NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1231

The 10-ft Space Simulator at the Jet Propulsion Laboratory

Douglas E. Lund

JET PROPULSION LABORATORY
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Approved by:

George G. Goranson

George G. Goranson, *Manager*
Space Simulators and
Facility Engineering Section

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Abstract

This report describes the JPL 10-ft space simulator facility that is used for JPL, NASA, and NASA authorized testing purposes. The report also provides sufficient technical information for proper planning of simulator tests.

The 10-ft Space Simulator at the Jet Propulsion Laboratory

I. Introduction

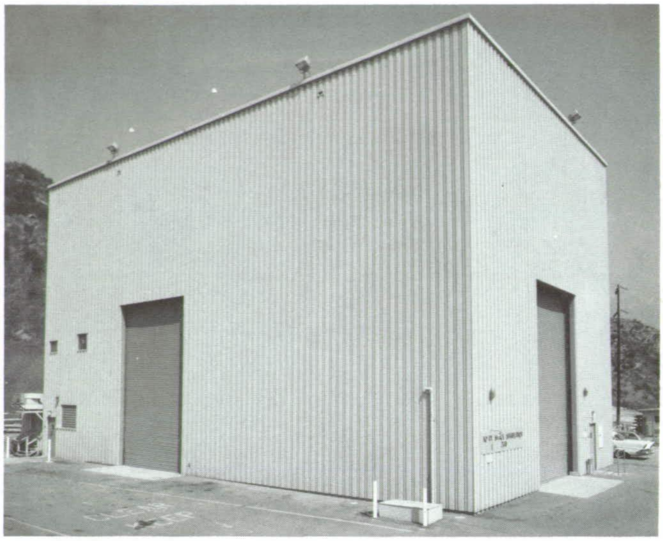
The JPL 10-ft space simulator provides the environment necessary for the testing of spacecraft, temperature control models, spacecraft subsystems, spacecraft hardware, and other miscellaneous items under simulated interplanetary conditions. Conditions of high vacuum, intense solar radiation, and extreme cold are produced in the space simulator to meet the required environmental conditions.

II. Description of the 10-ft Space Simulator

The 10-ft space simulator facility (Building 248) is located at the north end of the laboratory complex and consists of a large building (53 × 96 ft and 45 ft high) housing the space simulator, the vacuum and cryogenic pumping systems, and the solar simulation system. The facility building also contains an operation control console and a large main floor with space available for test vehicle buildup, test equipment maintenance, test vehicle control instrumentation, data readout, and visiting test personnel. Two large balconies (each approximately 18 × 40 ft) provide additional test equipment storage area. A 5-ton crane and 1.5-ton hoist are available for moving test hardware and equipment throughout the building. Figure 1 shows the space simulator facility and presents a floor plan showing the locations of the various systems and work areas.

A. Simulator Vacuum Chamber

The vacuum chamber is a cylindrical vessel 13 ft in diameter and 45 ft high. The bottom of the cylinder is approximately 17 ft above the building floor. The bottom of the vessel or "endbell" moves up and down on a 20,000-lb capacity hydraulic elevator lift for chamber entry of test hardware (Fig. 2). A personnel door with a viewing port into the chamber is located on the second level balcony.



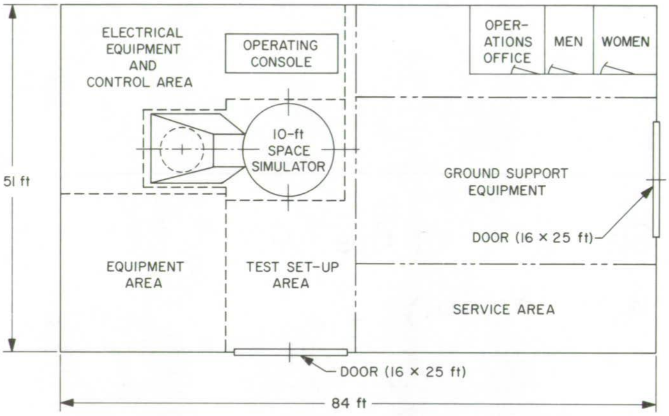


Fig. 1. Floor plan of the 10-ft space simulator

The inside working diameter of the vacuum chamber is 10 ft. The chamber shell is constructed of 304L stainless steel which provides high strength, low outgassing, and good corrosion resistance. Figure 3 presents a cross section of the space simulator showing the locations of some of the space simulator components.

B. Vacuum System

The 10-ft space simulator can be evacuated from atmospheric pressure to 5.0×10^{-6} torr in approximately 2 h.

Vacuum pumping is done by the JPL wind tunnel compressor plant, mechanical pumps, and diffusion pumps. These systems are schematically shown in Fig. 4.

1. Compressor plant pumping. The compressor plant is connected to the 10-ft space simulator by a 20-in. diameter pipe. The compressor plant provides four stages of compression and pumps 82,000 ft^3/min at atmospheric pressure down to 1075 ft^3/min at a pressure of 2 torr. The compressor plant pumping system can also evacuate the 10-ft space simulator from atmospheric pressure to a pressure of 30 torr in 90 s, thus making it possible to simulate various flight pressure changes.

A gaseous nitrogen bleed system is incorporated into the space chamber to permit control of pumping speeds. Figure 5 shows nominal pressure-time pumpdown curves and pumping speed data for the 10-ft space simulator. Figure 6 presents typical balloon ascent and descent pressure-time curves from a previous simulator test.

The compressor plant is equipped with a dryer to backfill the simulator with dry air to prevent moisture and contamination buildup inside the chamber. Another means available for backfill operations is the use of the laboratory high-pressure gaseous nitrogen system, which can be controlled to backfill at the desired rate.

2. Mechanical pumping. The mechanical pumping system consists of two mechanical vacuum pumps, two vacuum booster pumps, and a vacuum holding pump.

The mechanical vacuum pumps are located in two parallel circuits and are each operated in series with a vacuum booster pump. The mechanical vacuum pumps evacuate the space simulator (through the vacuum booster pumps) from atmospheric pressure down to 15 torr, or from approximately 50 torr if the wind tunnel compressor plant is used initially. The mechanical vacuum pumping speed at atmospheric pressure is 860 ft^3/min, and at 10^{-2} torr, the pumping speed is 320 ft^3/min.

The vacuum booster pump automatically starts when the simulator pressure reaches 15 torr and increases the pumping performance of the pump system. Simulator pressure drops to 10^{-3} torr quickly, and to 10^{-4} torr eventually. The vacuum booster pump pumping speed is 1940 ft^3/min at 250 μm down to 25 μm. Therefore, the mechanical vacuum pumps and vacuum booster pumps provide both simulator roughing and diffusion pump backup capabilities.

The vacuum holding pump evacuates the volume of the 32-in. diffusion pumps and the duct work to the simulator high-vacuum valves down to the desired foreline pressure. The vacuum holding pumping speed varies from 118 ft^3/min at 760 torr down to 36 ft^3/min at 10^{-2} torr.

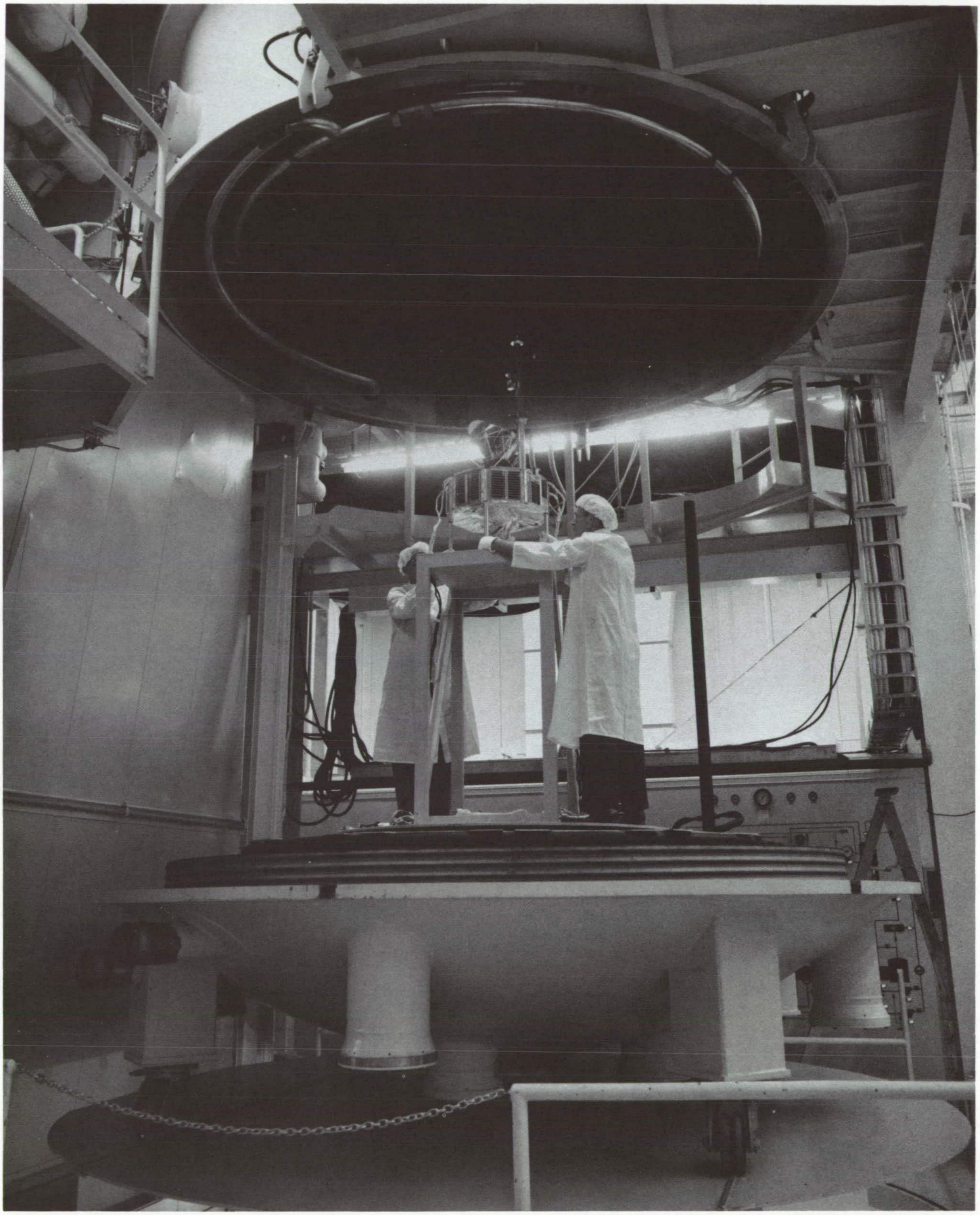


Fig. 2. Chamber entry for test hardware

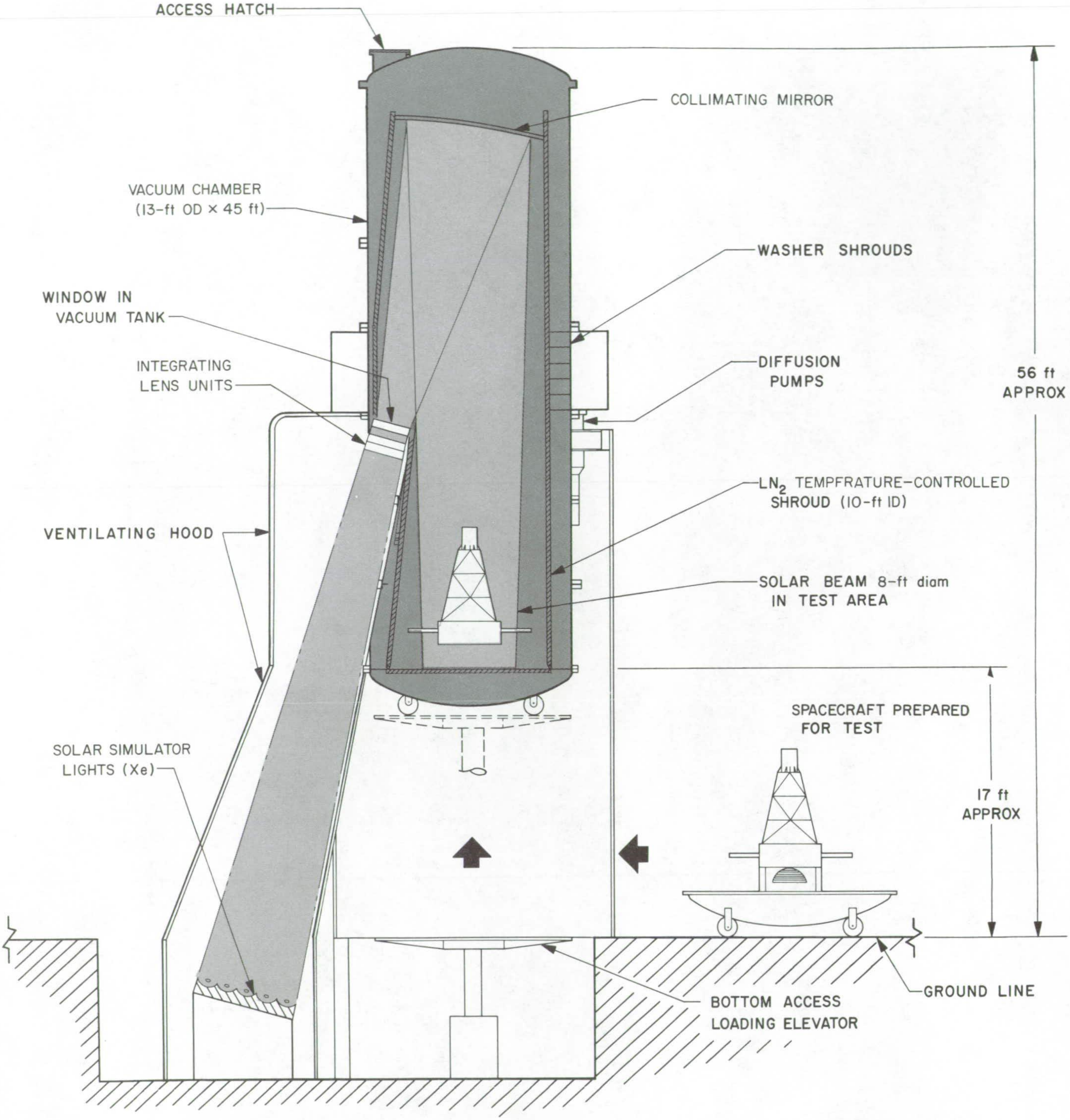
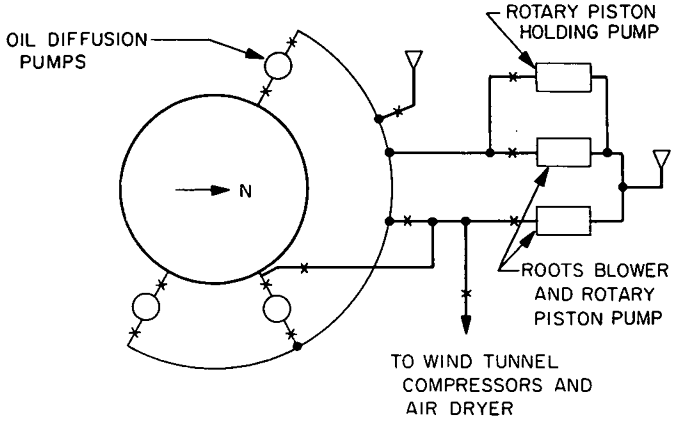


Fig. 3. Cross section of the 10-ft space simulator



PUMP TYPE	MAKE	MODEL	RATING
OIL DIFFUSION	CVC[a]	PMC-50,000	50,000 l/s
ROTARY PISTON	STOKES	148-H	40 ft^3/min
ROOTS BLOWER AND ROTARY PISTON	STOKES	1724	2634 ft^3/min (blower) 300 ft^3/min (piston)

[a] CONSOLIDATED VACUUM CORP.

Fig. 4. Vacuum pumping system

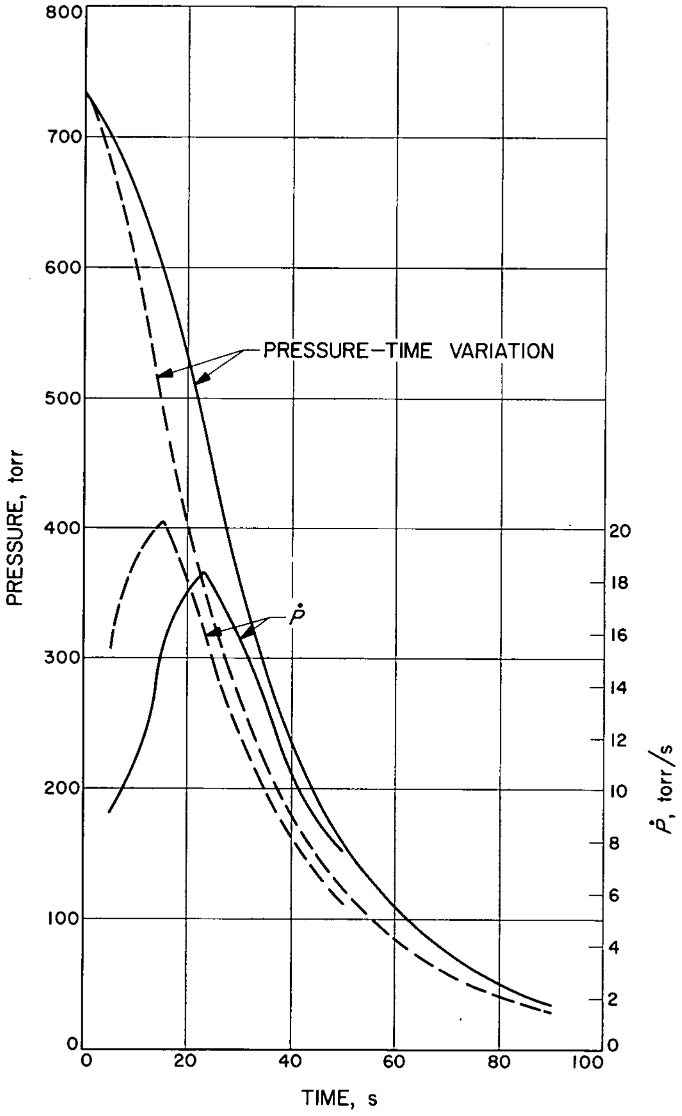


Fig. 5. Pumpdown pressure profiles

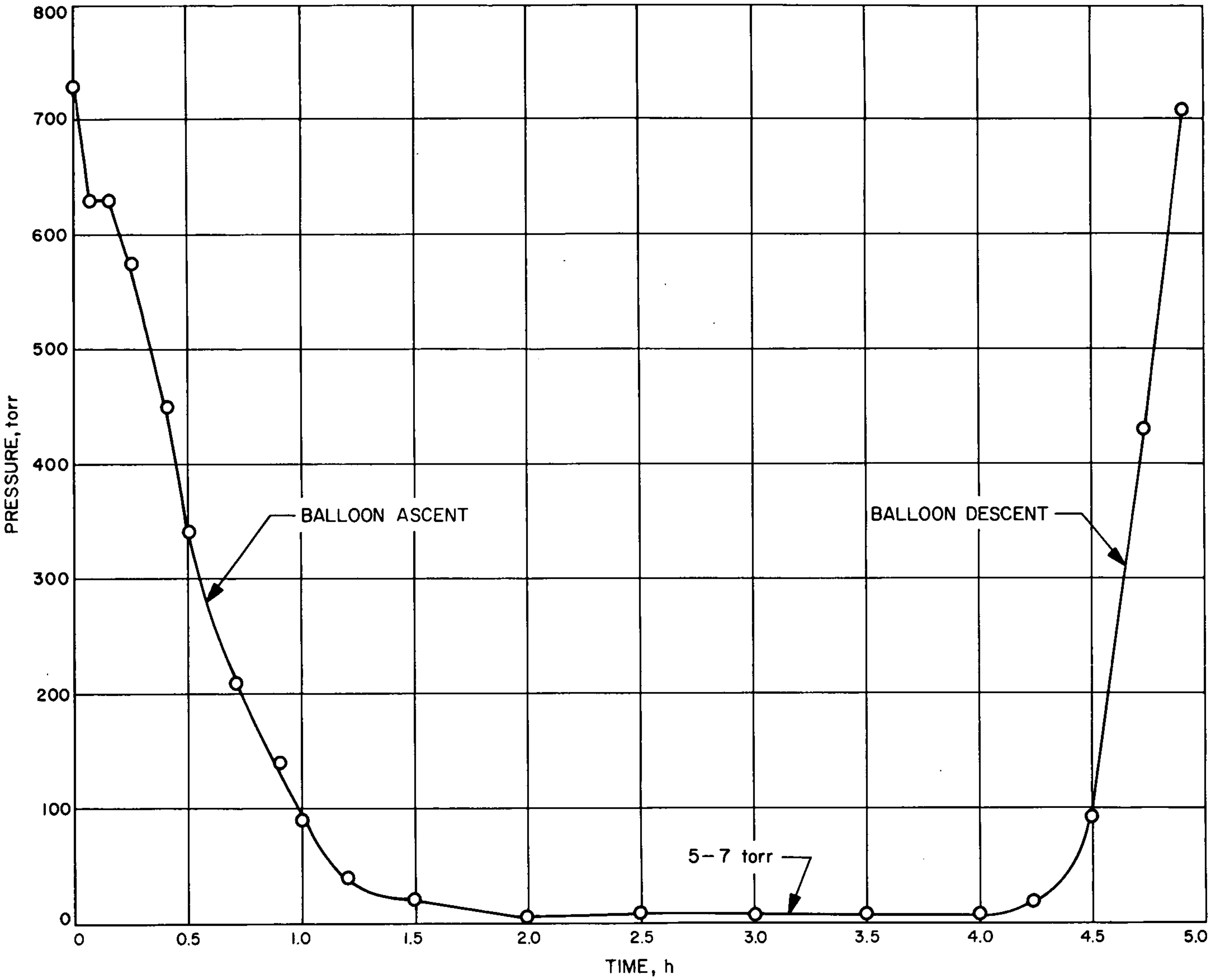


Fig. 6. Typical balloon gondola data

3. *Diffusion pumping.* The diffusion pump system consists of three 32-in. pumps located at approximately the 39-ft level of the chamber. Each diffusion pump is rated at 50,000 l/s and can operate in the pressure range from 10^{-3} to 10^{-10} torr. A complete pressure performance curve for a typical test operation is presented in Fig. 7.

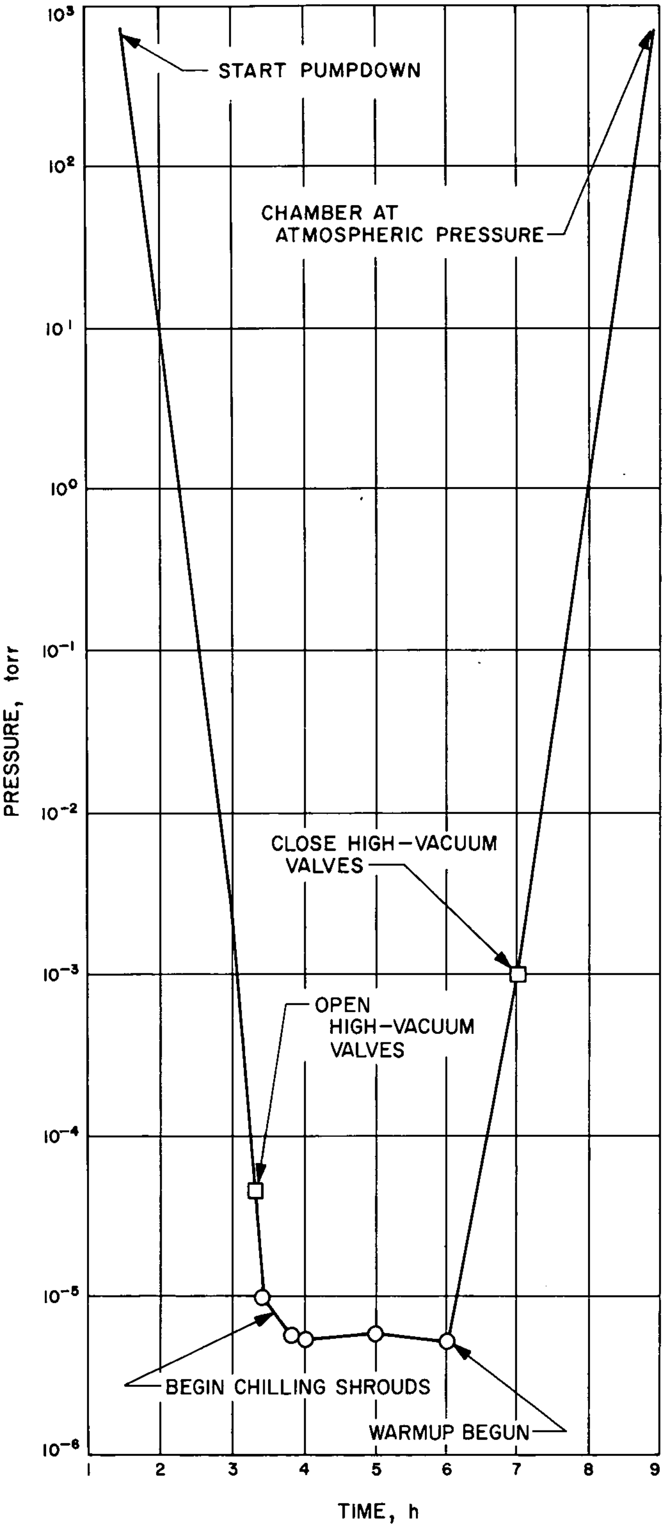


Fig. 7. Typical pressure profile

C. Solar Simulation System

Solar simulation in the 10-ft space simulator is accomplished by a JPL developed system that illuminates the spacecraft test volume with nearly parallel light that closely duplicates natural radiation from the sun. The solar system consists of twenty-five 5-kW Xenon short-arc lamps that are air-cooled and are mounted in ellipsoidal collecting reflectors, 16 in. in diameter. Light is transmitted from the Xenon lamps, through arrays of condenser lenses and projecting lenses and through a quartz window, to a 10-ft diameter spherical collimator. The light is then reflected to the spacecraft test volume as shown in Fig. 8. Figures 9–12 present some of the components which make up the solar simulation system. The design of the solar simulation system is described in Ref. 1.

A great deal of versatility, along with excellent overall collimation and uniformity, is provided by the solar simulation system. Either a 6.5- or 8-ft diameter light beam may be obtained within approximately 3 days, the time needed for changeover.

The 8-ft diameter light beam is capable of an irradiance level in excess of 140 W/ft^2, a uniformity of ±5%, and a collimation half-angle of 1.5 deg. With the 6.5-ft diameter beam, an irradiance level in excess of 290 W/ft^2 may be obtained (>Venus), along with a uniformity of ±5%, and a collimation half-angle of just over 2 deg. Each system contains a douser to interrupt the light beam between the lamps and the quartz window for simulating a solar eclipse.

The solar intensity can be increased to 900 W/ft^2 by either adding a number of 5-kW arc lamps to the system, or increasing lamp size to 20 or 30 kW. Some modifications would have to be made to the condenser lens frame to properly dissipate the additional heat load. Figure 13 presents solar performance capability of the 10-ft space simulator using 20-kW arc lamps.

The simulated solar beam is calibrated by surveying the beam with a 2- × 2-cm solar cell that is referenced to a radiometer. Solar calibration data for the 10-ft space simulator are presented in Fig. 14. Figures 15–17 show the solar uniformity and apparent source size.

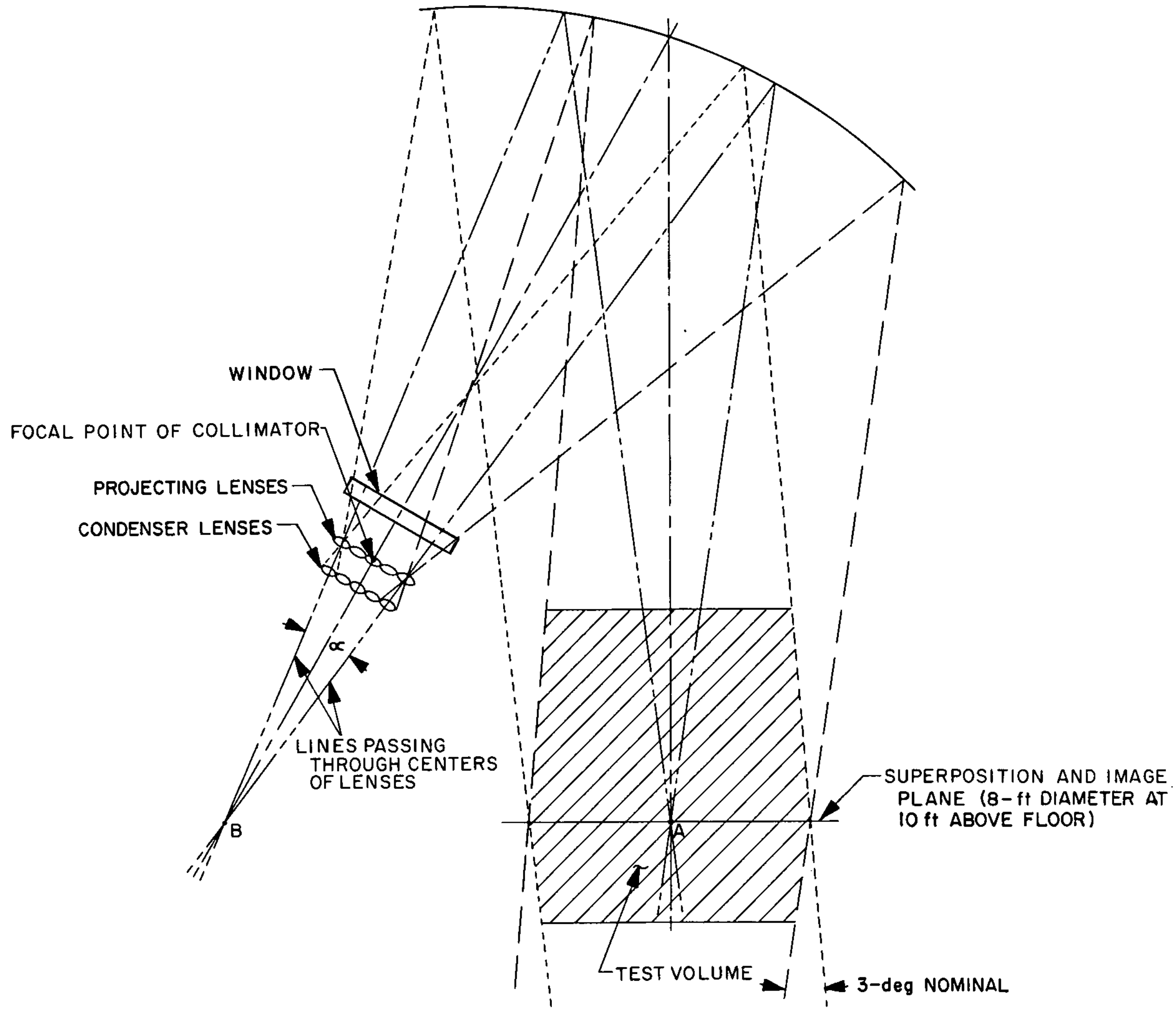


Fig. 8. Irradiated test volume

Fig. 9. Headlamp array

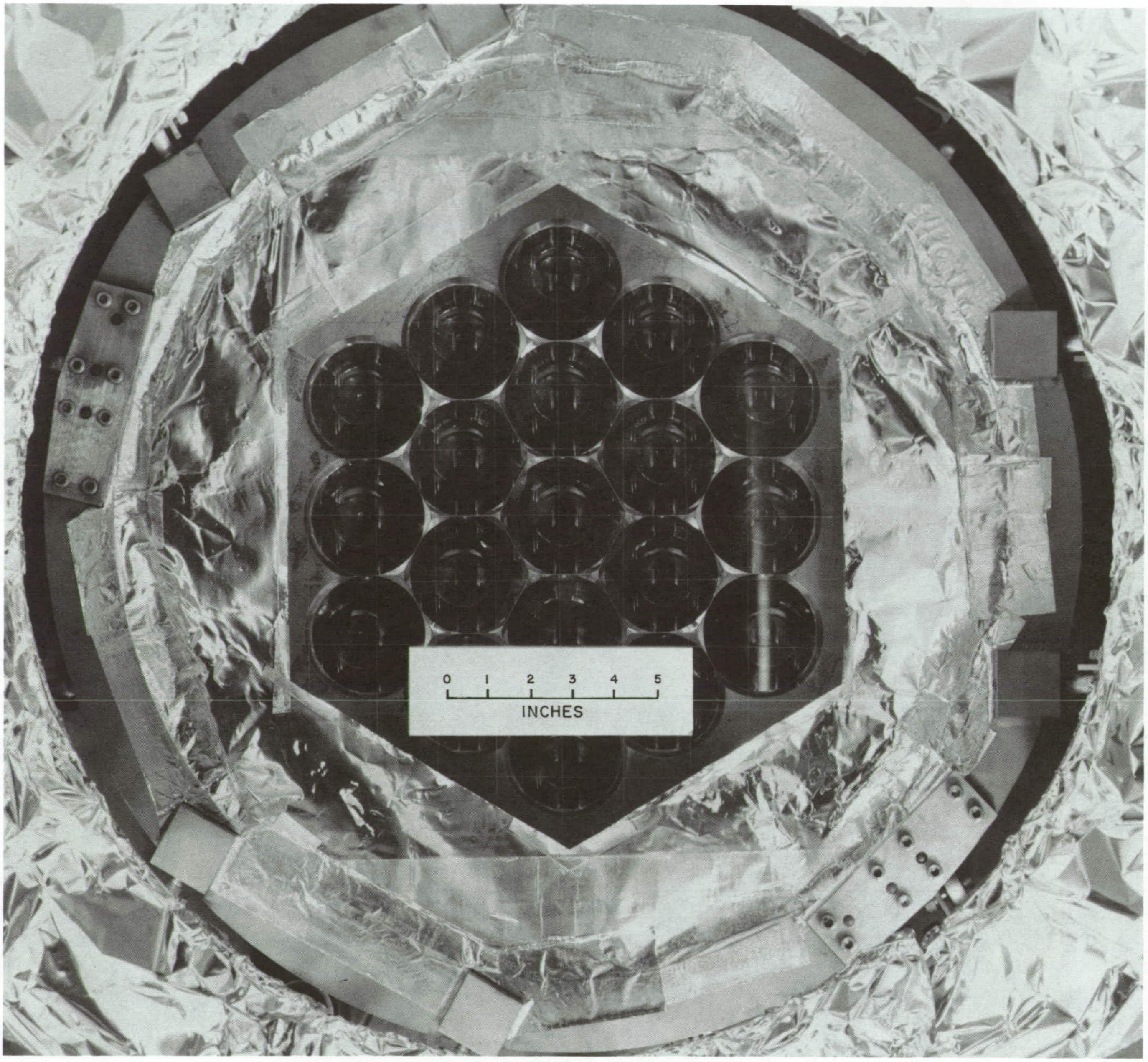


Fig. 10. Array of condenser lenses

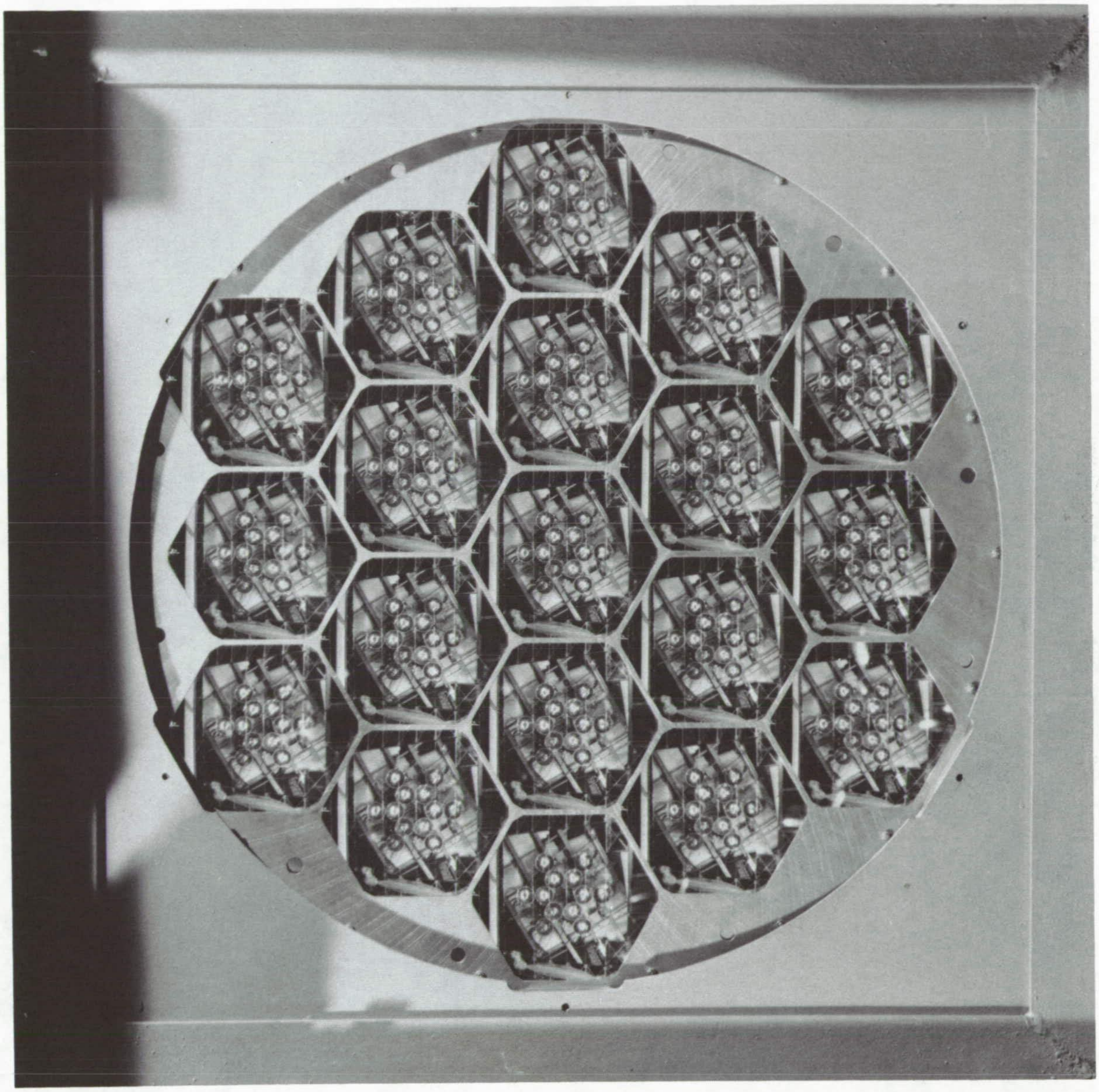


Fig. 11. Array of projecting lenses

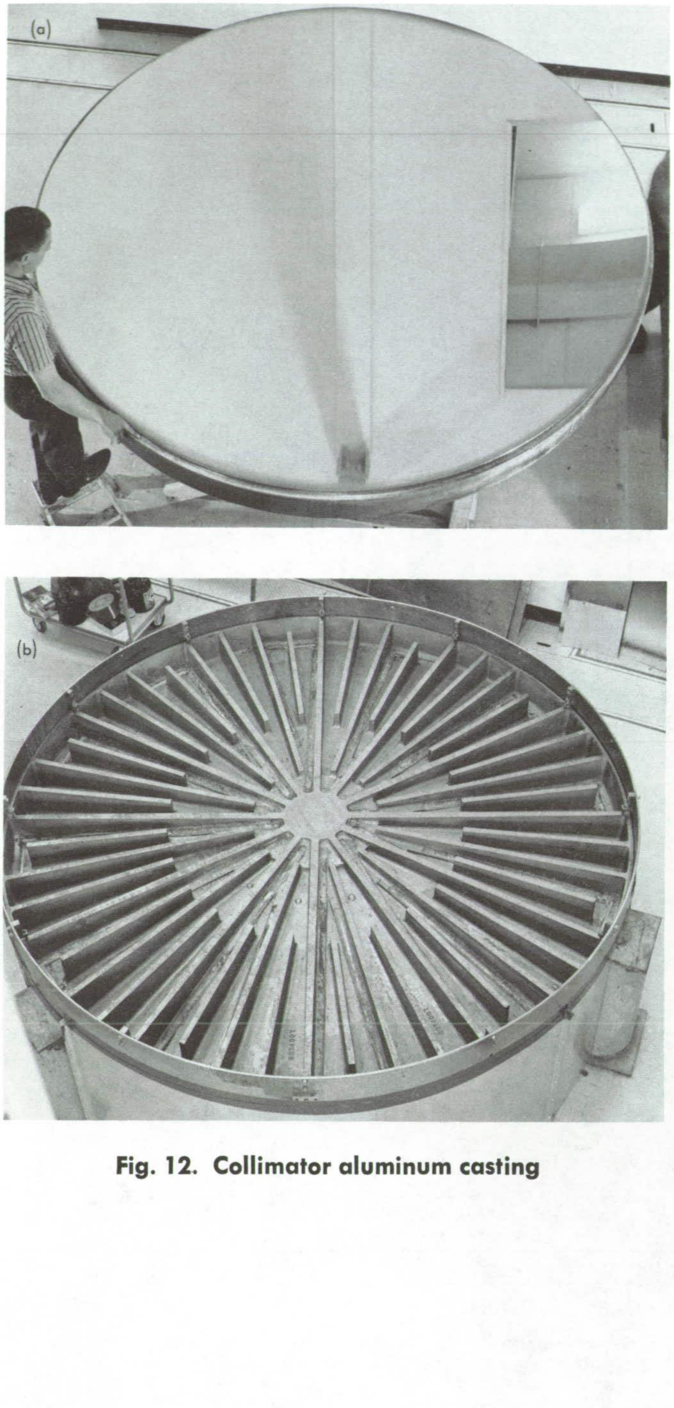


Fig. 12. Collimator aluminum casting

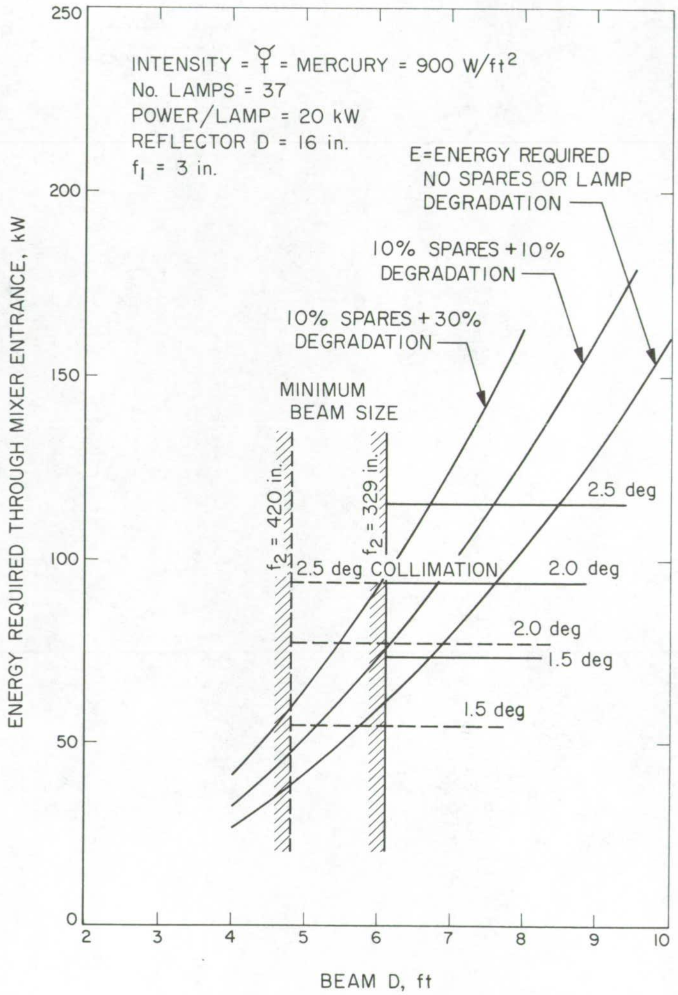


Fig. 13. Solar performance capabilities at 900 W/ft² (Mercury intensity)

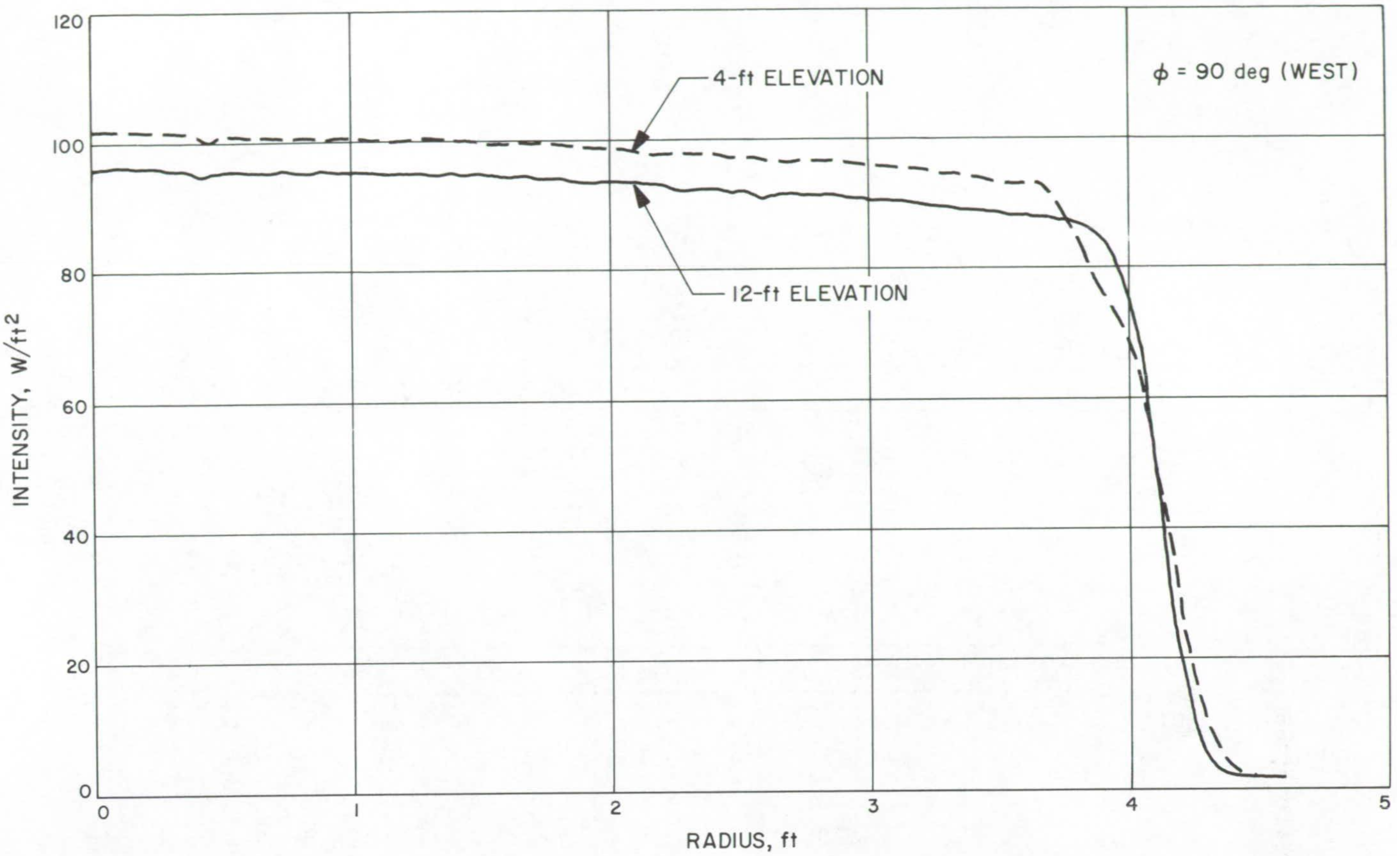


Fig. 14. Solar mapping data (6.5-ft beam)

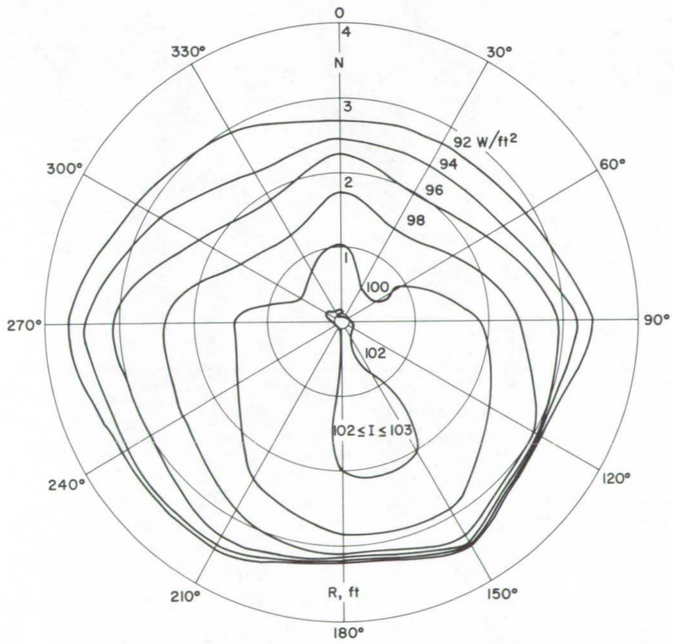


Fig. 15. Solar uniformity, 4-ft elevation (6.5-ft beam)

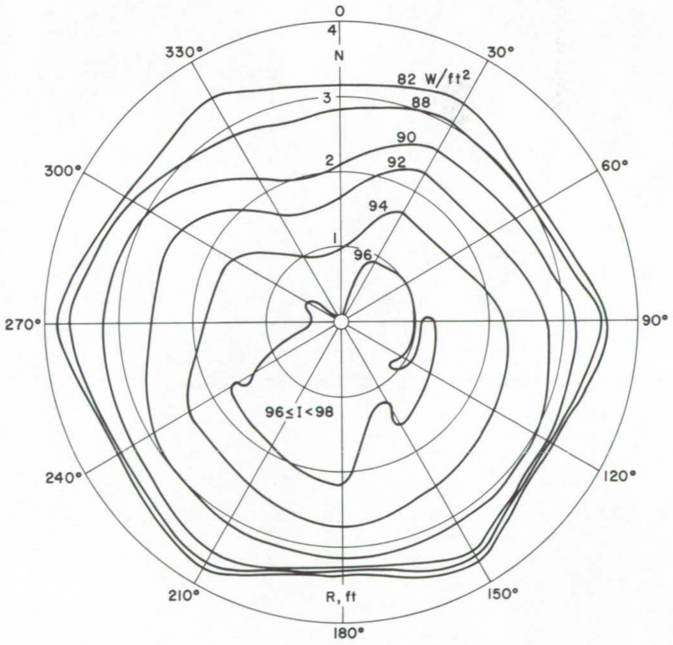
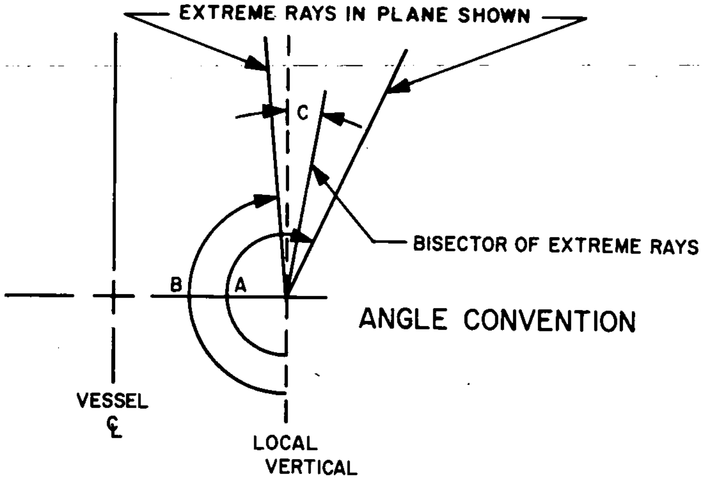


Fig. 16. Solar uniformity, 12-ft elevation (6.5-ft beam)



POSITION	ANGLE A	ANGLE B	A–B	ANGLE C
N	182° 12' 6"	177° 55' 54"	4° 16' 12"	4' 0" N
S	182° 46' 27"	178° 10' 42"	4° 35' 45"	28' 34" S
E	182° 4' 54"	178° 3' 17"	4° 1' 37"	4' 5" E
W	182° 32' 56"	178° 21' 54"	4° 11' 2"	27' 25" W

AVERAGE DIFFERENCE: N–S 4° 25' 59"
E–W 4° 6' 20"
INDICATED APPARENT SOURCE SIZE OF LESS THAN 2° 13', HALF-ANGLE

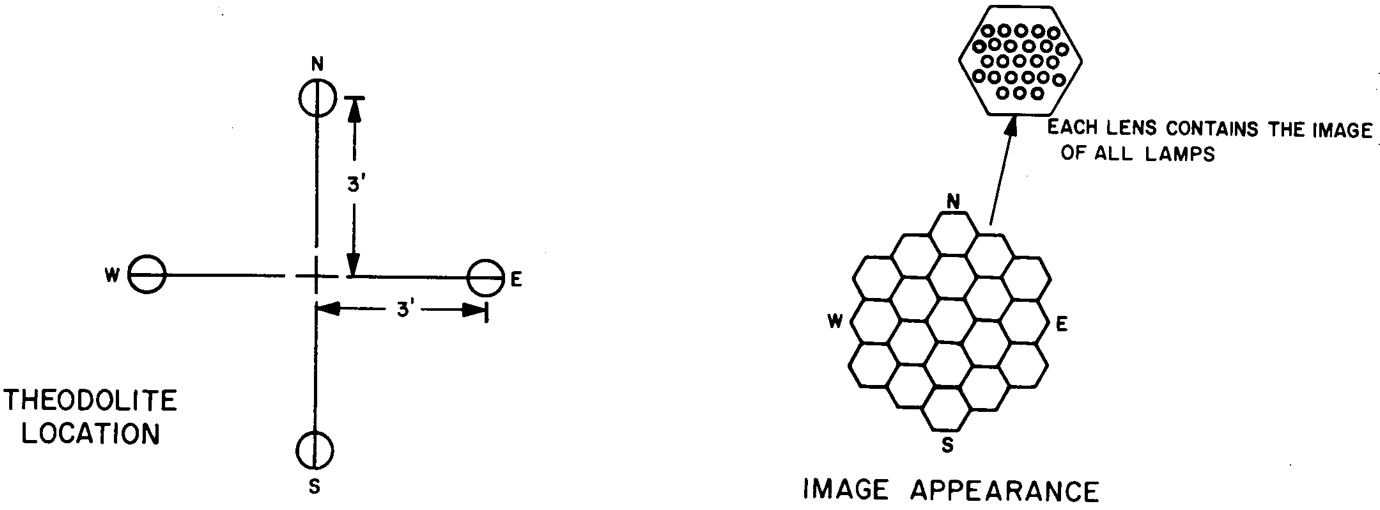


Fig. 17. Apparent source size for 10-ft space simulator (6.5-ft beam)

D. Cryogenic System

The simulator test volume temperature is controlled by stainless steel shrouds lining the chamber walls and floor. Except for the collimator (highly reflective) on the chamber ceiling and a few small areas not seen by the test volume, all areas are covered by shrouds. A high-absorptivity black paint has been applied to all shroud surfaces.

During testing, the chamber thermal environment may be maintained at a temperature of −310°F by cooling the shroud passages with liquid nitrogen. Chamber cooldown time to −310°F averages 30 min. Intermediate temperatures from −250 to +250°F may be obtained by either cooling or heating gaseous nitrogen which is pumped through the shrouds. Balloon ascent temperatures may be duplicated in this manner.

At the present time, the liquid nitrogen storage capacity is 28,000 gal. The facility consumption rate of liquid nitrogen is approximately 400 gal/h with all shroud systems cold.

E. Supporting Systems

The simulator electrical power supply is 1000 kV-A, 2400-V-(Δ) transformed to 480-V/277-V (Y), 3-phase power. This power is distributed to three motor control centers. Two of the motor control centers provide power that is distributed about equally to the various building and simulator systems, such as building lighting, solar rectifiers, vacuum pumps, diffusion pumps, LN_2 pumps, ventilation, etc. The third motor control center is an emergency bus.

The emergency bus is furnished electrical power from a 400-kW 3-phase 480-V diesel powered generator. The generator starts automatically within 3 s after power failure; power is available to the emergency bus in 15–17 s. This power operates the following: emergency lighting, control power, one diffusion pump, one vacuum pump and blower, GN_2 heater, a holding pump, one LN_2 supply pump, the mirror blower, mirror heaters, the building doors, shroud blower, four solar rectifiers, an air compressor, and four outlets from the power supply to the spacecraft command and monitoring equipment. An auxiliary generator creates 75-kW 3-phase 480-V power which is transformed to 120/208 V (Y) and is supplied to four additional outlets for ground support equipment in the event of emergency power generator failure.

Treated and filtered cooling water is furnished in a closed loop system having 4-in. supply and return lines. The water is pumped to the following: vacuum pumps and blowers, air conditioning, mixer lens and light douser, solar hood cooling coil, and the diffusion pumps. Each unit has an individually regulated water supply. City water is available for use in the event of an emergency.

Air is obtained from a laboratory-wide 115-psi distribution system. In the event that the supply pressure drops below 85 psi, a 10-hp emergency compressor starts automatically to supply air to the facility. This air supply is used for valve controls, solar hood ventilation, and utility outlets.

Gaseous nitrogen is obtained from a 2250-psi laboratory-wide distribution system and is reduced to 100 psi for distribution within the facility. The GN_2 is used:

(1) To drain the shrouds and baffles of LN_2.

(2) As the *fluid* for operating the shrouds between −250 and +250°F.

(3) For cooling the collimating mirror.

(4) For chamber backfill.

(5) For mechanical pump gas ballast.

(6) For pressurizing the Perlite insulation of the LN_2 storage tank.

(7) For valve controls.

III. Facility Instrumentation Systems

A. Pressure Measurements

Chamber pressure is measured and monitored by several types of systems. The Baratron pressure measuring system is the basic instrumentation used for monitoring pressures from 1 atm down to 10^{-4} torr. It consists of two pressure sensing heads and two Leeds and Northrup strip-chart recorders. One head senses pressures from 1 atm down to 10 torr, and the other from 10 to 10^{-4} torr.

Varian ionization gages are used for pressure measurements from 10^{-3} to 10^{-8} torr. Usually two gages are installed to cover gage failure. One gage output is recorded on one of the strip-chart recorders. Two other ionization gages are installed in the chamber to act as vacuum failure alarm systems. The data from these two gages may be used for environmental measurements, but the gages are not connected to a recorder.

Other instrumentations for pressure measurement are also available as follows:

(1) Cooke ionization gage controller, range from 10^{-3} to 10^{-9} torr.

(2) Magnevac vacuum gage system, range from 500 to 10^{-3} torr.

(3) Televac vacuum gage, range from 1 to 10^{-3} torr.

(4) Varian ionization gage and controller, range from 10^{-3} to 10^{-8} torr.

B. Solar Radiation Measurements

The Hy-Cal Model P-8400-B water-cooled Hy-Therm Pyrheliometers, of which JPL has seven, are used to set the solar intensity and to monitor this intensity throughout each test. Each consists of a circular thermal sensing area approximately 1 in. in diameter, and provides an output of approximately 5 mV per solar constant, both in air and in vacuum. These instruments are essentially linear (straight line response) and have been calibrated to 400 W/ft^2 (430.6 mW/cm^2). Each may be used with or without quartz windows. The window is normally used during measurements in air to reduce noise caused by convective air currents. Response time is 570 ms ($1/e$) or 60 s (99% of total response). They employ the Hy-Therm principle, with thermopile junctions on both sides of an insulating wafer which is irradiated on one side and attached to a heat sink on the other. This principle results in conductively dominated heat transfer making the response the same in air or vacuum.

The Hy-Cal pyrheliometer electrical output is normally recorded on a Speedomax H recorder with AZAR (adjustable zero and range), which allows a ±2- to ±100-mV span and a 0-, 10-, 20-, 30-, or 40-mV zero suppression. If additional radiometers are used, the outputs are simply read from a digital millivoltmeter or are fed into the Datex recording system. The recorder accuracy is 0.3% of full scale. The digital millivoltmeter accuracy is 0.1% of the reading ±1 digit and its sensitivity is 10 μV. No collimation tube or aperture limit is currently employed on the Hy-Cal pyrheliometers. Zero-irradiance readings must therefore be taken during vacuum operation.

Eppley Mark I radiometers using wire-wound and plated thermopiles (Fig. 18) are being evaluated. These

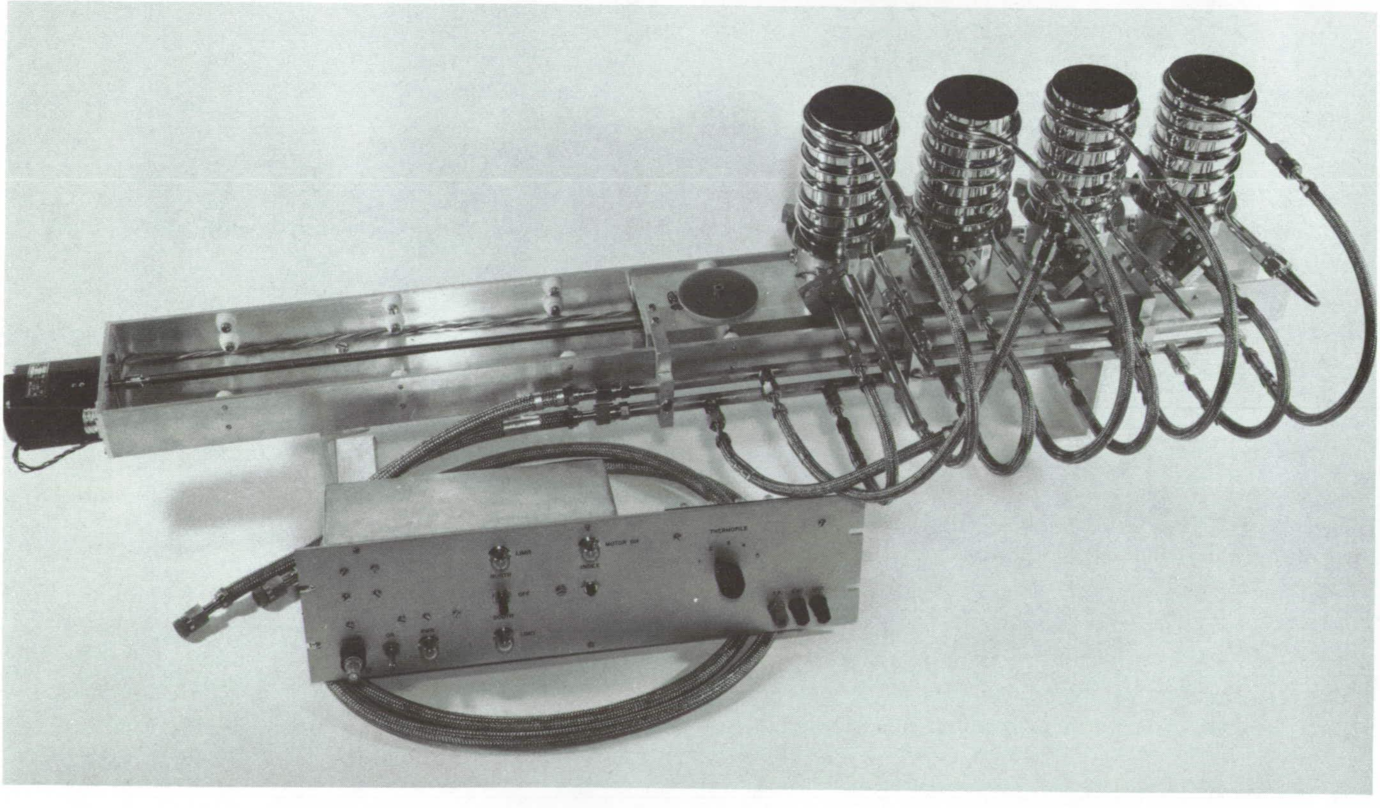


Fig. 18. Eppley Mark I radiometers

radiometers are much more rugged than the older Eppley Mark I radiometers (employing the bismuth-silver thermopiles) that have been used for several years at JPL. These newer radiometers will be used with JPL 7-deg acceptance angle, water cooled, baffled, blackened collimation tubes. These tubes reduce the zero-irradiance (solar simulation off) reading to an insignificant amount making the instruments direct-reading in vacuum, and eliminate the need for windows when used in air.

All instruments mentioned have been calibrated in air at Table Mountain, near Wrightwood, Calif. (elevation 7400 ft), against two Eppley Angstrom pyrheliometers that also have a 7-deg acceptance angle. No windows are used on the Eppley radiometers in air; the water cooled collimation tube eliminates wind and convective air current problems experienced in the past. Air-cooled collimation tubes have been employed during Hy-Cal pyrheliometer calibrations at Table Mountain and, in general, quartz windows have been necessary to obtain stable data. These calibrations supplement and act as a check of the radiometer manufacturers' calibration.

The JPL Instrumentation Section in conjunction with the Applied Mechanics Section have developed a cone radiometer. This device employs a nickel wire-wound cone inside a guard heater. The nickel wire acts as a highly sensitive resistance thermometer as well as a heating element. The guard is maintained at a preset constant temperature that is determined by the irradiance range desired. The cone temperature is slaved to the guard temperature by using the nickel wire as a heater element. In the vacuum environment of cold black space, all electrical power into the cone would be radiated out from the cone, following the formula $A\sigma T_r^4$, where A is the cone aperture area, σ is the Stephan-Boltzmann constant, and T_r^4 is the cone temperature. No heat transfer between the cone and the guard occurs, since both are at the same temperature. If the cone is now irradiated, less electrical power will be needed to maintain its temperature. This electrical power difference is a measure of the irradiance. The cone is useful only in vacuum; thermal equilibrium is required, therefore, the effective time constant (including the human operator needed in the present configuration) is long, on the order of minutes. The theoretical accuracy is reported to be better than 1%. This cone radiometer is still under development.

The Eppley Mark IV filter radiometer (Fig. 19) measures irradiation at the test location as a function of

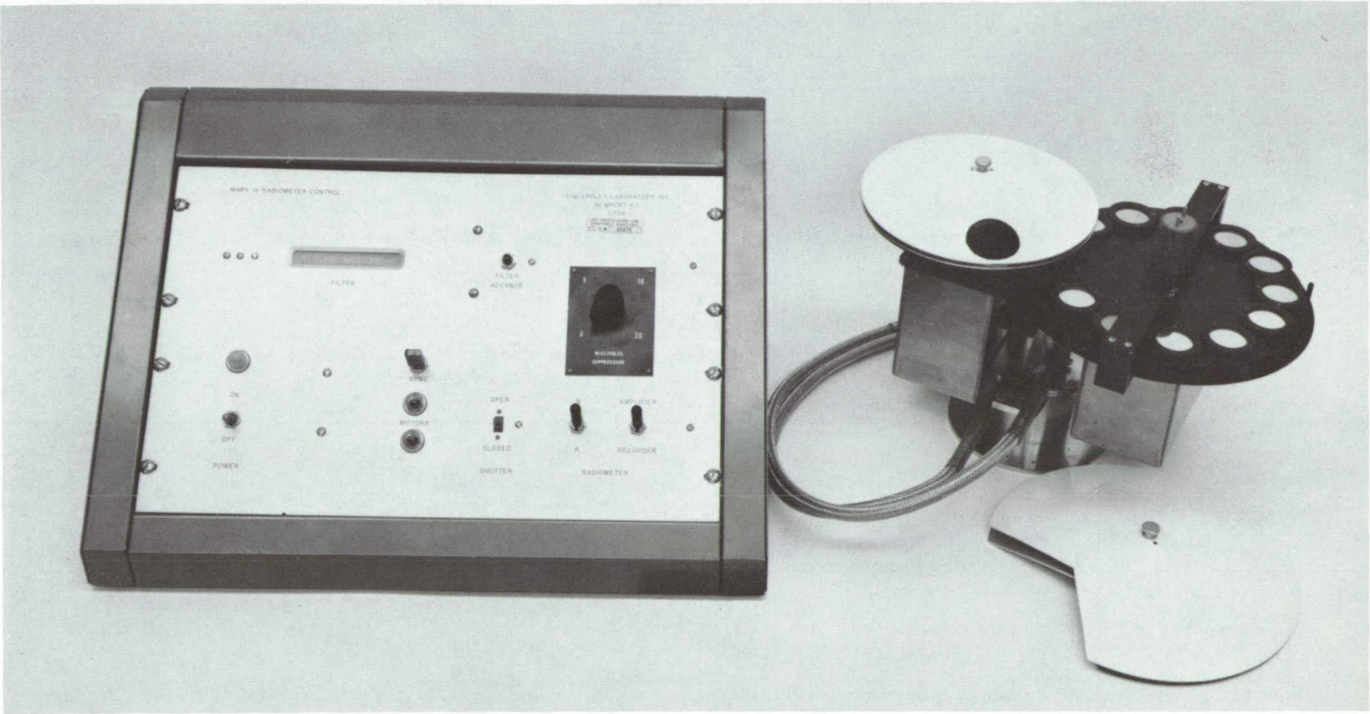


Fig. 19. Eppley Mark IV filter radiometer and control console

wavelength. It employs 12 narrow-band filters, which are remotely positioned one at a time over the radiometer from controls at a small remote console. Each filter is selected for appropriate bandwidth according to the source used. Different sets of filters are employed for mercury-xenon, xenon, carbon-arc, and tungsten filament lamps. Aperture openings in 1-deg steps from 5 to 15 deg are provided. A suitable opening is selected to accommodate the light beam divergence in the chamber. A remotely rotatable shutter reduces solarization of the filters; cooling-water coils permit temperature control of the thermopile assembly. The instrument will operate satisfactorily at 10^{-6} torr under cold-wall conditions. A quartz window is provided for use at atmospheric pressure. Sensitivity is 0.04 mV/W/ft^2 in air and 0.13 mV/W/ft^2 in vacuum. Response times to 98% of steady-state value for air and vacuum are 3 and 10 s, respectively.

C. Temperature Measurements

Up to 96 thermocouple temperatures can be recorded to monitor chamber operational performance. Sixty-one additional thermocouples are installed in the chamber and can be recorded when necessary. A Honeywell 24-channel recorder is normally used to record temperature data during chamber steady-state conditions. During transient chamber conditions, a Leeds and Northrup 72-channel recorder may also be used. The thermocouples mounted in the chamber are copper-constantan, with an operating temperature range from −320 to +300°F.

Test item temperature measurements are typically acquired by using chromel-constantan thermocouples mounted with C-56 silver cement and aluminum caps on the test vehicles. Two-hundred channels of thermocouple feedthroughs are available with two Pace thermocouple, 32°F, reference junctions. Data are recorded on two Datex data loggers with 200 channels each.

D. Data Handling

All transducer outputs appear in analog form at the patchboard in the recording area. The data are channeled through the appropriate signal-conditioning equipment and are either recorded in analog form or converted to digital data and then recorded. The complete record of a test can be stored on magnetic tape. This tape can be processed on the IBM 7094 computer, and selected parameters can be plotted. The data handling capability of the space simulator facility is described in detail in Table 1. Datex tape output is shown in Table 2.

Table 1. Data handling capabilities

Digital recorders		Analog recorders
Datex Data Logger		Strip Charts
Capacity	200 channels	Both 6- and 10-in. strip charts are available for continuous recording of test parameters.
Voltage input	±10 mV	
Scanning rate	2 channels/s	Oscillograph
Thermocouple type	Chromel-constantan, referenced to 32°F	A direct-writing oscillograph with 24 channels is available for analog recording.
Temperature ranges	±300°F 200 to 1800°F	Magnetic Tape
		A portable magnetic tape unit is available, when required, for recording 14 channels of data.
Output	Printed paper tape in mV or in °F (Table 2)	
PDP-4 Computer[a]		
Capacity	400 channels	
Voltage input	±10 mV	
Scanning rate	50 channels/s, max	
Thermocouple types	Chromel-constantan Copper-constantan	
Output	Edited listing on printer at test site	

[a] In Central Recording Service, remote from space simulator.

Table 2. Paper tape output from the Datex digital data recorder

Time				Channel identification			Data in °F			
1	8	3	0	2	1	0	0	0	6	6
1	8	3	0	2	0	9	0	0	6	7
1	8	3	0	2	0	8	0	0	7	0
1	8	3	0	2	0	7	0	0	6	8
1	8	3	0	2	0	6	0	0	7	1
1	8	3	0	2	0	5	0	0	7	2
1	8	3	0	2	0	4	0	0	7	1
1	8	3	0	2	0	3	0	0	7	1
1	8	3	0	2	0	2	0	0	6	9
1	8	3	0	2	0	1	0	0	6	9
1	8	3	0	1	5	0	0	0	1	0
1	8	3	0	1	4	9	0	0	1	0
1	8	3	0	1	4	8	0	0	1	0
1	8	3	0	1	4	7	0	0	1	0
1	8	3	0	1	4	6	0	0	0	9
1	8	3	0	1	4	5	0	0	0	9
1	8	3	0	1	4	4	0	0	0	9

IV. Required Information for Testing

It is necessary that the Space Simulators and Facility Engineering Section be apprised of all information pertaining to a proposed test well in advance of the actual testing time. This information is required to properly schedule, prepare, and conduct a test in the JPL 10-ft space simulator.

Test information is disseminated through the following methods:

(1) A test proposal, which is written by the sponsoring agency, supplying the test purpose and justification, required simulator test conditions, test item instrumentation, required data output, and potential problem areas.

(2) An advanced planning conference, which is held at JPL well in advance of the test date, completing the test planning between the simulator user and the JPL personnel.

(3) A pretest conference, which is held at JPL two weeks before testing, providing detailed information for run schedules, instrumentation, test hardware and installation drawings, list of visiting personnel, etc.

Initial test inquiries and communications should be directed to the Manager, Space Simulators and Facility Engineering Section, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, Calif. 91103.

Reference

1. Bartera, R. E., and Barnett, R. M., *Development of the Jet Propulsion Laboratory Solar Simulator Type A*, Technical Report 32-638. Jet Propulsion Laboratory, Pasadena, Calif., July 15, 1964.