see curve Fig. 25)	?	?
Calibration Method	?	Thermocouple feedback Heat flux sensor feedback	?	Thermocouple feedback Heat flux sensor feedback	?	?
Heat Management						
Working Fluid Flow/ Quality	?	~25 gpm	Demineralizing plant, 2 bed system designed for contin- uous operation of 40 gpm	300 gpm @ 80 psi 120 gpm @ 1000 psi Recirculate conditioned water Pump-thru heat exchanger	?	?
Cooling System Flow/ Heat Rejection	~700 gpm Closed-loop water system with 300,000 gal. stor- age tank 4,200,000 Btu/hr cooling tower	Air Circulation--no specific heat rejection system identified	2 cooling systems 1-600 gpm - 4.4 x 10 ⁶ Btu/hr 2-3440 gpm - 1.0 x 10 ⁷ Btu/hr	Heat exchanger - tube/tank intake from water main - discharge to sewer	Heat exchanger system for heat rejection in alti- tude chamber	Cooling tower ~100 psi and 200 gpm

Table VI. (Continued)

	Sandia Laboratories Albuquerque, New Mexico	NASA Flight Research Center Edwards, California	USAF Flight Dynamics Lab. Wright Patterson AFB Dayton, Ohio	McDonnell Aircraft Co. St. Louis, Missouri	NASA J.S.C. Houston, Texas	Rockwell International Downey, California (NASA J.S.C. Owned)
<u>Data Handling</u>						
Data Recording	Honeywell DDP-116 Midwestern Mod 4000 Tape Deck Vermont Res Mod 108A Magnetic Drum Astrodata A to D Converter ASR-35 Typewriter Mohawk Data Sciences 4320 printer Soroban Mod 6002 card reader	1200 measurement channels A to D Converters Tape Decks - IBM 360 9-track format IBM 360 Gen Purp Comp 20 channel CRT displays	Nearly 2000 data channels	400 channel Control Data Acquisition System 100 channel Dymec digital magnetic tape 50 channel Mini-data digital magnetic tape Quick-Look printers	?	New digital (state of art) 7 "stand alone" mini computers, real time plotting and display ~300 channels of milli- volt instrumentation - any mix
Instrumentation	Calorimeters Radiometers Thermocouples Strain gages	320 Strain gages 400 Thermocouples 80 position transducers	"Plenty"	Thermocouples	?	?
<u>Other Services</u>						
Boiler	50,000 lb/hr steam @ 175 psig 100,000 ft ³ /min overhead draft fan	?	?	150 psi saturated steam	?	?
Storage Tanks	High pressure, large volume Nitrogen, Oxygen, and Argon gas storage	?	?	?	?	?
Compressed Air	2,800 ft ³ storage @ 140 psi	845 ft ³ /min @ 60 psi 16 tiedown slots @ 6' O.C. 7 Instrument Wire Trenches 7 Electrical Power Trenches 5 Mechanical Trenches Closed-Circuit TV Monitors Remote Control of tilt, pan, focus, and zoom	?	Normal "shop air" air tools, etc. Indoor 50' high bay area Structural Test jig with reinforced flow	?	?
<u>Contact</u> *	Mr. Paul Adams (505) 264-3169	Mr. Walt Sefic (805) 258-3311 X674	Mr. H. B. Lowndes, Jr. Mr. Fred Hussong (513) 255-3973	Mr. Dick Q. Durant (314) 232-5076	Mr. Don Tillian (713) 483-2376 Mr. Dick Bricker (713) 483-3166	Mr. Murry Suppanz (213) 922-2063
<u>Reference</u>	SC-RR-67-438 "The Sandia Corp. Radiant Heat Facility" August 1967	NASA TM X-1868 "NASA High Temperature Loads Calibration Labora- tory" September 1969 Visit: 19 December 1974		"High Flux, High Temperature Radiant Heating--A Review of Capability" May 1974		

* The individual listed provided most of the information listed and is not necessarily associated directly with the ownership or operation of the facility.

3.1.1 The French CNRS Solar Furnace

The French solar furnace is located in the Pyrenees at Odeillo-Font Romeu (altitude, 5900 feet), about 20 miles east of Andorra. At this location the sun shines as many as 180 days a year and solar intensities as high as 1000 watts per square meter are common. The solar furnace was completed in 1950 at a cost of about \$2,000,000.

The parabolic reflector has a focal length of 59 feet (18 meters), is 130 feet high and 175 feet wide, and is composed of 9500 mirrors 17.7 inches by 17.7 inches ($1/2$ m x $1/2$ m). Since the parabolic reflector is too large to track the sun, 63 smaller mirrors (heliostats) set in eight tiers are used to follow the sun and reflect its ray in parallel beams onto the parabola. The heliostats are 24.6 by 19.7 feet and each is composed of 180 mirrors 19.7 inches by 19.7 inches.

The movement of each heliostat is automatically guided by electronic controls operated by reflected rays. The accuracy of the control is 1 min of arc, but due to dispersion on the flat glass, 5 min of arc are obtained on the reflected rays.

A solar beam of constant energy is directly horizontally southward to a paraboloid reflector of 1923 sq m intercepted area. This paraboloid contains 9500 single glass panes, bent by mechanical constraint and adjusted to reflect maximum radiation to the focal plane, situated 18 m from the apex of the parabola. The precise adjustment of these two devices, completed on October 1, 1970 took about two years.

Results of tests concerning the energy received at the focal image are as follows:

(1) The energy collection closely agrees with calculations, taking into account the factors of reflectivity of glass, and the dispersion due to imperfect curvature of mirrors and to shading. (2) Power beyond 1000 kW was obtained with the device, when the incident solar energy was more than 0.1 W/sq cm. (3) The energy concentration in the center of the focus-image is equal to black-body radiation around 3800 degrees C.

The orientating device (Collector subsystem, Figures 5 & 6) consists of 63 independent heliostats which are automatically operated by photoelectric control of their reflected rays. The driving parts, electronically coupled with the photoelectric control, are hydraulic. A reservoir of oil under pressure (Figure 6, point C) furnishes the hydraulic azimuth activation of the heliostats.

Each heliostat collecting surface, which is 45 sq m, is made of 180 flat glass panes, back-silvered and covered with copper and varnish.

It should be noted that the vitreous reflection, which is important above some value of the inclination of the incident rays, correctly shares in the lighting of the paraboloid.

Furthermore, the arrangement of heliostat positions appropriately accounts for the apparent diameter of the sun. In such a way a reflected beam which is homogeneous and equivalent to that which would be given by only one large orientator can be achieved.

Figure 7 gives the distribution of the flux density on a vertical plane located 18 m from the apex of the paraboloid. The value $d = 17$ cm (6.6 inches) represents the diameter of the image of the sun given by a mirror of low aperture (Gauss image) near the focal axis. The energy scanning of the geometrical focal vertical plane on an east-west line across the focal axis gives the profile of distribution shown in Figure 8 (curve 0). Behind this plane a considerable decrease in the heat flux density is noticed (curves at the distances $d/2$ and d from the focal plane, Figure 8).

Since the paraboloid is truncated at the bottom, the energy distribution at the focus comes chiefly from the side and upper parts of the reflecting area.

Figure 5. Schematic of 1000 kw Solar Furnace

Figure 6. Solar Furnace Scheme

Figure 7. Distribution of Heat Flux Density on a Vertical Plane

Figure 8. Profile of Heat Flux Density

3.1.2 U. S. Army Solar Furnace

Characteristics. The Thermal Effects Facility (Solar Furnace) at White Sands Missile Range is a solar furnace of the focusing type which utilizes an effective aperture to focal length ratio of less than one. It consists of four main components: the heliostat, the attenuator, the concentrator, and the control and test chamber. The heliostat consists of 356 mirrors, each 2 feet by 2 feet mounted on a steel frame 40 feet wide and 36 feet high. In operation, it reflects the sun's rays to the concentrator. The concentrator consists of 180 spherical mirrors, each approximately 2 feet by 2 feet and mounted on a steel frame 30 feet by 30 feet and located 96 feet south of the heliostat. Each mirror comprising the concentrator is individually focused to concentrate the sun's rays at the same point on the focal plane, which is located inside the test and control chamber. The attenuator which is located between the test and control chamber and the concentrator consists of a louver structure whose blades can be adjusted to regulate the amount of sunlight reaching the concentrator. The test chamber which is eight feet by eight feet in cross-section normal to the parallel sunrays from the heliostat and 16 feet in length, contains the controls for the heliostat and the attenuator. The control chamber also contains the controls for the exposure shutter for exposures as short as 0.1 second and for the slow water-cooled shutter designed to protect the exposure shutter until just before the exposure is made.

Operating Characteristics

Flux Level. The thermal flux at the focal plane of the solar furnace depends primarily on the amount of reflected sunlight reaching the concentrator. This quantity is controlled by the attenuator. The attenuator is operated from the control chamber. The image of the sun at the focal plane is approximately four inches in diameter. The maximum flux obtainable at the center of the image is 100 cal/sq cm per second (approximately 420 W/sq cm) at the focal plane. Larger exposure areas can be obtained, but at lower flux levels by defocusing; i.e., moving away from the focal plane.

Pulse Width. The solar radiation pulse at the focal plane is determined by the exposure shutter. The length of time the exposure shutter stays open is preselected by the operator at the control console. In addition to the fast shutter, a pulse shaper can be swung into position in the converging beam about 40 inches in front of the focal plane. The pulse shaper consists of an array of 16 radial vanes, each 1-1/2 feet long. These vanes are driven at variable speed by a specially constructed cam controlling the irradiance at the target. It modifies an otherwise rectangular pulse at the focal plane into shaped thermal pulses corresponding to the range of nuclear weapons from 25 kt to the megaton range. There is some variation in shape over this range because of the acceleration of the vanes necessary to produce this shape.

Environment. A graph of the solar irradiance in calories/sq cm per second as a function of distance from the image center at the focal plane is shown in Figure 9. This graph was obtained using a radiometer at the solar furnace's former location at Natick, Massachusetts.

Size of Experiments. Because of the small exposure volume of the test chamber, the dimension of the test item along the focal plane of the solar furnace cannot be greater than approximately four feet. Instrumentation cables may be brought out of the test chamber through conduits provided for that purpose.

Support Capabilities

Staff. The primary purpose of the White Sands Thermal Facility is to provide a source of radiation for experiments designed to investigate radiation effects on materials and components of interest to the Department of Defense. Facility personnel will operate the solar furnace and provide full operational support. The on-site professional staff is readily available to the experimenter for consultation.

Electronics and Shop Facilities. Instrumentation is available to experimenters through previous arrangements with the technical coordinator. Also, a machine shop and the services of a machinist are available for needs that may arise during the course of the experiment or through previous arrangement.

Experiment Preparation Laboratories. Adequate experiment preparation laboratories, personnel offices, security storage, radioactive storage, radiation chemistry laboratories, and conference rooms are available at the site.

Figure 9. Irradiance Profiles at Best Image Position

3.1.3 Arnold Engineering Development Center (AEDC), Arnold Air Force Station, Tullahoma, Tennessee.

AEDC has several solar simulators. The one of some interest to the receiver test experiments is a 140 KWe device with an efficiency of approximately 40%, delivering approximately 54 KWth to the test surface. This simulator could produce, through an optical concentration system, approximately 20 solar concentrations at best. The other simulators do not have the concentrating capability even though the largest is of approximately 800 KWe which produces low flux levels (1-2 solar concentrations).

The solar simulator is an off-axis, integrator system producing a well collimated and uniform beam over an 8-ft-diam by 8-ft-high test volume. The intensity within the test volume is one solar constant with a uniformity of ± 5 percent and a decollimation of ± 1.8 deg. The energy spectrum is typical of the 20-kw xenon short-arc lamp, seven of which are located in the source array. This spectrum is very similar to that of the sun except for an excess of energy in the near infrared. The simulator spectrum can be adjusted to more closely match the solar spectrum by filtering and by addition of 5-kw mercury-xenon lamps to the source array.

Planet Albedo and Radiance Simulator. The planet albedo (reflection of solar energy from a planet) and planet radiance are simulated by one system with as many as 1500 T-3 quartz-envelope tungsten filament lamps mounted in individual reflectors which may be spaced around the test article to irradiate it to the desired amount.

Each lamp has an output continuously adjustable from 0 to approximately 24 W/sq ft at a distance of 30 in. in front of the lamp reflector unit. This output is to within ± 5 percent and extends approximately ± 40 deg. to each side of the output centerline. The lamp units may be installed in multiples to further increase the level of the radiant energy. The lamps may be grouped in banks, each with its individual control circuit, so that the desired distribution of energy can be achieved on the vehicle surface. There are 50 channels of control circuits, each capable of delivering up to 15 kw.

The simulator units are attached to a birdcage arrangement surrounding the test vehicle. The birdcage is supported by the article handling system and is adjusted and tailored to adapt to different test article shapes, sizes, and requirements.

3.1.4 NASA Lewis Research Center, Cleveland, Ohio.

NASA Lewis has both a solar simulator and a thermal simulator. The solar simulator is housed in the space power facility chamber, 120 ft. high and 100 ft. in diameter (see Figure 10_) and is capable of radiating a 450 sq. ft. area with approximately the flux of one sun. By employing a focusing mirror, the flux level of approximately 10 suns can be achieved. Other focusing devices would have to be obtained to reach the 500 to 1000 times solar flux desired. With a nominal output level of approximately 50 KWth, the resulting test area would be about 1/2 sq. ft. if the radiation were uniformly distributed. The thermal simulator has about 7 MWe input power for 1 KW tungsten lamps mounted in aluminum. This unit was configured in a 16 ft. diameter by 57 ft. high, can be altered for various shapes, but is currently non-operational with little hope that it would be available.

Figure 10. Space Power Facility Solar Simulator

3.1.5 Jet Propulsion Laboratories, Pasadena, California.

JPL has a solar simulator using 37-30 KWe Xenon lamps. The radiation is directed through an optical "mixer" to 20 inches in diameter, producing approximately 11 solar concentration. Details and description of this facility were not available at the time of publication of this document.

3.1.6 G.E. Solar Simulator

The major component of the Space Environment Simulation Laboratory is the 54-feet high by 32-feet diameter solar-thermal-vacuum chamber. Capable of accommodating complete spacecraft up to 21 feet in diameter weighing as much as 44,000 pounds, the space chamber provides vacuum conditions from 10 to the minus 6 to 10 to the minus 9 Torr and the cold black characteristics of space. The interior surfaces of the solar-thermal-vacuum chamber are maintained at extremely low temperatures to simulate the low energy, completely absorbing characteristics of space. A system of black cooling panels is employed through which liquid nitrogen is circulated. (See Figure 11 and Table VII).

All surfaces facing a test vehicle have an emissivity of 0.95 or higher. The cryogenic panels are arrayed as shown in the schematic diagram and are covered with a three-quarter inch thick honeycomb. The baffle effect of the finned array combined with the multiple bounce path of the honeycomb produces the high emissivity. The off-axis design of the collimator affords simulation of the "cold, black, space" characteristics.

Energy radiated from a test spacecraft to the collimating mirror is reflected to the cold chamber walls rather than re-radiated back to the spacecraft.

Radiation of about 30 solar constants occurs at the lens which covers a 16 inch diameter. Conceivably this can be re-imaged to achieve 100 solar constants on an 8 inch diameter area.

The GE Solar Simulator uses Xenon compact arc lamps as the source of radiant energy. Xenon, traditionally, is used as the best practical source for solar simulation. A comparison of the irradiance of the Xenon simulation and the air mass 2 sun is tabulated below:

<u>Wavelength Band</u> <u>----(Microns)----</u>	<u>Air Mass Two</u> <u>% of Total Energy</u>	<u>G.E. Simulator</u> <u>% of Total Energy</u>
0.25 - 0.40	2.67	5.3
0.40 - 0.70	44.30	30.8
0.70 - 1.10	36.15	41.7
1.10 - 1.50	9.55	11.5
1.50 -	<u>7.33</u>	<u>10.5</u>
	100.00%	100.0%

FIG. 11. Space Environment Simulation Laboratory

TABLE VII
SOLAR-THERMAL-VACUUM CHAMBER

CHARACTERISTICS

VACUUM CHAMBER	
Size	Cylinder, 32 ft. diameter by 54 ft. high
Access	Upper hemisphere removable - door in side, 40 in. by 84 in.
Material	304 L stainless steel 3/4 in. thick
Vacuum	10 to the minus 5 to 10 to the minus 9 Torr
VACUUM PUMPING	
Cryogenic	100 degrees K condensables (LN2) 3.4 x 10 to the eighth liters/second 20 degrees K condensables (GHe) 2.3 x 10 to the sixth liters/second
Oil Diffusion	Non-condensables (He, H2, Ne) 20,000 liters/second
WALL EMISSIVITY	0.90-0.95
SOLAR SIMULATION	
Source	15-ft. diameter 148 5 kw xenon arc lamps
Collimator	Off-axis quadrisected glass mosaic paraboloid
Collimation	±3 degrees to ±5 degrees
Intensity	120 watts/sq. ft. (feedback control)
Uniformity	±15% (volume and plane)
Maintenance	Lamps replaceable during operation
TEST CAPABILITY	
Size	21-ft. diameter by 30 ft. high
Weight	44,000 pounds
OPERATING TIME	
Startup	7 hours to 10 to the minus 7 Torr
Shutdown and warmup	20-24 hours
INSTRUMENTATION	800 channels for thermocouples

3.1.7 Sandia Laboratories Radiant Heat Facility, Albuquerque, New Mexico.

The Sandia Radiant Heat Facility is part of a high-temperature testing complex located in the Sandia Laboratories Remote Test Area. The facility was built to provide laboratory simulation of high-temperature environments on large assemblies. A wide range of thermal environments has been simulated: from high-level, short-duration programs simulating the thermal energy from a nuclear burst or launch pad abort fire; to intermediate-level and long-duration programs simulating transportation accident fires; to low-level, intermediate-duration programs simulating aerodynamic heating. The name, Radiant Heat Facility, comes from the fact that the radiant thermal energy is used as the primary mode of heat transfer. In the simulation of aerodynamic heating, no attempt is made to reproduce the mass flow effects.

The facility has eight channels of programmable, three-phase power controllers. Long-duration programs can be operated at a sustained level of 5 MW. Peak power level is approximately 20 MW for 40 seconds, twice an hour.

Thermal input is produced with either high-power lamps or graphite-resistance heaters. The radiant spectrum produced by these heat sources is shifted towards the infrared as compared to the solar spectrum.

Test items up to 17 ft. high can be accommodated inside the facility; an outdoor test pad is also available. The facility is located in a remote test area with widely separated facilities; thus, adequate safety precautions can be made for testing hazardous systems such as high-pressure steam generators.

Test data acquisition and reduction is accomplished on a dedicated, computerized data system located in the test complex.

Additional services which are available in the complex are: (1) a closed-loop cooling water system with a 300,000-gallon storage tank, (2) a 4,200,000 Btu/hr cooling tower, (3) a boiler capable of producing up to 50,000 lb/hr of steam at 175 psig, and (4) high-pressure, large-volume nitrogen, oxygen, and argon gas storage tanks.

Testing programs which could be handled include:

1. Evaluation of sections of full-scale items at rated heat flux levels.
2. Evaluation of scale models.
3. Evaluation of engineering design problems such as flow stability and thermal stress effects.

Figure 12 shows the location of the Radiant Heat Facility (Bldg. 6530) and the remote facility control point (located in

Bldg. 6540) relative to other facilities in Sandia's Environmental Test Area III. Figures 13 and 14 show the floor plan and elevation of the test bay of the Radiant Heat Facility.

I. POWER CONTROL APPARATUS

Control modules of the Radiant Heat Facility (RH-1) consist of eight channels of three-phase electrical pulsers designed to control alternating current pulses to electrical heaters. Electromechanical servo systems program and control each channel of the facility to effect temperature-time heating, heat flux control as a function of time, and simulation of aerodynamic heating.

A. Electrical Power Supply

The Radiant Heat Facility (RH-1) is supplied by a 44,000-volt transmission line which is separate from the transmission line used by all other facilities in Area III. Voltage to the ignitron controllers of the RH-1 facility is reduced to 2400/4160 grounded wye in a 5000-kVA transformer.

B. Maximum Power Capabilities

The maximum power output capability of the eight channels of the RH-1 facility is based on 95 percent of full-wave conduction of the ignitron tubes with a 2.4-kilovolt supply. The original specifications of the facility called for thermally rating the individual phase transformers to be suitable for one test of 40 seconds duration per hour to a maximum of 2.4 megawatts for each of the control channels, or a total of 19.2 megawatts for the eight control channels. Several years of operating experience has proven the original rating to

be conservative. No apparent degradation of the transformers has been observed as a result of two tests per hour at the specification thermal rating.

Higher current ratings are available in larger ignitron tubes which could increase the maximum power rating to 3.0 megawatts per channel; however, only one three-phase transformer bank is presently installed through which this power could be utilized.

D. Maximum Current Capabilities

Maximum current capability of the RH-1 facility is based on 95 percent of full-wave conduction of the ignitron tubes and is ruled by a number of thermal and electrical characteristics inherent in the ignitron tubes. Table VIII is a tabulation of operating maximums of the eight control channels.

D. Control Modes

Four basic modes of programming and feedback control are available in the RH-1 facility. These are:

Figure 12. Location of Radiant Heat Facility

Figure 13. Floor Plan of Radiant Heat Facility

1. Heat Flux as a function of time (QT)
 - a. by power feedback,
 - b. by heat rate sensor feedback, and
 - c. by optical pyrometer feedback.
2. Temperature-Time (T-T)
 - a. by thermocouple feedback, and
 - b. by optical pyrometer feedback.
3. Simulation of Aerodynamic Heating (EI) by
 - a. thermocouple and power feedback.
4. Constant Temperature (Soak)
 - a. by thermocouple feedback.

The methods of feedback most readily available and most commonly used are "power feedback" in the Heat Flux as a function of time (QT) mode; "thermocouple feedback" in the Temperature-Time (T-T) mode; and in the Simulation of Aerodynamic (EI) mode, both "thermocouple" and "power" feedback are required.

Thermocouple feedback is required in the Constant Temperature (Soak) mode.

E. Controls and Programmers

Controlling and programming the facility may be done by either manual procedures or by automatic procedures. Each three-phase channel consists of one master phase and two slave phases; the two slave phases respond to the master phase by equalization of the load voltage. The Channel Number 1 master phase can control subsequent channel master phases by the same load voltage equalization. Master-slave control is available in either manual or automatic operation.

The RH-1 program console consists of eight drums for programming q (heat flux), TD (temperature), and h (heat transfer coefficient) and two drums for programming Taw (adiabatic wall temperature). Drum rotation is accomplished by a DC positional servo-mechanism so that all drums rotate at the same rate, continuously variable from 10 to 3000 seconds for full rotation.

Automatic programming of q , TD , h , and Taw command functions is accomplished by cutting the desired curve shape on aluminized graph paper and fitting the graph paper to an appropriate program drum. The command functions are generated as voltage analogs from multiturn potentiometers, which are positioned by electrical servo-mechanisms driven by the curve followers. Skew rate (maximum probe follow rate) of the follower mechanism is approximately 5 inches per second; maximum travel from zero to full scale is 7 inches which makes the programmer faster in response than most commonly used heater loads.

TABLE VIII

OPERATING MAXIMUMS AND ELECTRICAL CONNECTIONS

<u>Channel No.</u>	<u>Max. RMS Volts</u>	<u>Max. RMS Current/ Amps</u>	<u>RMS 3 Sigma Power (Megawatts)</u>	<u>Electrical Connections to Heater Load</u>
1	480	1660	2.4	Open or closed delta
2	480	1660	2.4	Y
3	480	1660	2.4	Isolated phases
4	480	1660	2.4	Open or closed delta
5	480 & 600	1660 & 1340	2.4	Open or closed delta
6	480	1660	2.4	Open or closed delta
7	480	1660	2.4	Open or closed delta
8	2400	400 (est.)	3.0	Not controlled through ignitron tubes
8	480	1660	2.4	Open or closed delta
Any channel	120/ 240	6600/ 3300	2.4	Y, delta or isolated phases
Any channel	240/ 480	1240/ 620	0.9	Y, delta or isolated phases
Any channel	480	1660	2.4	Y, delta or isolated phases

NOTE: All channels may readily be reconnected to open or closed delta configuration.

II. QUARTZ INFRARED LAMPS

A. Lamp Characteristics

A large amount of the testing at the Radiant Heat Facility involves heat fluxes in the range from 10 to 200 Btu/sq ft-sec. These low-to-medium-level heat fluxes are normally provided by heater arrays equipped with T-3 tubular quartz

infrared lamps. The T-3 quartz lamp consists of a tungsten filament sealed in an inert gas-filled quartz tube $\frac{3}{8}$ inch in diameter. The normal sizes used are 10, 16, and 25 inch, which corresponds to the heated length of the filament. Also, 5 and 38-inch lamps are available for special uses.

1. Heat Concentrations

The normal heat concentration of the quartz lamp is 100 watts per linear inch of heated filament. The 10- and 16-inch lamps are available with heat concentrations of 200 watts per linear inch, while the 10-inch lamp is also available with a heat concentration of 360 watts per linear inch of heated filament. The 100-watt per inch lamps have either a clear or translucent quartz tube. The translucent tube is desirable when a small number of lamps are being used and an even heat distribution is needed to avoid hot spots. The high output lamps are available with clear quartz tubes only. The T-3 quartz lamp offers the highest heat concentration of any infrared source of this type.

2. Effects of Under and Overvoltage (Lamp Life)

One of the features of the T-3 lamps is their ability to handle overvoltages for short times. The normal life of the lamp is 5000 hours when operated at rated voltage, which is 240 volts for the 10-inch lamp as an example. When operated at 225 percent of rated voltage, the lamp life drops to 5 or 6 minutes at most; however, at this overvoltage, the power output of the lamp increases to more than three times the rated power output. This allows the T-3 lamp to be used when very high peak heat fluxes with short duration are required which could not be obtained at the normal rated voltages. Figure 15 gives the power and color temperature output of a typical quartz lamp when operated above and below normal rated voltages.

3. Warm-up and Cool-down Characteristics

The T-3 quartz lamp has a small thermal mass, thus allowing very rapid heat-up and cool-down rates. When the rated voltage is applied to the lamp as a step increase, the output will reach 70 percent of the rated output in 2 to 3 seconds. The lamp will cool down to 20 percent of rated output in 2 to 3 seconds after power is shut off.

B. Heater Array Design

To take advantage of the features of the quartz infrared lamp, it is necessary to install it in a heater array which will direct the radiant energy from the lamp toward the test item. The heater array then serves as a support for the lamps, by holding them in the desired arrangement, while

Figure 14. South Elevation of Test Bay

NOTE: Color Temperature
2500° K. at
100% Voltage

Figure 15. Voltage characteristics of T-3 Quartz Lamps

providing a reflector behind the lamps, which is normally gold plated. It is also necessary to provide cooling for the lamp seals and the quartz tube. The end seals are normally cooled by water cooling the lamp holders, although it is sometimes possible to merely air cool the seals when low level tests are required. The quartz tubes are cooled by blowing air over the tube surface either radially or axially as the design permits. In some tests, where the higher heat fluxes are required, it becomes necessary to water cool the reflector in order to avoid destroying the heater array.

III. GRAPHITE RESISTOR HEATING

Graphite resistor heating is used to simulate such environments as launch pad abort fires or the thermal energy from nuclear bursts. It is also used for heat shield or other types of material studies.

Programmed pulses of various shapes, flux levels, and pulse durations can be obtained using the automatic control equipment.

The type of flat graphite resistor normally used is shown in Figure 16. The thickness of the resistor used is either 0.375 inch or 0.750 inch; however, the other dimensions are the same as shown.

One, two, or three resistors are used depending upon the size of the test specimen and the flux rate required. With the resistors run horizontally, support rods have to be used to prevent the resistor from sagging and closing the gaps, thereby shorting out sections. When the resistors are mounted vertically, no supports are necessary. Electrical arcing across the resistor slots is reduced by blowing inert gas across the graphites from a manifold.

A. Heat Flux Levels

The incident flux levels obtainable will range from the maximum flux level obtainable from the quartz lamp up to about 420 Btu/sq ft-sec incident. The maximum level attainable on any test specimen depends upon the shape and size of the item and whether or not it can be mounted in a test fixture that has a high reflectivity.

All of the higher flux levels have been obtained, using a shutter in front of the test item so that the graphite resistors can be brought up to temperature before the test item is exposed to the heat flux. Refrasil cloth is used to cover the shutter to help protect it from the high exposure temperatures.

B. Pulse Characteristics

1. Pulse Types

There are three main parts of the heat pulse that can be varied. These are the rise and fall time with their associated shapes and the duration of time at the peak.

2. Rise

There are several methods of controlling the rise time of the heat flux pulse. One method is to use the natural rise in temperature of the graphite resistor which runs about 20 seconds for a temperature required to reach 350 Btu/sq ft-sec. A slower rise time than the above method can be obtained by programming power to the resistors at a slower rate. Another method is to use a shutter between the graphite resistors and the test item. The resistors are brought up to the required temperature, the shutter is opened, and the rise time is practically instantaneous.

3. Fall Time

The fall off due to the natural cooling of the graphite resistors to 20 percent of max flux occurs in approximately 10 seconds. The heat flux can be cut off near the end of the pulse by the use of the shutter which causes a sudden drop of the flux to zero. The heat flux can also be cut off at maximum heat flux by the use of a shutter.

4. Pulse Durations

The pulse duration is dependent upon the peak power input level. In general, the higher the flux level, the shorter the pulse duration that can be obtained. A level of 350 Btu/sq ft-sec can be maintained for approximately 30 seconds if a good reflective surface is used to hold the test specimen.

C. Heater Array Design

Most tests are run using the graphite resistor heater arrays with a water cooled and gold plated reflector behind the graphite resistors to reflect as much of the radiant energy as possible. Other arrays may be designed to follow the contour of various shapes. These would then be backed by a water-cooled, gold-plated reflector which would also support the electrode rods screwed into the resistors.

3.1.8 NASA High Temperature Loads Calibration Laboratory, "Heat Facility," Edwards Air Force Base, Calif.

Introduction

The NASA High Temperature Loads Calibration Laboratory at the Flight Research Center, Edwards, California, has the capability of testing structural components and complete vehicles under the combined effects of loads and temperatures, and calibrating and evaluating flight loads instrumentation under conditions expected in flight. The laboratory provides close support of flight-to-flight program planning by structural-integrity testing, instrumentation calibrations, and analysis of unexpected problems encountered in the course of exploratory flights.

General Description

The laboratory is a hangar-type structure with a small shop and office area attached to one end to accommodate the operations staff. It is located adjacent to Rogers Dry Lake and is connected to the dry lake and the Edwards Air Force Base runways by a ramp and taxiway.

Hangar Test Area. Figure 17 is a sketch of the building layout. The hangar-door opening is 40 feet (12.2 meters) high and 136 feet (41.6 meters) wide. Additional access to the test area from the exterior is provided by personnel doors and an equipment door. Access to the test area from the shop area is provided by two equipment doors. The unobstructed test area is 150 feet (45.7 meters) long by 120 feet (36.6 meters) wide by 40 feet (12.1 meters) high. There are 16 tiedown slots spaced 6 feet (1.8 meters) apart, 7 instrument wire trenches, 7 electrical power trenches, and 5 mechanical trenches.

The cross-sectional dimensions of the trenches are 10 inches (25.4 centimeters) by 12 inches (30.5 centimeters). The mechanical trenches distribute hydraulic power, water, and compressed air to the test area. The maximum load capability of the tiedown slots is 15,000 pounds (67,000 newtons) uplift every 2 feet (0.6 meter). Figure 18 shows a sketch of a typical tiedown slot. A 5-ton (44,000-newton) overhead crane services the entire hangar test area.

Control Room. The control room for the heating equipment, loading equipment, and data-acquisition system is on the second floor. Two observation windows, 11 feet (3.4 meters) wide by 4 feet (1.2 meters) high, and a closed-circuit television system are provided for monitoring the test area. The television system has several cameras which can be positioned in the hangar test area; one can be controlled remotely from the control room for tilt, pan, elevation, focus, and zoom. A two-channel intercommunication system is provided between the control room and the twelve acquisition sites of the data-acquisition system in the hangar test area. Audio and video tape machines provide voice communication and visual recording of the test.

Power Distribution. Twenty megawatts of 480-volt, three-phase, 60-cycle power are available for distribution to 512 solid state SCR, or 2.3 megawatts to 24 ignitron power regulators. Hydraulic power consists of a 4.5 gallon per minute (284 cubic centimeter per second) supply operated at 3000 pounds per square inch (20.7 meganewtons per square meter). Compressed air is supplied by a 125-horsepower (93,250-watt) compressor capable of delivering 845 cubic feet per minute (0.398 cubic meter per second) at 60 pounds per square inch (413.7 kilonewtons per square meter).

Equipment Configuration and Capabilities

Hydraulic and Thermal Load Control Systems. The hydraulic and thermal load control systems have the capability of loading and heating test specimens simultaneously by following programs of load and temperature. The hydraulic and thermal load control systems are programmed by the same type of function generator and by similar controllers. Both the function generators and the hydraulic and thermal load controllers are digital devices.

Two manually operated air-hydraulic pumps are also available for manual loading of structures with hydraulic jacks. The capacity of each jack is approximately 8,000 pounds (35.6 kilonewtons).

Thermal Loading System. The available programmed heating equipment consists of: (1) a 512 channel direct digital control system employing solid state SCR power regulators capable of a total of 20 megawatts available for a single test, or (2) 24 analog channels using ignitron power regulators, each with a power capacity of 100 kilowatts. Electrical power is connected to the power control channels from the transformers with bus bars. Connection of electrical power to the lamps is by flexible cable with high-temperature insulation. Cables to the lamps are routed through floor trenches.

The primary protective or fail-safe capability used with the heating equipment is a voltage-limiting system which enables the operator to limit the voltage applied to the heat lamps for each channel control. To use this system effectively it is necessary to know the amount of power needed to achieve the

heating rates and temperature levels required by the tests. Once this information is known, it is necessary to limit the power applied to each channel to avoid exceeding these values.

Heat is applied to the specimen through the use of infrared quartz lamps which are available in various lengths from a 5-inch (12.7-centimeter) lighted length to a 32-inch (81.3-centimeter) lighted length. Reflector arrangements are readily adaptable to individual requirements for heating rates in the range of 0 to 100 Btu/sq ft-sec (1.13 MW/sq m) and temperatures up to 3000 degrees F (1922 degrees K).

Data-Acquisition System. The instruments whose outputs are to be recorded are connected to acquisition "sites" near the test setup. Each acquisition site can accommodate up to 100 channels of any instrumentation mix. Twelve acquisition sites are available, so that the system can handle up to twelve hundred channels. The sites contain signal conditioning and strain-gage-bridge balancing equipment. They also convert data from analog to digital form for transmission to the control room. This configuration minimizes effects of electrical noise generated by the thermal loading system. Each site has its own air-conditioning unit to improve the reliability of its performance in the changing thermal environment.

The data acquired by the acquisition sites are routed to the control console, which is the interface between the test conductor and the data-acquisition system. The console contains a number of displays which keep the test conductor informed about the progress of the test. The control console, in turn, communicates with a high-speed digital computer which acts as a command and control device for the data-acquisition system. Under stored program control, it commands the channel sampling sequence and the sensitivity at which each channel is measured. Data are formatted in the computer for output magnetic-tape units. Information is recorded on magnetic tape in IBM 360 9-track format. Data are reduced on the NASA Flight Research Center System 360 general-purpose computer.

Numeric displays of test time and data from any one channel (reduced to engineering units if desired) and a bar graph displaying analog lines whose lengths are proportional to data from any 32 selected channels are available at the control console. Also, three strip-chart recorders are connected to the control console to provide quick-look analog time histories of up to 24 channels of information. If desired, an X-Y plotter can be connected to two strip-chart channels to produce, in real time, a plot of one variable versus another. Twenty alarm lights are available to indicate noteworthy or hazardous conditions. The lights can also be used for automatic test shutdown. To observe the test, the test conductor sits in front of a large window overlooking the test area. For more detailed, close-up viewing, closed-circuit television is provided. The control room, which is remote from the test area, can be connected by an inter-communication system to any acquisition site.

Instrumentation. The transducers available for use in the facility include strain gages, thermocouples, load cells, and position transducers.

A strain-gage laboratory within the facility provides the capability for installing and testing strain gages under environmental conditions of heat and load. Various types of strain gages, including those requiring welded and flame-spray attachments, can be installed. Thermocouples can also be installed in the strain-gage laboratory. The thermocouples used are typically spot-welded chromel-alumel.

Forty-eight potentiometric displacement transducers are available with the following specifications:

<u>Range</u>		<u>Resolution</u>		<u>Cable Tension</u>		<u>Quantity</u>
<u>in.</u>	<u>cm.</u>	<u>in.</u>	<u>mm.</u>	<u>oz.</u>	<u>N</u>	
0 to 1	0 to 2.54	±.002	0.05	9	2.5	4
0 to 6	0 to 15.24	±.011	.28	9	2.5	14
0 to 12	0 to 30.48	±.022	.56	9	2.5	12
0 to 12(a)	0 to 30.48	±.017	.43	19	5.3	4
0 to 24	0 to 60.96	±.042	1.07	14	3.9	14

- (a) This transducer has a separable cable which permits the cable to release when its range is exceeded without damage to the component parts.

Twenty-four dial-gage displacement-measuring devices are also available with ranges varying from 3/8 inch (0.95 centimeter) to 4 inches (10.16 centimeters).

Figure 17. Building Layout of NASA High Temperature Loads Calibration Laboratory

Figure 18. Cross Section of Typical Tiedown Slot

3.1.9 Radiant Heat Facility, Flight Dynamics Laboratory,
Wright-Patterson Air Force Base, Dayton, Ohio.

The High Flux, High Temperature facility is in the Structures Laboratory. Employing quartz lamps and graphite radiant heaters, this facility is capable of flux levels in excess of 100 W/sq cm with a continuous input power of 23 MWe and over 50 MWe for a five minute period. A great deal of nuclear pulse simulation work is being conducted on test panels of up to 6 ft by 6 ft. Grid flux control flexibility can be achieved. Nearly 2,000 data channels are available as is instrumentation. This laboratory is manpower limited for the next year and currently fully scheduled with tests. Availability beyond that time is not certain.

The need for conducting structural test programs at elevated temperature has resulted in the facility as it stands today. 50,000 KW of controlled electrical power is available with the necessary heat controls and switchgear to conduct tests up to 3000 degrees F. As an integral part of the facility, a large high speed data acquisition and processing system was included as well as programmed loading systems.

A large liquid nitrogen facility, including a 10,000 gallon Dewar, cryogenic pumping, piping test basin, and barrier, is available within the Structures Test Facility.

Heating System. With 23,000 KVA continuous power and a peak power of 50,000 KVA available for testing, the Air Force Flight Dynamics Laboratory Structural Test Facility has the capability of testing many large structures while simulating their true thermal environment.

In order to control this large amount of power, two systems are available; the 580 KVA and the 25/60 KVA system. The larger system has 80 channels of 580 KVA each. The controllers for this system make up what is referred to as the Heat Control Computer System. The Heat Control Computer is a magnetic drum, electronic storage computer for calculating the amount of power required to simulate aerodynamic heating or cooling of a given test specimen and to control the flow of electrical energy in accordance with these calculations. The equipment is capable of generating 170 simultaneous functions (time versus other selected parameters) and six time bases.

The analog portion of the equipment is capable of controlling test temperatures to 7500 degrees F. Function generators are provided for linearization of standard thermocouples and power measuring devices.

The 25/60 KVA system provides 210 - 60 KVA controllers and 550 - 25 KVA controllers. These controllers function in the time versus temperature or preset power level modes only. Program inputs to the controllers are analog signals which come from external function generators.

Temperatures may be programmed as Heat Flux Density (Q) or Time Temperature, both on real-time basis. This controlled electrical power feeds special radiant-heat lamps in custom designed reflector assemblies to achieve the thermal simulation. Range of temperature simulation is 150 degrees F to 3000 degrees F on large surface areas, with heat fluxes of 110 Btu/sq ft/sec.

Data Acquisition and Processing System. The Data Acquisition System provides a complete instrumentation capability in support of the structural integrity testing performed on advanced aerospace vehicles. The measurements performed by this system fall into two basic categories: indications of structural response, and environmental control system feedback sensing.

The heart of the instrumentation is the Data Acquisition and Processing System (DAPS) which has 1928 data channels. This system is a time-shared commutated system, with maximum sampling rates of 100 samples per channel per second. All data are converted into digital form and are both recorded on magnetic tape and entered on-line into a CDC-1604B computer which produces a real-time test data display. Recorded data can be processed later (off-line) by the same computer. The system's hard copy output is both tabular and graphical, on paper, and/or on microfilm. The real-time continuous monitoring of structural response by advanced computing equipment results in a failure-prediction and prevention capability that precludes catastrophic failure.

The electrical outputs from these transducers are recorded by a variety of instruments, depending on the nature of the particular test. The primary data acquisition device utilized for the majority of tests is the High Speed Digital Data Handling System.

It is this rapid response capability which allows meaningful application of limit-alarming and failure indication methods. Failure prediction, together with computer control of test input parameters can form the basis of a completely automated test program. The sensors most utilized in this work are capable of measuring force, elongation, acceleration, flow, pressure, thermal heat flux, cryogenic and elevated temperature, and unit elongation (strain) over a broad temperature range.

AN/GJQ-9 Programmer Comparator. The AN/GJQ-9 Programmer Comparator (Q-9) is a central checkout system that automatically coordinates the activities of several systems in the Structures Test Facility.

The Q-9 can energize equipment, check its condition, put it into operation, and shut it down. The Q-9 also has the capability of recording the performance of a piece of equipment as well as any malfunctions that occur during the process. In the event of a malfunction that cannot be rectified, the Q-9 can be made to substitute alternate equipment and continue the overall plan.

Since the Q-9 can sense 2000 test points and perform another 2000 operations, it is extremely useful in conducting large and complex test programs where electrical, electronic, hydraulic, pneumatic, and cryogenic systems are involved, thus saving a tremendous amount of manpower and time.

Demineralized Water System

Description. The demineralized water system is made up of the Radiant Cooling Water Circulating System, the R. F. Cooling Water Circulating System, and the Water Demineralizing Plant.

a. Radiant Cooling Water Circulating System

Maximum water temperature in	
system	113 degrees F
Water circulated	600 G.P.M.
Volume of water in system	2000 Gallons
Rate of heat removal	4,440,000 Btu/hr

b. R. F. Cooling Water Circulating System

Maximum water temperature in	
system	120 degrees F
Water circulated	3440 G.P.M.
Volume of water in system	5600 Gallons
Rate of heat removal	10,000,000 Btu/hr

c. The demineralizing plant is a two bed system consisting of a sand filter, cation unit, vacuum de-aerator, and a strong base anion exchanger. It is designed for continuous operation at 40 GPM and processes 19,200 gallons of raw water between regenerations.

Designed effluent quality:

Silica (ionized soluble) not to
exceed 0.3 PPM
Electrolyte (ionized soluble
solids) not to exceed 4 PPM
Conductivity not to exceed 10 micro-ohms
which corresponds to a minimum
specific resistance of 100,000
ohms per cubic centimeter.

Purpose.

(a) The radiant cooling water circulating system provides low conductivity water to the 80 ignitron power controllers in the elevated temperature test facility.

(b) The RF Cooling Water Circulating System is used almost entirely for reflector cooling in support of elevated temperature test programs. The one exception being the single induction heating loop on the 4th floor.

(c) The water demineralizing plant is used to maintain water quality in the two circulating systems.

3.1.10 Radiant Heat Facility, McDonnell Aircraft Co., St. Louis, Missouri.

During the past decade, the Space Simulation and Systems Laboratories of the McDonnell Aircraft Company has built up a substantial capability in the area of high flux and high temperature radiant heaters.

Beginning with quartz lamp banks this capability has grown, with the inception of graphite radiant heaters, such that cold wall heat fluxes approaching 500 Btu/sq ft-sec and temperatures approaching 5000 degrees F are achieved with test article areas ranging up to 32 square feet.

Graphite Heater Experience

Contractual Work.

"Design and Fabricate a Graphite Radiant Heater Capable of Delivering 100 Btu/sq ft-sec over a 16.5 x 26-inch Area" (Contract No. NAS1-8387). The heater assembly was used by NSAS-LRC for evaluation of hydrogen-cooled panels under simulated hypersonic flight heating conditions.

"Design, Development, Fabrication, and Testing of a High Heat Flux Radiant Graphite Heater System" (Contract No. NAS1-8921). The goal of this effort was to develop a radiant heater capable of delivering 250 Btu/sq ft-sec to a four square foot cooled specimen in a pressure environment between atmospheric and 250 psig. Figure 19 shows the 26 x 26-inch graphite radiant heater that was delivered to NASA-LRC at the conclusion of the effort.

"Graphite Radiant Heater Modules" (Contract No. F33(615)-69-C-0074). This contract, with the AFFDL-WPAFB, was to design and fabricate six graphite radiant heater modules to upgrade the AFFDL heat flux capability. These modules were nominally 4 x 12 inches and operated from conventional ignitron power supplies.

"Design and Fabrication of a High Temperature Heating Array" (Contract No. NAS9-13091). A 26 x 30-inch graphite radiant heater was delivered to the Structures Test Section of NASA-JSC for use in testing Space Shuttle TPS.

"Design and Fabrication of a High Temperature Leading Edge Heating Array" (Phase I, Contract No. NAS9-13091; Phase Ia, Contract No. NAS9-13544). The requirement of this contract was to develop a graphite radiant heater array capable of heating a 60-inch section of full-scale Shuttle leading edge to 3500 degrees F in a pressure environment ranging from atmospheric down to 0.5 torr. A 36 x 5 inch prototype heater was fabricated and used to evaluate design concepts and performance predictions. Presented in Figure 20 is a pictorial view of the 72-inch collapsible heater module whose detail design was completed as a part of this contract. This heater, in the 72-inch configuration, is used in the leading edge heating array while in

the 48-inch configuration (center section removed and shorter heater elements installed) it is used in the 48 x 96-inch flat heating array shown in Figure 21.

In-house Work.

An early graphite radiant heater was used in a Company funded regeneratively-cooled engine inlet study. This heater was capable of delivering 120 Btu/sq ft-sec over a 4.5 x 72-inch area.

A cylindrical, three-phase graphite heater system was designed and fabricated for testing the microwave properties of antenna windows during simulated entry heating conditions. This heater was capable of applying over 500 Btu/sq ft-sec to the antenna window located at the bottom of the cylinder while simultaneously allowing the passage of microwaves up through the hollow center.

A forerunner of the Shuttle TPS Heating Array built for NASA-JSC, was fabricated for use in the MDC Laboratory for Shuttle TPS investigations. This heater, covered with a coated columbium reradiating susceptor plate to allow the specimen to be exposed to an oxidizing atmosphere while the heater operates in an inert environment, is capable of heating a 24 x 24-inch insulating panel to 2500 degrees F. Over 1000 thermal cycle tests have been successfully run with this apparatus.

Hot End Elements. One method of forming large and/or irregular shaped radiant heating arrays is to use a large number of small heater modules stacked end-to-end and side-to-side. Advantages of this sort of arrangement are: (1) utilization of "standard" heater units, (2) the possibility of infinite expansion to any size array, and (3) a large number of individual control zones for applying a spatial heat flux profile. One of the problems in a multi-modular array is the spatial uniformity of the delivered heat flux across the inevitable gaps that exist between the modules. Side-to-side stacking presents no uniformity problem because the inter-modular gap can be made the same as the inter-strip gap. However, the problem becomes severe in the end-to-end configuration because of the necessity of providing thickened ends on each strip for electrical connection and current turnaround. These thickened ends run substantially cooler than the active area of the heater strip so that when they are co-planar with the strips, a wide "cold stripe" is formed between the ends of adjacent heaters. This problem was solved at the MDC Laboratory by the invention of the unique hot end element (U.S. Patent No. 3,573,429). The hot end element has the thickened ends of each strip "tucked under" the strip, thereby allowing the active heating portion of the strip to extend all the way to the end. These elements were originally installed on the 4 x 12 inch modules, but recent investigations have shown their feasibility in lengths up to at least 36 inches. An experimental 36 inch hot end element was successfully operated in the previously described Leading Edge Prototype heater.

Heater Control and Transient Behavior. The graphite radiant heaters that have been designed and built in the MDC Laboratory have been operated at voltages varying from 14 to 480 volts, depending upon the application. This power is supplied, with or without a step-down transformer, from standard ignitron power controllers in various size ranging all the way up to the largest available ("E" size, 2000 amp at 480 volts). For most development work it is sufficient and desirable to manually control the ignitron, but for a number of tests controlled power was supplied to the heater by means of either set-point control or feedback control utilizing both thermocouple and heat flux sensor outputs as the feedback signal.

The transient behavior of a graphite heater is much like any other type of heater inasmuch as the response is largely dependent upon the test specimen being heated. This is particularly true in the cooling case when a hot insulating test article will re-radiate energy to the heater elements causing a relatively slow cooldown, whereas with an actively cooled specimen the cooling rate of the heater assembly is spectacularly rapid. Since graphite has no undesirable thermal shock properties, full power can be applied to a heater instantaneously with a typical response like that shown in Figure 22.

Heat Exchangers. The effort for NASA-IRC to develop a graphite radiant heater suitable for evaluating hydrogen-cooled panels required the design and fabrication of a water-cooled heat exchanger to simulate the test article. The design criteria for this heat exchanger included absorption of 250 Btu/sq ft-sec without local vaporization which could cause total failure from the tube burnout. The design selected consisted of a bank of 0.25-inch diameter x .030 inch wall copper tubes arranged one immediately next to the other to form a solid wall of tubes not unlike the "water walls" often seen in high performance steam boilers. This heat exchanger is composed of eight sections of thirteen tubes each and is connected so that the water flow is down one section and back on an alternate section. This arrangement is able to generate a large heat transfer film coefficient with a modest pressure drop and relatively low flow rates all of which contributes to the efficient use of the water available.

Facility Capability

Power.

Total available steady state electrical power 7.5 MW.

Peak transient power 34.5 MW for 60 sec (time determined by transformer temperature, less than 90 degrees C).

Thermal power deliverable to test article 4.5 MW.

Power contrsllers

3 channels of "E" Ignitron (2000 amp, 480 volts each)

54 channels of "P" Ignitron (200 amp, 480 volts each)

Water System.

300 gpm at 80 psi

120 gpm at 1000 psi

Data Systems.

400 channel Central Data Acquisition System.

100 channel Dymec digital magnetic tape system.

50 channel mini-data digital magnetic tape system.

Quick-look printers.

Computer processing for overnight availability of graphical or tabular data in engineering units.

Test Area.

Indoor 50-ft high bay area.

Structural test jig with reinforced floor.

High pressure test cell, 50-ft high bay.

Figure 19. Graphite Radiant Heater

Figure 20. Heater Module

Figure 21. Flat Heater Array

Transient Test

Figure 22. Typical Response

3.1.11 NASA Johnson Space Center, Houston, Texas.

A 5 MWe radiant heat facility is being developed at the NASA J.S.C. to facilitate the heavy test commitment of the space shuttle program. The primary objective for these tests, and therefore the configuration of the facility, is to simulate the reentry conditions for the space shuttle vehicle relative to pressure and temperature. Details and descriptions were not available at publication time for these facilities. However, the heating units and controls are being fabricated by McDonnell Douglas (see Section 3.1.10). This facility is heavily committed to the space shuttle program with testing scheduled through Nov. - Dec. 1975. It might then be available on an "as available" basis.

3.1.12 Rockwell International, Downey, California. This facility of 5 MW capacity, is owned by NASA J. S. C. and is also heavily committed to the space shuttle program and would be available on an "as available" basis upon NASA approval. Details and description of this facility were not available at publication time.

3.2 Collector

There does not seem to be any unique facility requirements for the engineering and development testing for the collector subsystem. In general, participating contractors will have adequate facilities for conducting tests employing an optical bench, laser grid, or Foucault tests as well as those tests for the structure and tracking mechanisms. As the sun is the prototype energy source, there is little reason to employ any other except for optical bench tests on the reflective surfaces. There are a variety of techniques in the literature which can be used to measure mirror surface accuracy. Generally, no exotic testing facility is required. Where long distances are needed, any unobstructed line of sight may be usable.

The following facilities are identified to illustrate the general capabilities for flat or long focal length mirrors.

3.2.1 Optical Evaluation Facility, Sandia Corp., Livermore

This facility consists of two basic units: (1) the optical bench, consisting of a laser/grid setup, and (2) a full-gimbaled mount, constructed to test tracking and control systems and to evaluate mirrors. Figure 23 schematically represents the laser/grid test setup. A laser is used to project a grid pattern on the mirror being tested and the reflected image is photographed. Figures 24 and 25 show images produced by the point loading technique and the spin casting process (parabolic). The full-gimbaled mount is shown in Figure 26.

Closed Loop Sensor. A simple but effective sensor is available which consists of a tube that sits in the reflected solar radiation and is aligned with the aperture of the cavity. A pin hole or lens at the low end of the tube directs or focuses the reflected image of the sun onto four photocells located at the upper end of the tube. Figure 27 shows this quad photocell configuration.

Photocells 1 and 3 operate together into a differential operational amplifier to provide a vertical error signal. Photocells 2 and 4 operate similarly to produce a horizontal error signal. The error signals drive the respective axis of the mirror until the reflected image falls onto the center of the quad photocell. As long as the sensor tube is correctly aligned, the reflected radiation will be properly redirected.

Either photovoltaic or photoresistive cells work equally well. Photoresistive cells presently are about five times less expensive, however. When a signal is generated on one of the photovoltaic cells, it is amplified and drives the servo mechanism on the appropriate axis. If photoresistive cells are used, the pairs operate as a balanced bridge. As the resistance goes down on the cell with the most light, a signal is sent to change the corresponding mirror axis.

An in-line sensor with both a wide angle acquisition and a precision tracking sensor incorporated into a single tube has been built and tested. A hole is located in the center of the wide angle quad photocell so that as the image of the sun moves in on the wide angle sensor, it eventually goes through the hole and falls onto the second quad photocell which allows precise mirror adjustment. The two quad photocells operate electrically in parallel.

Testing. To test tracking accuracy, a gimbaled mount was built on which a 6-foot diameter mirror can be mounted. The axes of the mount are driven by AC motors running through a 75,000:1 gear ratio. Tracking accuracy was monitored using a target made of 48 adjustable photocells located in a cross pattern. Preliminary testing indicates the mount tracks within ± 2 minutes.

Contact: Mr. Tom D. Brumleve (415) 455-2941
Mr. Alen Skinrood (415) 455-2501

Reference: SAND 74-8017 "Status Report on High Temperature Sclar Energy System", Sept 1974

Figure 23. Mirror Test Setup

Figure 24. Image of Point-Loaded Mirror

Figure 25. Image of Centrifugally Cast Epoxy Mirror

Figure 26. Full Gimbaled Mount

Figure 27. Quad Photocell Configuration

3.2.2 Optical Evaluation Facility, NASA Lewis Research Center,
Cleveland, Ohio.

The unique feature of this facility is their solar concentrator inspection device. This device is particularly useful in inspecting relatively short focal length mirrors such as their 20 ft diameter, 9 ft focal length parabolic concentrator. When testing the surface accuracy of their collimator mirrors of 61 meter radius, Foucault tests were conducted. The solar concentrator inspection device does not seem to be applicable to the measurement of long focal length or flat mirrors such as are being considered for the collector subsystem heliostats. No other unique equipment or tests were identified at this facility which would be of particular use for testing the collector subsystem components.

Contact: Mr. John L. Pollock (216) 433-4000 x354

Reference: Report 20-Foot Solar Concentrator Inspection NASA
TMX-68042 "400 Kilowatt Argon Arc Lamp for Solar
Simulation", pp 4 & 5.

3.2.3 Naval Weapons Center, China Lake, Calif.

OPTICAL EVALUATION. This facility consists of several instruments to measure non-normal incidence transmittance, normal and non-normal incidence reflectance, attenuated total reflection, and scattering from mirrors and windows.

What the facility can do. Specular reflectance and transmittance at normal incidence can be measured from the vacuum ultraviolet to the intermediate infrared. Specular reflectance can be measured as a function of angle of incidence in the ultraviolet and visible spectral regions, and attenuated total reflection can be measured in the visible and infrared. Scattering from optical surfaces can be measured as a function of scattering angle or as total hemispherical scattering from the ultraviolet to the infrared; the roughness of a surface can be calculated from the scattering measurements. The accuracy of all measurements is at least 10 times better than is possible with commercially available instruments.

How the facility works. Several instruments are available, all of which have been built at Michelson Laboratory. freedom from systematic errors. In all types of measurements light of a single wavelength falls on the sample, and the amount reflected, transmitted, or scattered is determined. (Figure 28).

Sample Requirement. For most types of measurements the samples should be in the form of disks 1.520 inches in diameter and 0.25 to 0.375 inch thick, with one surface flat to within a wavelength of light and polished to a mirror finish. For some of the reflectance and scattering measurements, the samples can be actual mirrors up to 40 centimeters in diameter with radii of curvature larger than 11.5 centimeters.

Processing Time. Processing time is variable, depending on the type of measurement desired. In most cases measurements take about 15 minutes per data point after the initial adjustments have been made.

Contact: Dr. S. Douglas Elliot (714) 939-2830
Dr. Jean M. Bennett 939-2869

Figure 28. Schematic Diagram of an Apparatus to Measure Scattering from a Sample
(The specularly reflected beam follows the solid line and the scattered light is represented by the dashed lines.)

3.3 Thermal Storage. Due to the unique requirements for Thermal Storage for the proposed Solar Thermal Central Receiver Power System, only the existing facilities at the Sandia Laboratories, Livermore have been described as these descriptions were readily available. Other facilities may or may not be available to meet the needs of specific subsystem concepts. These facilities are being developed as a result of prior interests of the A. E. C. in this field of research.

3.3.1 Sensible Heat Storage Test Facility, Sandia Laboratories, Livermore, Calif.

The Sensible Heat Storage Test Facility is made up of the following three circuits:

- (1) Heater or collector simulator systems.
- (2) Storage systems.
- (3) Load simulator systems.

Instrumentation is included to obtain data at critical points throughout the system. This will allow measurement of the efficiency of the system and verification of the proper operation of specific components. In addition, control equipment is included for automatic operation of the system.

Collector Simulator System. This system consists of a heater with pump, heat exchanger and normal safety equipment. The heat transfer fluid, Monsanto Thermanal 66, can be used at temperatures up to 650 degrees F. A temperature control valve regulates a heat by-pass system. In addition, there are flow meters and a number of visual and recording instruments for temperature and pressure.

Storage System. The storage system consists of the heat exchanger, a storage tank, two pumps, and an evaporator tank. This system also has the required safety features. At present it is designed to use (1) water at 450 degrees F and 450 psi, (2) Thermanal 66 at 550 degrees F for the storage fluid. This system has two temperature control valves which control two heat bypass circuits. There are also flow meters and visual and recording temperature and pressure indicators. In addition, the storage tanks can use the thermocline principle and has 26 thermocouples for recording the storage temperature at different heights from the bottom of the tank. Two diffusers are used for supplying and removing fluid from the tank without disturbing the thermocline. The instrumentation in this system is sufficient to record the amount of energy at critical points plus the capability of monitoring the operation of the diffusers. (See Figures 29 and 30).

Load Simulator System. The Load Simulator System is designed to bring city water to an evaporator tank. It includes instrumentation to measure the efficiency of the heat transfer and the changing of cold water to steam. This system will have programmed loads that will call for output from the storage tank.

General Comments. This facility is now being assembled and will be operational in the spring of 1975. If desired, the present storage system can be replaced with other storage systems for test and evaluation. Maximum operating temperatures and materials and fluid compatibility would have to be examined.

Components in the system are:

Heater: Fulton Fultemp Thermal Fluid Heater No. 10T
Output - 326,000 Btu/hr

Opr. Temp - 600 degrees F max
Opr. Press - 75 psi
Fuel - No. 2 Fuel Oil

Heater Pump:

Power - 7.5 HP
Capacity - 10 GPM

Heat Exchanger:

Cross Flow Construction
Q - 330,000 Btu/hr
Heat Transfer Oil - 550 to 450 degrees F
Storage Water - 350 to 450 degrees F

Storage Tank:

Volume - 1775 gallons
Working pressure - 450 psi
Wall thickness - 1 inch
Heat capacity - 1,250,000 Btu at 100 deg.
change in T
Insulation - (1) wall, super insulation and
vacuum
(2) top and bottom glass wool
blanket

Storage Pumps:

(2) RSB Centrifugal Type CPK300
Power - 3 HP
Capacity - 10 GPM

Evaporator Tank:

Cross Flow Construction
Q - 160,000 Btu/hr
Storage water - 450 to 350 degrees F
Supply water - 55 to 220 degrees F

Contact: Mr. A. C. Skinrood (415) 455-2501
Mr. T. D. Brumleve (415) 455-2941

Reference: Sandia Laboratories Memo Jan 7, 1975
R. A. Milby to A. C. Skinrood
"Sensible Heat Storage Test Facility"

SLL-73-0263
"Sensible Heat Storage in Liquids"
T. D. Brumleve, July 1974

Figure 29. Sensible Heat Energy Storage System Schematic

Figure 30. Experimental Test Facility
Sensible Heat Storage of Liquids