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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1231

Revision 1

# The 10-ft Space Simulator at the Jet Propulsion Laboratory

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CALIFORNIA INSTITUTE OF TECHNOLOGY
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Prepared Under Contract No. NAS 7-100
National Aeronautics and Space Administration

## Preface

The work described in this report was performed by the Environmental Sciences Division of the Jet Propulsion Laboratory.

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## Tables



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# Contents (contd)

## Figures (contd)

## 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 Jet Propulsion Laboratory 10-ft space simulator provides the environment necessary for the testing of spacecraft and other space applications hardware under simulated interplanetary conditions. Conditions of high vacuum, intense solar radiation, and a cold-black heat sink similar to the void of space are produced in the space simulator to meet the required environmental conditions. The space simulator contains a volume of 5000 cu. ft. High-altitude environments such as those experienced by high-altitude balloon gondolas can also be provided. The facility is unique in that it provides solar simulation of very high uniformity and low-source size. In addition, the wind-tunnel system provides rapid evacuation, simulating rapid ascent of spacecraft during the launch phase.

## II. Description of the 10-ft Space Simulator

The 10-ft space simulator facility, Building 248, is located at the north end of the JPL complex and consists of a large building (51 × 84 ft and 45 ft high) housing the space simulator, with its 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 and storage, 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. The space simulator facility and a floor plan showing the locations of the various systems and work areas are shown in Fig. 1.

### A. Simulator Vacuum Chamber

The vacuum chamber is a cylindrical vessel; its outside dimensions are 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.

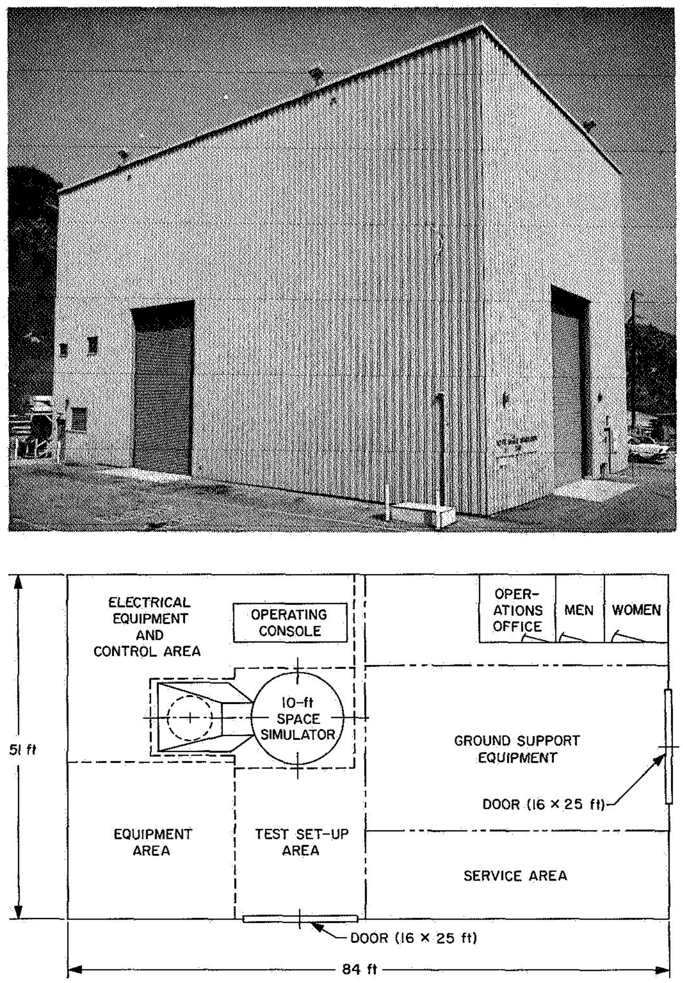



**Fig. 1. The 10-ft space simulator**

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. A cross section of the space simulator indicating the locations of some of the space simulator components is shown in Fig. 3.

### B. Vacuum System

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

Vacuum pumping is accomplished by the JPL wind-tunnel compressor plant, mechanical pumps, blowers, and diffusion pumps in that sequence. A schematic of these systems is shown in Fig. 4.

*1. Compressor plant pumping.* The wind-tunnel 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 of $\approx$750 torr to a pressure of 30 torr in 90 s, thus making it possible to simulate various flight pressure changes, such as initial spacecraft launch ascent.

A gaseous nitrogen bleed system and valve position controls are incorporated into the space chamber to permit control of pumping speeds. Nominal pressure-time pumpdown curves and pumping speed data for the 10-ft space simulator are shown in Fig. 5. Typical balloon ascent and descent pressure-time curves from a previous simulator test are presented in Fig. 6. In this case, the wind-tunnel compressors were not required.

There are three means of backfilling the chamber: (1) the compressor plant is equipped with a dryer to backfill the simulator with dry air to prevent moisture and contamination buildup inside the chamber, (2) the JPL high-pressure gaseous nitrogen system can be controlled to backfill at the desired rate, and (3) the "clean tent" air system can be used to backfill the chamber with filtered temperature and humidity-conditioned air.

*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 pumps automatically start when the simulator pressure reaches 15 torr and increases the pumping performance of the pumping system. Simulator pressure quickly drops to $10^{-3}$ torr, and eventually to $10^{-4}$ torr. The pumping speed for the vacuum-booster pump is 1940 $ft^3/min$ at 250 $\mu$ (0.25 torr), down to 25 $\mu$ (0.025 torr = $25 \times 10^{-3}$ torr). The mechanical-vacuum and vacuum-booster pumps can provide both simulator roughing and diffusion-pump backing capabilities.

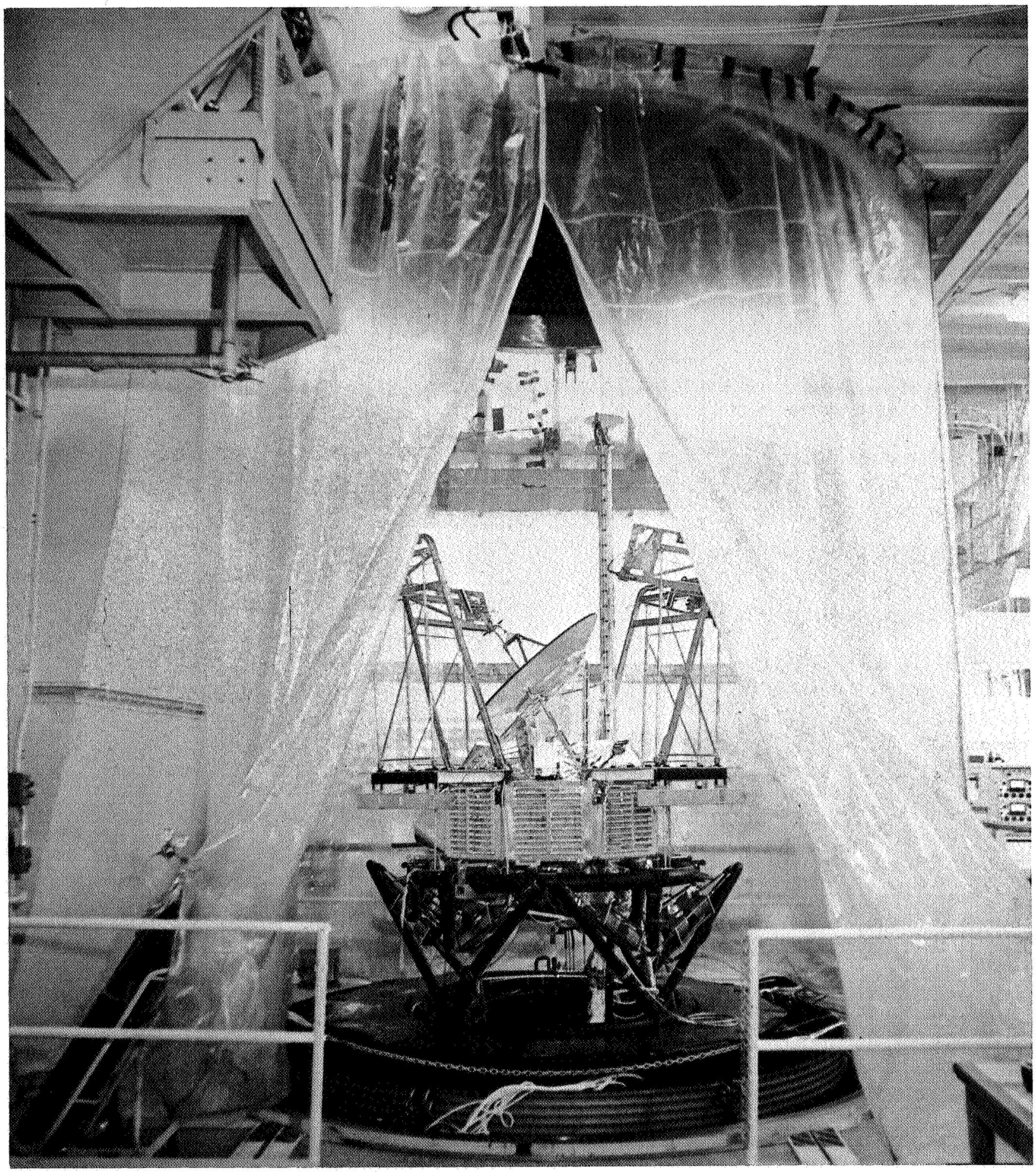


Fig. 2. Chamber entry for test hardware

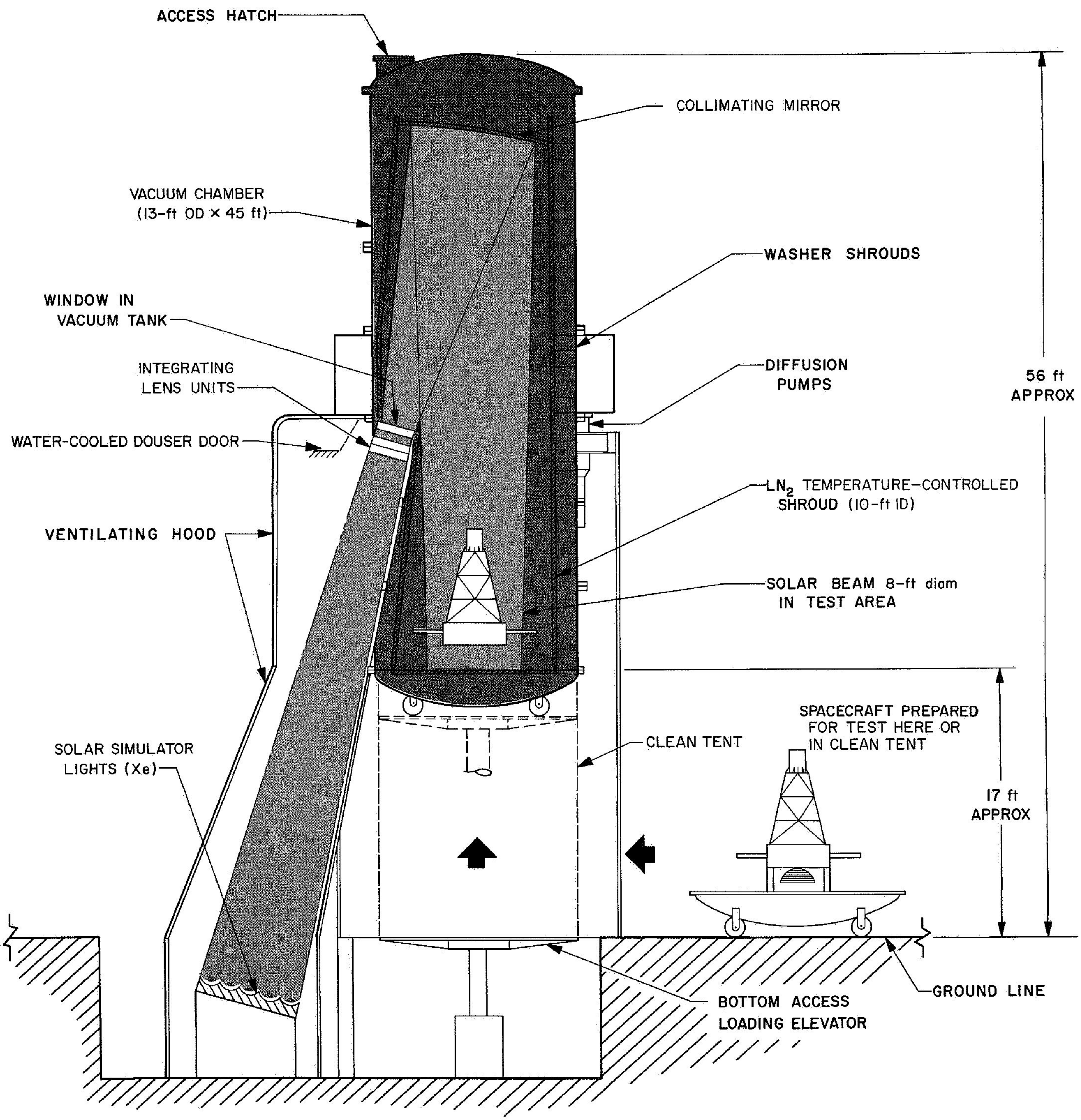
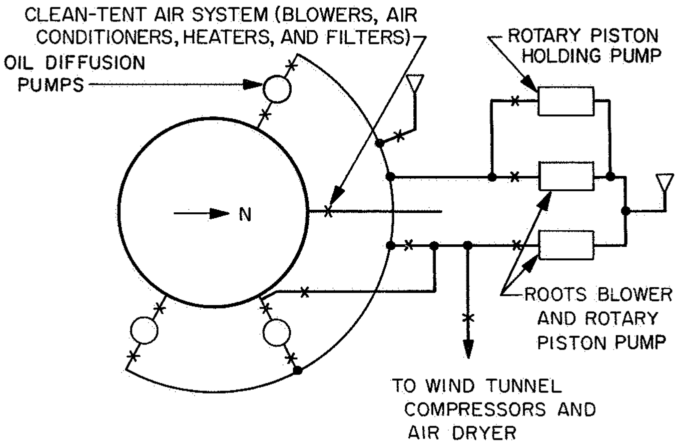



Fig. 3. Cross section of the 10-ft space simulator




| PUMP TYPE | MAKE | MODEL | RATING |
|---|---|---|---|
| OIL DIFFUSION | CVC[a] | PMC-50,000 | 50,000 l/s |
| ROTARY PISTON | KINNEY | KDK-150 | 150 $ft^3$/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**

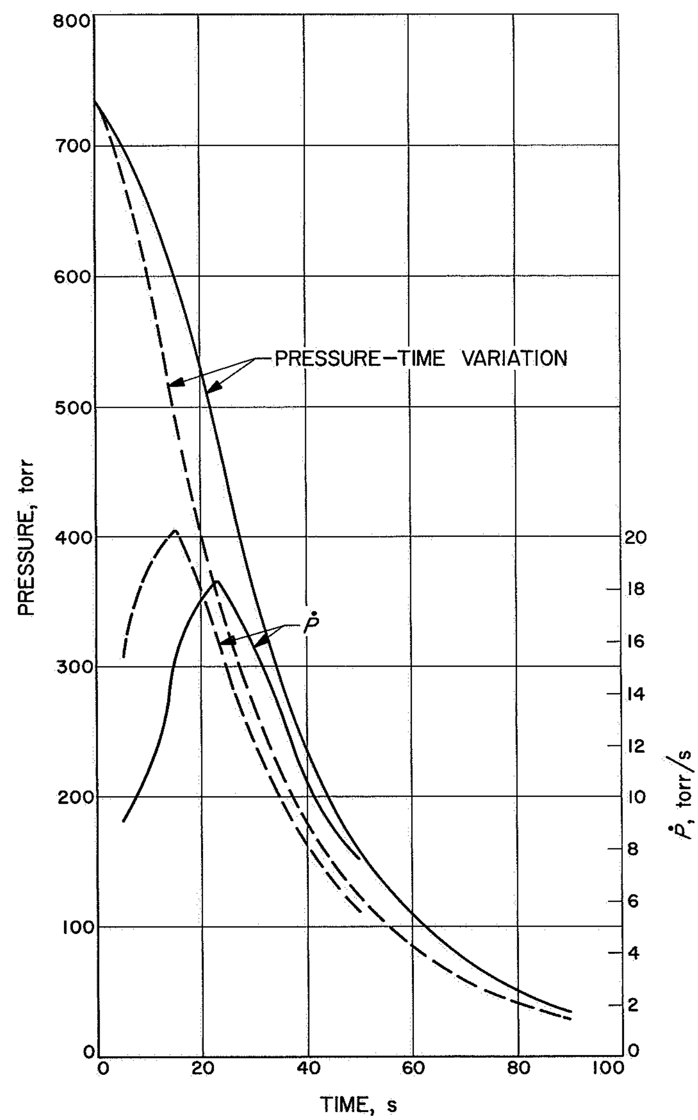



**Fig. 5. Pumpdown pressure profiles**

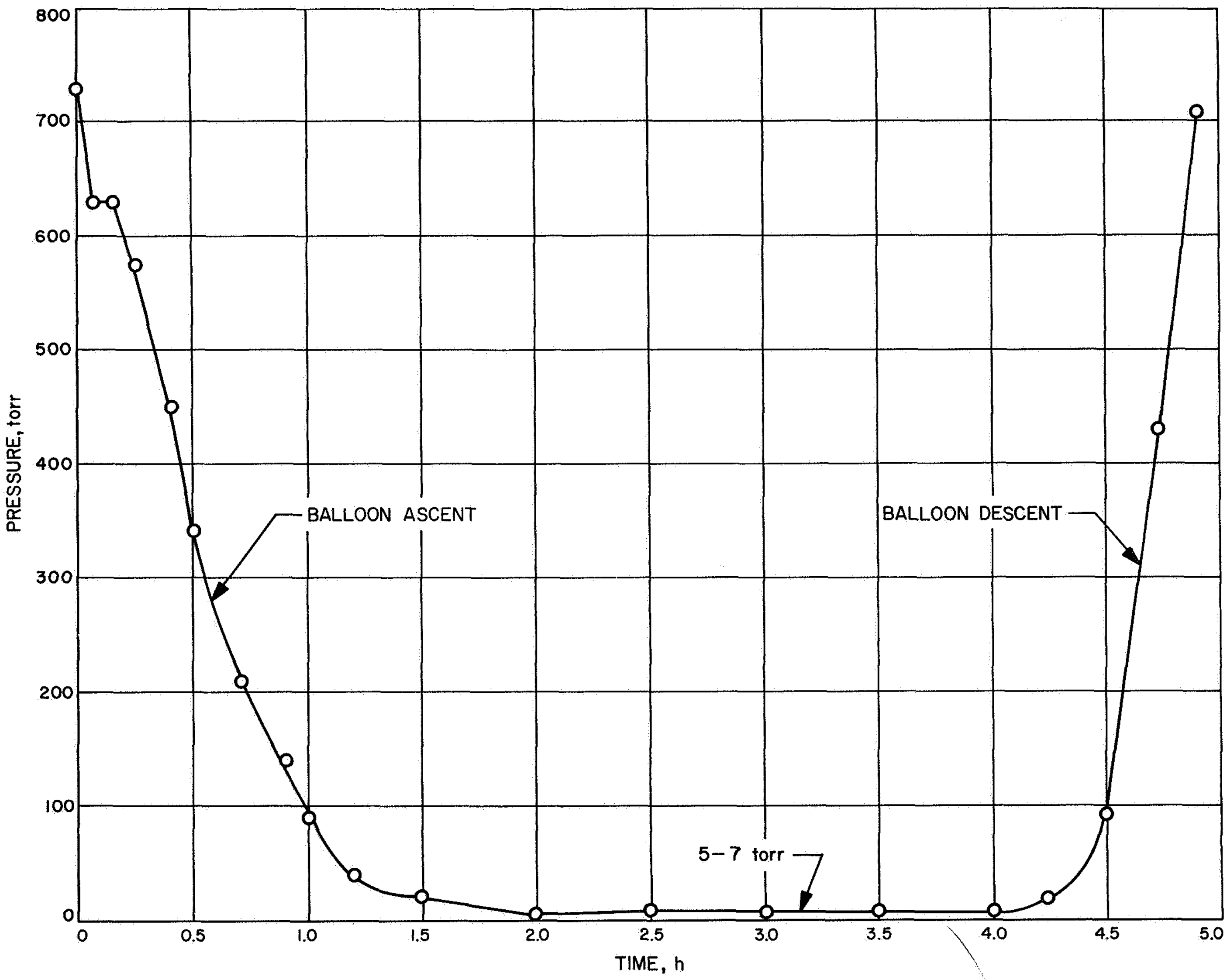



**Fig. 6. Typical balloon gondola data**

The vacuum-holding pump evacuates the volume of the three 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.

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 torr-liters/s and can operate in the pressure range from $10^{-3}$ to $10^{-10}$ torr. A pressure performance curve for a typical test operation is presented in Fig. 7.

### 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 (collimated) light that closely duplicates natural radiation from the sun. An array of twenty-five 5-kW xenon-compact arc lamps provides simulated solar energy that is directed into the chamber through a 19-lens optical mixer and transfer lens. The energy from each of the 19 separate channels fills the entire area of the solar beam; i.e., the energy from each channel is superimposed on that from each other channel in the test area. (The superposition obtained from the mixer allows changes in intensity by igniting additional lamps with no change in solar beam characteristics.) The solar beam is reflected down to the test volume by a one-piece 10-ft-diameter collimating mirror located in the top of the chamber (Fig. 8). The one-piece collimator eliminates nonuniformities associated with segmented collimators. Some of the components which make up the solar simulation system are shown in Figs. 9–12. 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 can be provided. Approximately 3 days are required for light beam changeover.

The 8-ft-diameter light beam is capable of an irradiance level in excess of 160 W/ft$^2$, a uniformity of $\pm 5\%$, and a collimation half-angle (apparent source size) 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), with a uniformity of $\pm 5\%$ and a collimation half-angle of just over 2 deg. A douser is provided to interrupt the light beam between the lamps and the quartz window for simulating a solar eclipse (Fig. 13).

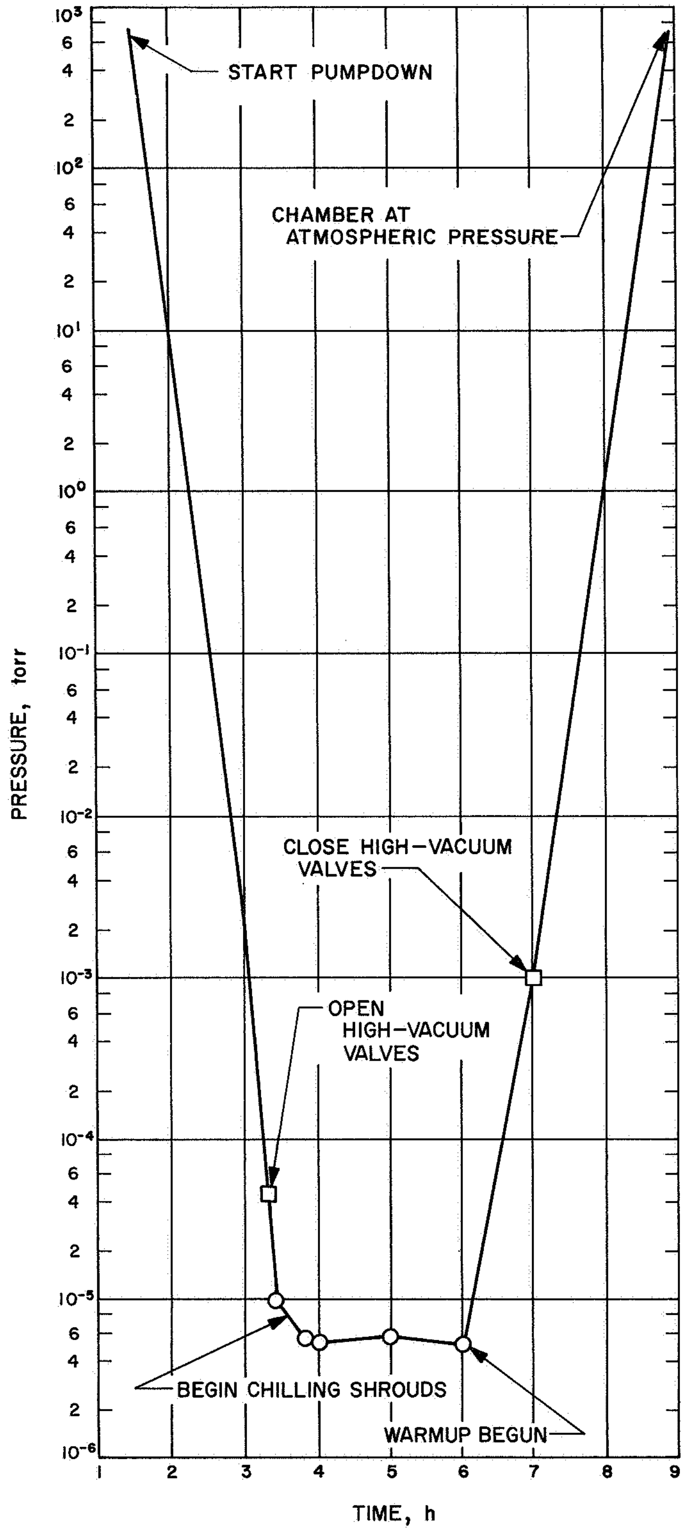



**Fig. 7. Typical pressure profile**

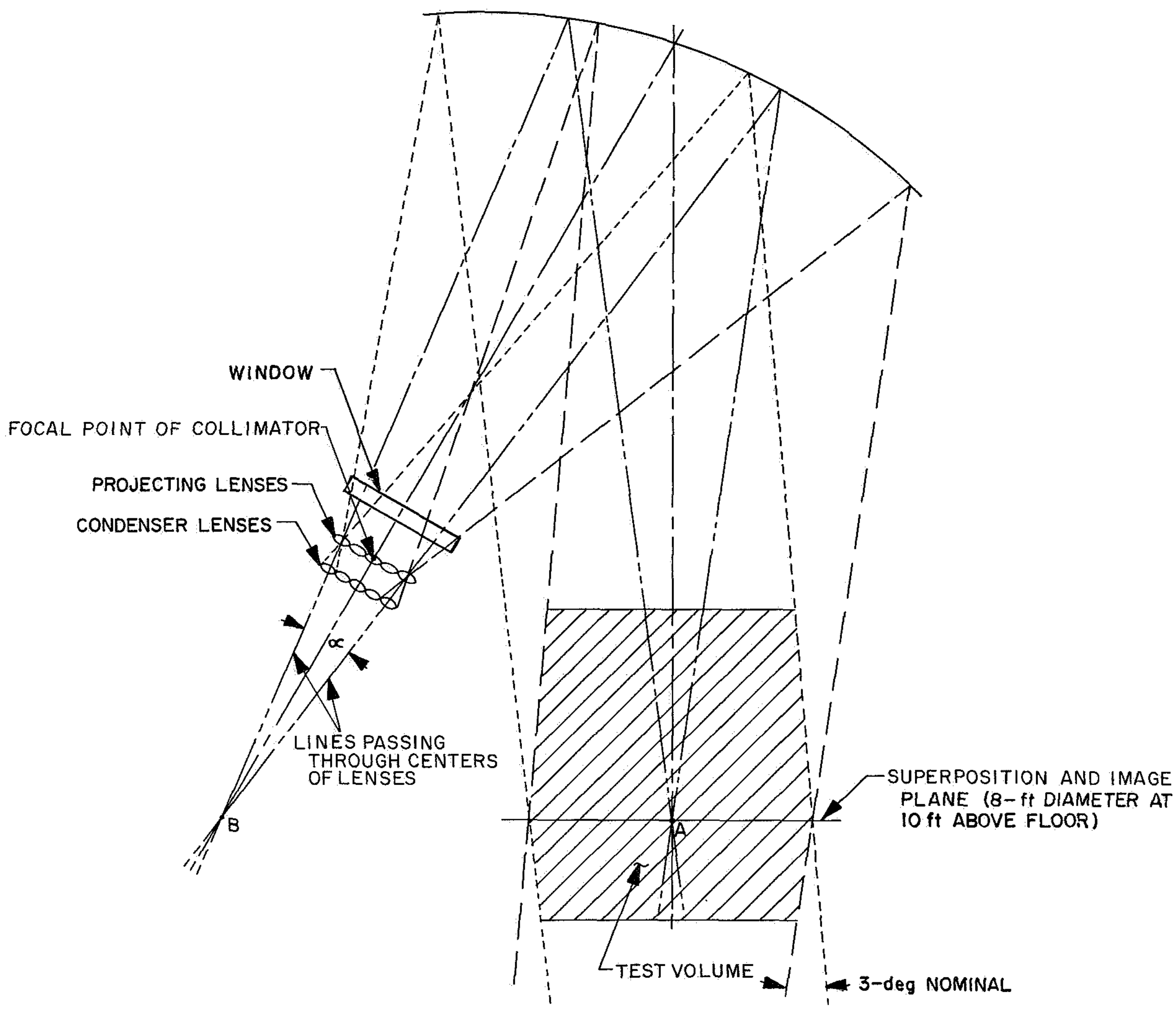



Fig. 8. Irradiated test

Fig. 9. Headlamp array

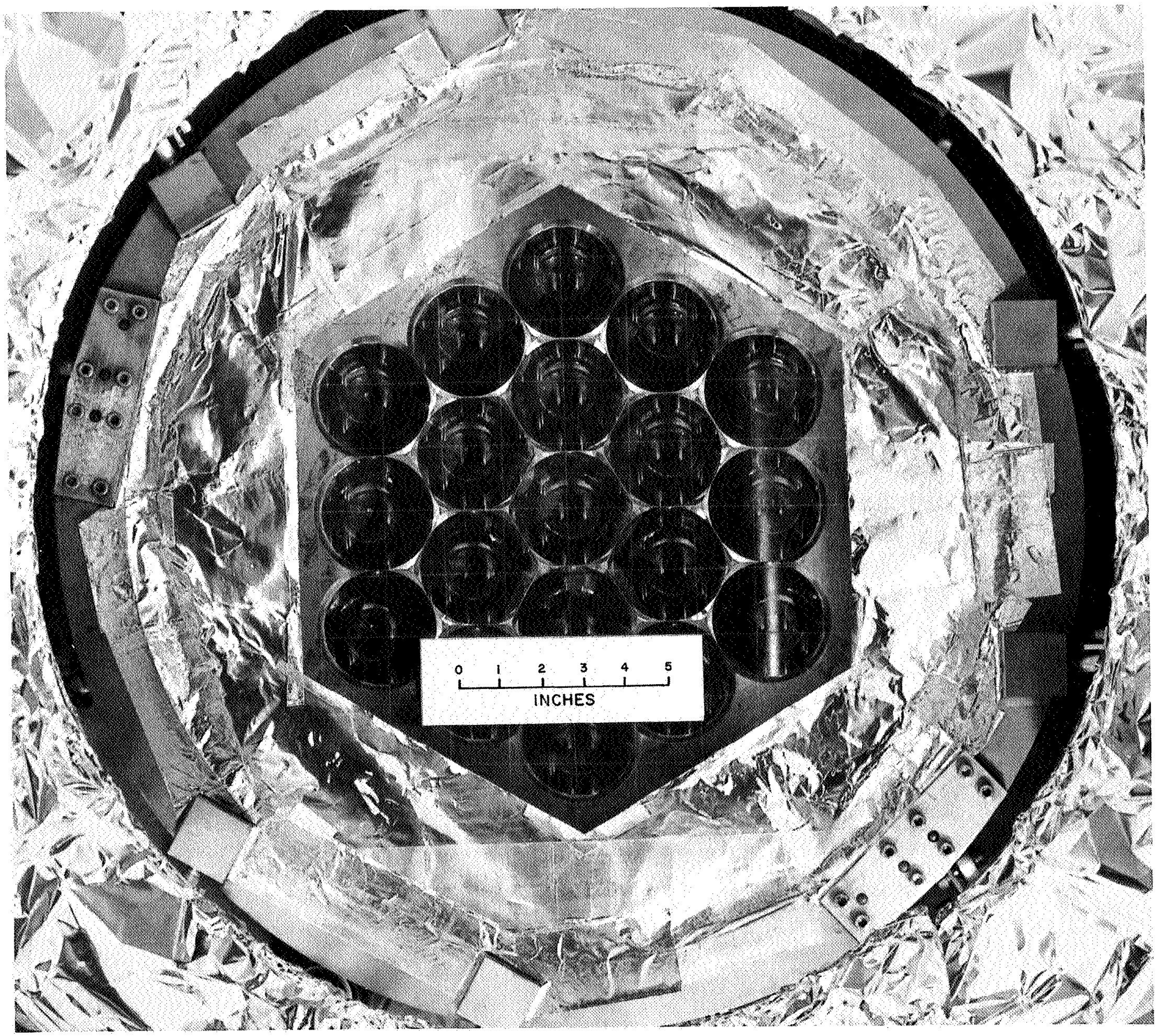



Fig. 10. Array of condenser lenses as viewed from headlamp side

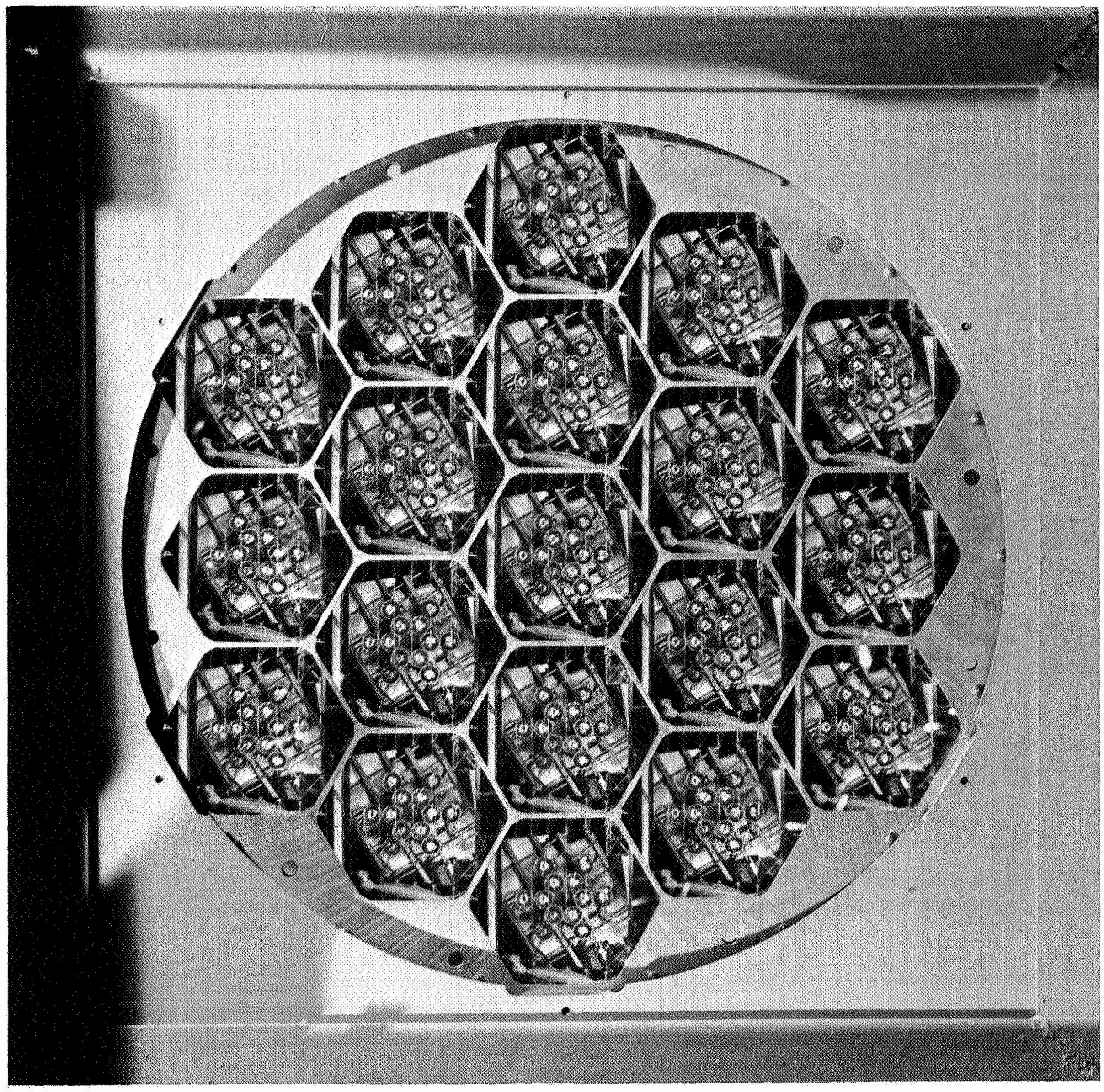


Fig. 11. Array of projecting lenses looking back into xenon sources (this picture was taken of the full-scale mockup showing a 12-lamp source array)

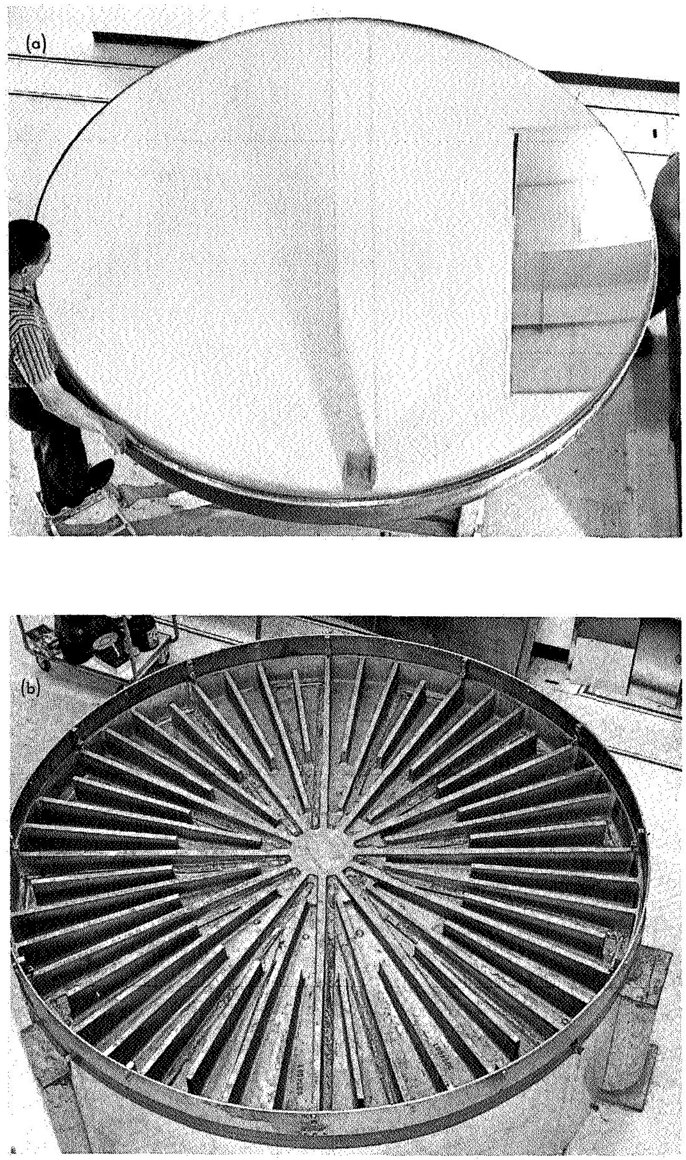


**Fig. 12. Collimator aluminum casting before cooling tubes were installed along the ribs: (a) front; (b) back**

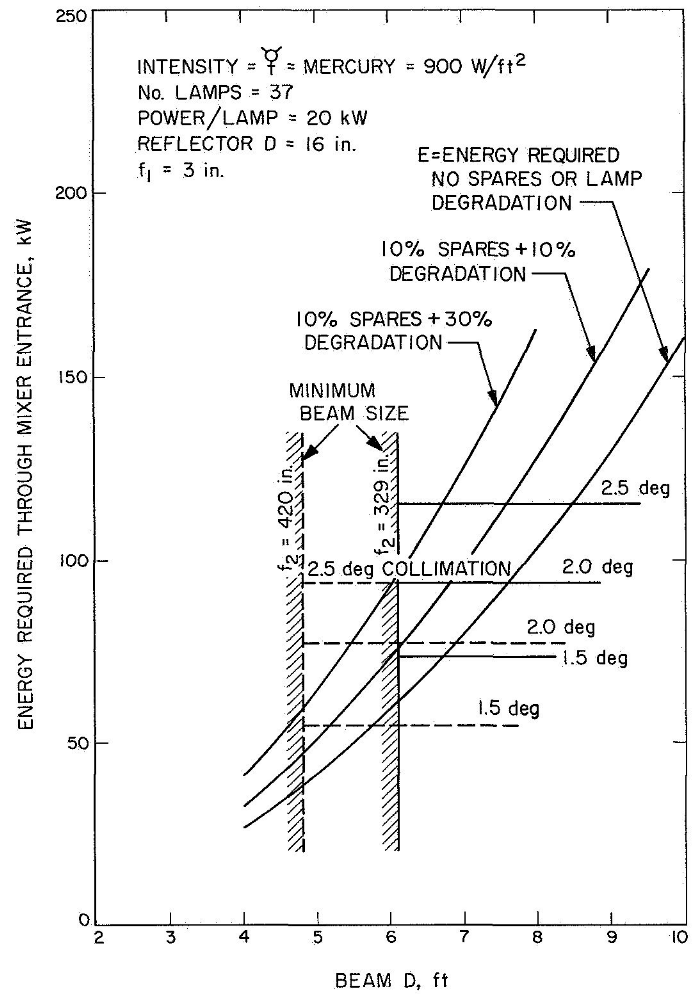



**Fig. 13. Solar performance capabilities of 900 W/ft² (Mercury intensity)**

Analytical studies indicate that the solar intensity can be increased to 900 W/ft² by either adding 5-kW lamps to the system, or increasing lamp size to 20 or 30 kW. The condenser lens frame would have to be modified to properly dissipate the additional heat load. Calculated solar performance capability of the 10-ft space simulator using readily available 20-kW arc lamps is shown in Fig. 13.

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. Solar uniformity and apparent source size are shown in Figs. 15–17.

### D. Cryogenic System

The chamber walls and floor are lined with stainless-steel temperature-controlled shrouds. These shrouds simulate the highly absorptive and nonreflective void of space and trap radiant energy emanating from a test article, thus effectively preventing energy from returning to the test article. Except for the collimator (highly reflective and, therefore, having low IR emission) and a few small areas not seen from the test volume, all areas are covered by shrouds. A high-absorptivity black paint has been applied to all shroud surfaces.

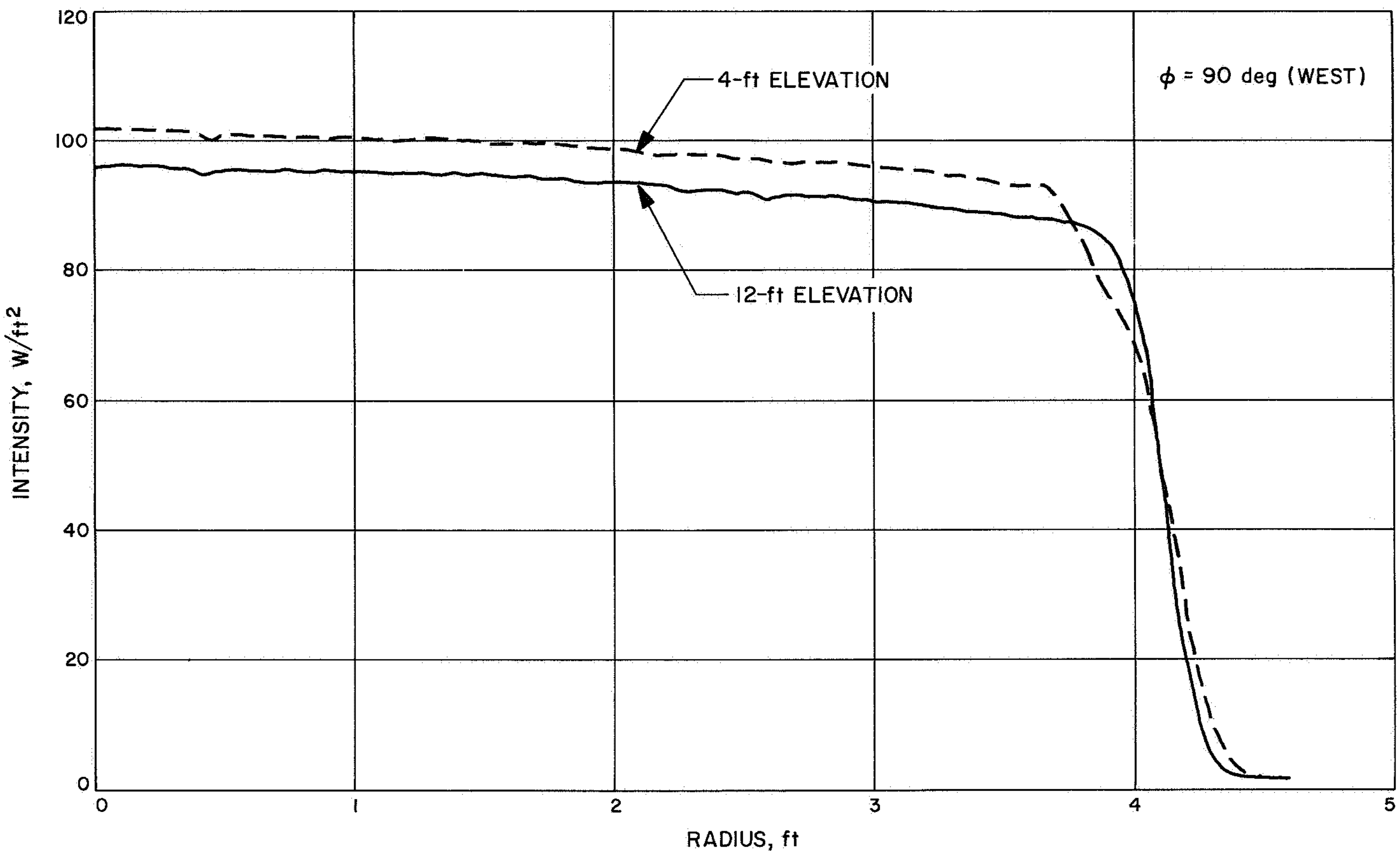



**Fig. 14. Solar mapping data (6.5-ft beam)**

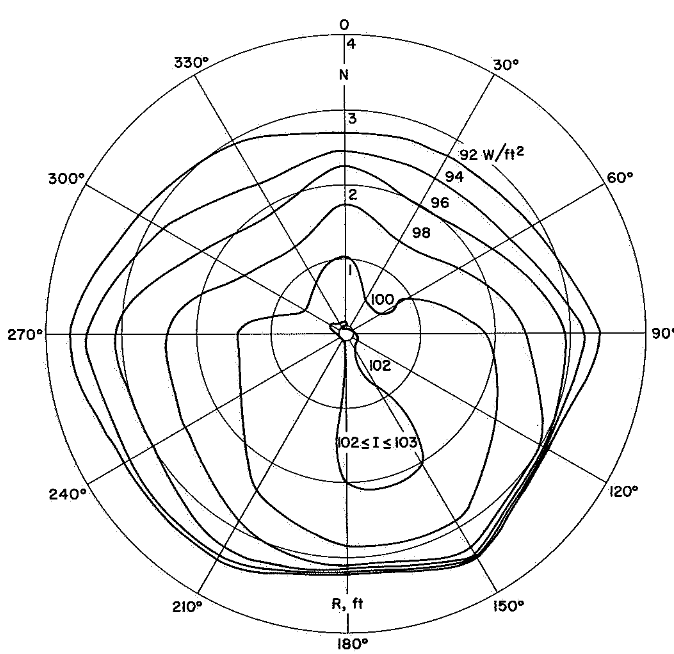



**Fig. 15. Solar uniformity, 4-ft elevation (6.5-ft beam)**

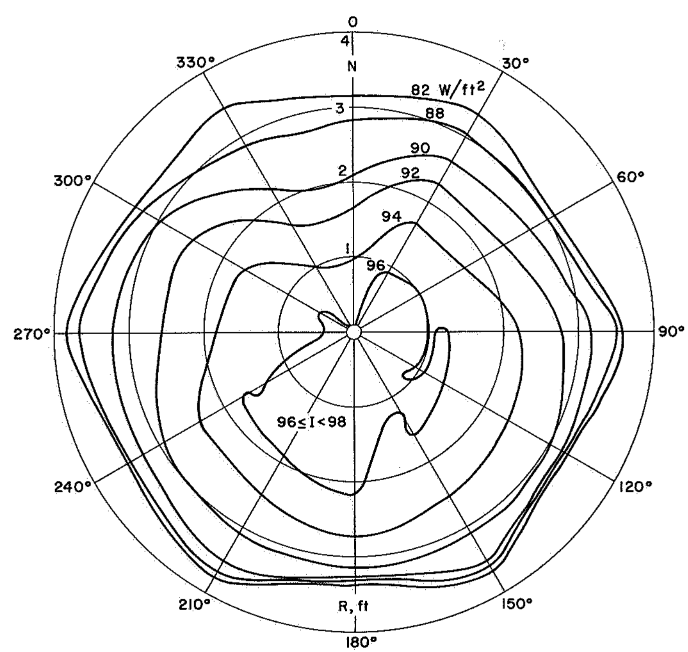
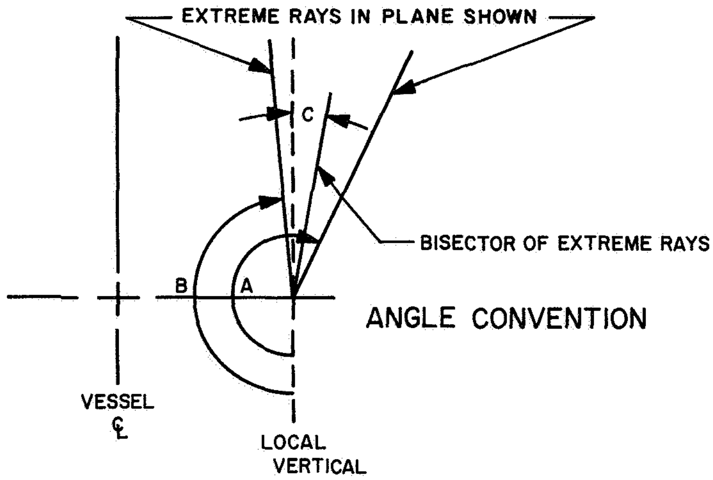
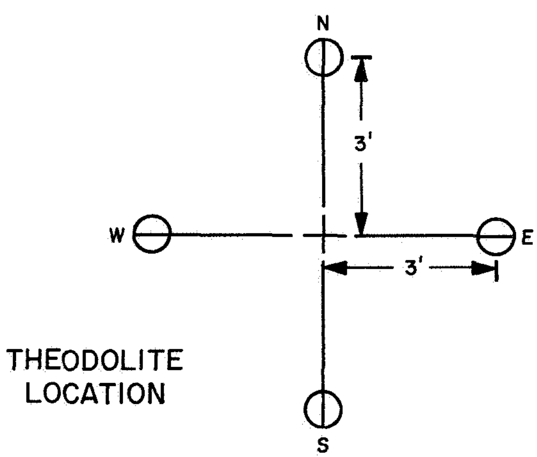



**Fig. 16. Solar uniformity, 12-ft elevation (6.5-ft beam)**




| 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



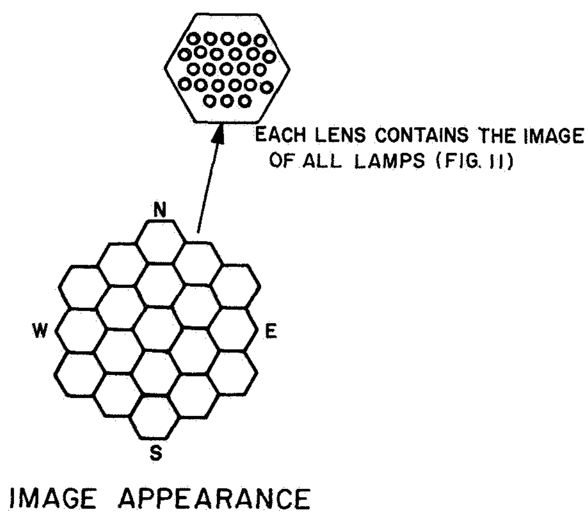




**Fig. 17. Apparent source size for 10-ft space simulator (6.5-ft beam)**

During testing, the shrouds 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 circulated 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.

In the emergency mode, 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 equipment: emergency lighting, control power, one diffusion pump, one vacuum pump and blower, $GN_2$ heater, the holding pump, one $LN_2$ supply pump, the mirror blower, mirror heaters, shroud blower, shroud heater, seven solar rectifiers, and an air compressor. A separate auxiliary generator supplies 75-kW, 3-phase, 480-V power that is transformed to 120/208 V (Y) and is supplied to four outlets for test-item ground support. The 75-kW generator is manually started and switched to the supply bus.

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.

Compressed air is provided at 100 psig from either a JPL source or a local compressor which is powered from an emergency electrical supply. The air supply is used for valve controls, solar lamp and hood ventilation, and utility outlets.

Gaseous nitrogen is obtained from a 2000-psi JPL distribution system and is reduced to 120 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 temperature control of 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) As level control in the liquid nitrogen separator.

Filtered conditioned air is provided to the clean tent and for backfill when testing flight spacecraft. Air is temperature- and humidity-controlled by refrigeration and heating units at ground level on the East side of Building 248. The air is ducted from the ground level conditioning units to the filter bank and blowers on top of the building. The air is then ducted through the roof into the side of the chamber.

## 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 $10^{-2}$ torr. It consists of two pressure-sensing heads and two strip-chart recorders. One head senses pressures from 1 atm down to 1 torr and the other from 10 to $10^{-2}$ 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; their 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 instrumentation for pressure measurement is 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) Wallace and Tiernan precision aneroid manometer.

## B. Solar Radiation Measurements

The Hy-Cal Model P-8400-B water-cooled Hy-Therm pyrheliometers, of which JPL has four (Fig. 18), 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 adjustable zero and range (AZAR), which allows a $\pm 2$- to $\pm 100$-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 $\pm 1$ digit and its sensitivity is 10 $\mu$V. No collimation tube or aperture limit is currently employed on the Hy-Cal pyrheliometers. Zero-irradiance readings must, therefore, be taken during vacuum operation.

The JPL Instrumentation Section in conjunction with the Applied Mechanics Section has developed a cone radiometer (Fig. 19). This device employs a platinum wire-wound cone inside a guard heater. The platinum 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 platinum wire as a

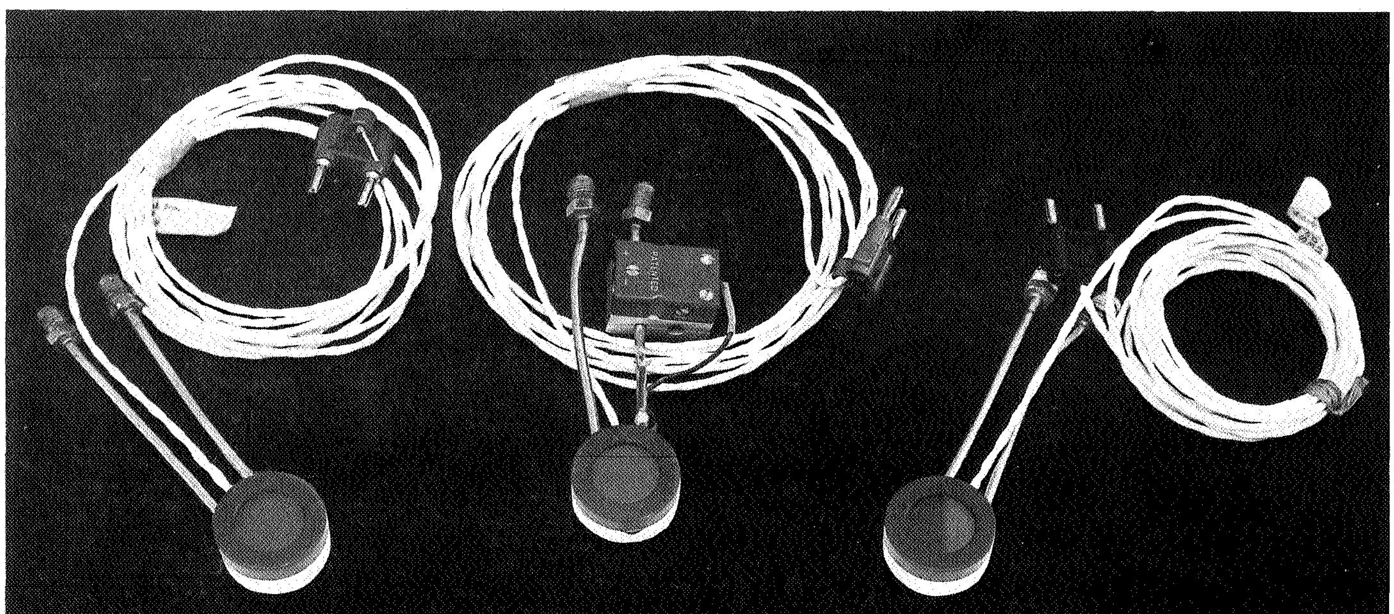


Fig. 18. HyCal radiometer

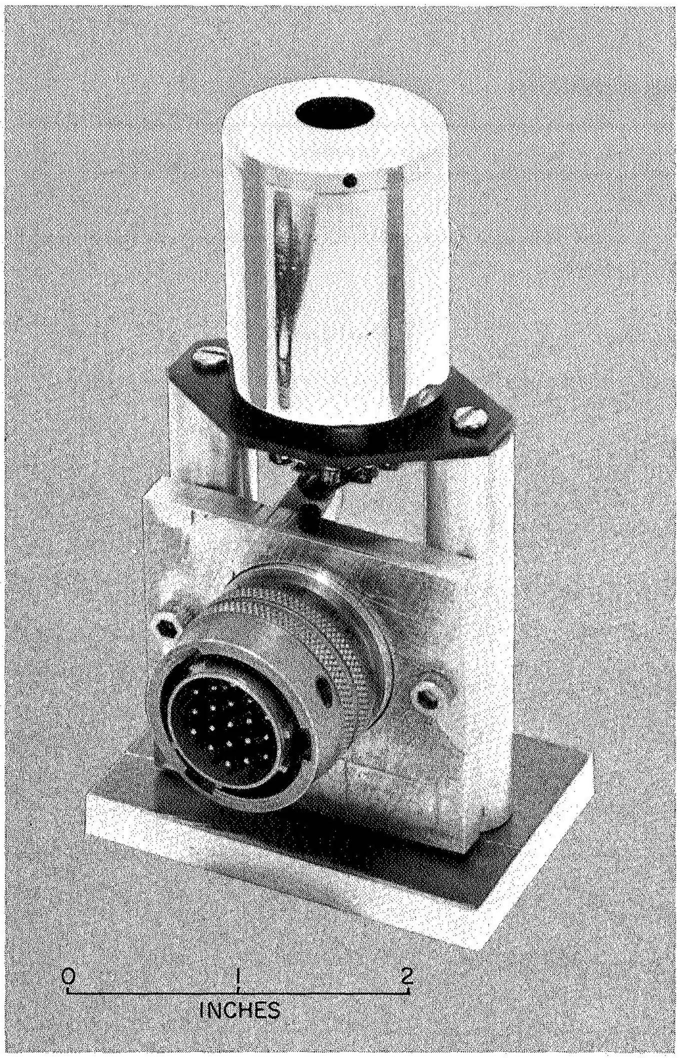



Fig. 19. Cone radiometer

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, $\sigma$ 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%. The cone radiometer is used as the absolute solar intensity reference for spacecraft tests.

### C. Temperature Measurements

Up to 96 thermocouple temperatures can be recorded to monitor chamber operational performance. An additional 61 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. There are 200 channels of thermocouple feedthroughs available with 2 Pace thermocouple, 32°F, reference junctions. Data are recorded on 2 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 capacity of the space simulator facility is described in detail in Table 1. Datex tape output is shown in Table 2.

## 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 plan, schedule, prepare, and conduct a test in the JPL 10-ft space simulator.

Steps required before any testing activity are:

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

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 or 200 to 1800°F | Magnetic Tape |
| Output | Printed paper tape in mV or in °F (Table 2) | A portable magnetic tape unit is available, when required, for recording 14 channels of data. |
| PDP-4 Computer[a] | | |
| Capacity | 400 channels | |
| Voltage input | ±10 mV | |
| Scanning rate | 50 channels/s, max | |
| Thermocouple types | Chromel–constantan<br>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, °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 |

(2) An advanced planning conference, 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, 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, California, 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.