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LOW-COST, AIR MASS 2 SOLAR SIMULATOR

by Kenneth Yass and Henry B. Curtis

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract

A low-cost, air mass 2 solar simulator for testing flat-plate solar collectors was developed and operated at Lewis. Total cost was less than \$10 800/m^2 (\$1000/ft^2). It consists of an array of 143 tungsten-halogen 300-watt lamps, each having integral dichroic coated reflectors. A second array of 143 respective hexagonal-shaped plastic Fresnel lenses are located approximately 1 focal length from the lamps. The simulator will produce a uniform collimated beam covering an area of 1.2 by 1.2 m (4 by 4 ft). Design features, construction details, and component costs are given, as well as measured results on a 12-lamp prototype.

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SUMMARY

A low-cost, air mass 2 solar simulator for testing flat-plate solar collectors was developed at NASA Lewis. Its basic feature is an inexpensive lamp and lens combination that exhibits a near air mass 2 solar spectrum. The simulator consists of an array of 143 lamps and their corresponding lenses. Each lamp is a 120-volt, 300-watt tungsten halogen lamp having an integral ellipsoidal open reflector. The reflector is dichroic coated. Each hexagonal-shaped plastic Fresnel lens, measuring 15 centimeters (6 in.) across the flats, is located at a distance equal to its focal length from the reimage caustic of its respective lamp. All the lamps are located in a plane, positioned 15 centimeters (6 in.) from each other, and form hexagonal shaped arrays. The simulator will produce a uniform collimated beam, which will cover an area 1.2 by 1.2 meters (4 by 4 ft) at a distance of 4.6 meters (15 ft) from the lenses. Area coverage can be scaled up or down by the addition or deletion of lamps. To verify the predicted performance of the simulator, a prototype consisting of a 12 lamp-lens array was assembled and its output parameters measured. Preliminary results are reported. Total cost was less than $10 800 per square meter ($1000/ft^2). Also given are design features, construction details, and component costs of the completed simulator.

INTRODUCTION

Much of the development and testing of Earth based solar collectors has been done in nature's own laboratory, that is, by exposure to the Sun itself (ref. 1). Obvious disadvantages of depending on the Sun, however, are limited daylight and inclement weather. One alternative to such dependence is to use a solar simulator capable of duplicating most of the Sun's characteristics as they might appear to a solar collector on the Earth's surface. On a clear day when the Sun angle is 60° from the zenith, the optical

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path of the Sun's radiation to the Earth's surface produces the air mass 2 (AM2) solar curve or spectrum. This spectrum best represents the average North American sunlight. It is different from the air mass 1 (AM1) spectrum, when the Sun is located at its zenith (directly overhead), or the air mass zero (AM0) spectrum, which is obtained when the collector is located outside the atmosphere in Earth orbit (ref. 2).

At Lewis, several research programs in the area of solar energy utilization are currently under way. In support of these efforts, a low-cost solar simulator for testing flat-plate solar collectors was developed. Irradiating these collectors in an environment independent of weather conditions will permit the evaluation of their performance variation due to controlled variations in collector design. Radiant flux from the simulator should be typically that which is associated with the air mass 2 solar spectrum, the type of radiation to which ground based solar collectors normally would be exposed.

After collector designs have been tested indoors under simulated conditions, testing will be transferred outdoors. Outdoor tests will continue under less than ideal conditions, and will take into account the diffuse component of radiation from the sky.

The air mass 2 solar simulator described in this report was designed to meet the needs of, but, not limited to, the flat-plate solar collector program. It is reasonably low in cost at less than \$10 800 per square meter (\$1000/ft^2) of irradiated surface. The important feature and advantage of this simulator is that the inexpensive lamp-lens combination exhibits a near air mass 2 solar spectrum. Also, depending on the need for larger or smaller areas to be irradiated, the number of lamp and lens pairs in the array can be increased or reduced.

DESIGN GOALS

The design goals of the solar simulator are based on the requirements of the flat-plate solar collectors (ref. 3). The simulator must be capable of irradiating an area 1.2 by 1.2 meters (4 by 4 ft) at a distance of 4.6 meters (15 ft) from the simulator with a radiant flux density that is continuously variable from 50 to 110 milliwatts per square centimeter (45.5 to 100 W/ft^2). The upper goal is about 145 percent of the air mass 2 solar constant of 75.7 milliwatts per square centimeter (70.3 W/ft^2 or 240 Btu/hr-ft^2). The value of 75.7 milliwatts per square centimeter for AM2 is obtained by using the ratio AM2/AM0 from reference 2 and the latest absolute value of the AM0 solar constant from reference 4. The total irradiance distribution is to be uniform to within ±7 percent, and the collimation full angle, or the preferred term "solar beam subtense angle", (ref. 5) is to be less than 10°. Spectral irradiance in the test area should approximate the air mass 2 solar spectrum. Continuous operation for tests of up to 30 hours is also required.

The complete simulator is to be reasonably low in initial and operating costs, and have relative ease of operation and maintenance. These requirements practically limit the components to readily obtainable shelf items. Also, the low ultraviolet content of irradiation suggests that the usual expensive xenon lamps and quartz optics used in air mass zero simulators could be replaced with cheaper substitutes. These requirements are fulfilled by the solar simulator described herein.

SIMULATOR DESIGN

A view of the indoor test facility at the Lewis Research Center is shown in figure 1. The solar simulator is suspended to irradiate the collector on the floor below at zero incidence angle and at a separation distance of 4.6 meters (15 ft). This position is adjustable through angles of 25° to 72° from the horizontal to accommodate different collector tilt angles. Electrical power is controlled from a remotely located console.

The simulator's dimensions are approximately 1.9 by 1.9 meters (75 by 75 in.) by 1.3 meters (50 in.) deep. The rear section tapers to a 0.8-meter (30-in.) diameter opening for exhausting the cooling air. Construction material is mainly aluminum. Total weight is estimated at 500 pounds.

A cutaway view of the simulator is shown in figure 2. The square frontal section is covered with 143 hexagonal lenses in a closely fitted array. A structurally reinforced plate containing 143 lamps is parallel to and behind the lens section. It is approximately 28 centimeters (11 in.) from the lenses. The optical axis of each lamp is coincident with that of its respective lens. In figure 3 the lens holder and lamp holder sections are shown separated before assembly. The two rectangular openings on each of the four edges of the lens section will be occupied by intake air filters (see fig. 2).

Power to the lamps is controlled through two switches at the console. Each switch operates a motor driven bank of autotransformers, and the output voltage is directed to half the lamps of the simulator. The wiring plan effectively divides the load between two 200-ampere capacity mains. Although other wiring and control schemes exist, this multiple autotransformer arrangement was used because the components were on hand and idle at the time.

Utility requirements are approximately 44 kilowatts of 120-volt, single-phase electrical power for the lamps and 1.1-kilowatts (1.5-hp) of 208-volt, three-phase power for the exhauster motor.

LAMPS

The lamps, designated Quartzline ELH by the manufacturer (General Electric), are commercially available and intended for use in film projectors. They are rated 300 watts at 120 volts. Each lamp is constructed in two parts: a tungsten halogen bulb with an axial filament, and a 5-centimeter (2-in.) rim diameter open ellipsoidal reflector. The bulb is set into the reflector, and the electrodes are cemented at the base to form a rigid unit. This assembly is referred to as the "lamp" in this report. The reflector is stippled, and it has a front surface dichroic coating, which reduces the infrared content of the reflected radiation. The lamp has a reimage point (rather, a caustic or envelope) about 2.5 centimeters (1 in.) in front of the reflector rim, a beam angle of 20°, a color temperature of 3350 K, and an average life of 35 hours. It requires forced-air cooling.

Two similar lamps, Quartzline ENG and ENH, are available from the manufacturer, but with the following specified differences: ENG has a color temperature of 3400 K and an average life of 15 hours; ENH has a color temperature of 3200 K and an average life of 175 hours. Obviously, increased brightness can only be attained at a sacrifice of lamp life at rated power. The choice of the ELH lamp is a compromise in this consideration. A single lamp and its holder is shown in figure 4. The holder design permits the lamp to be spring loaded when inserted into position. A later model holder incorporates a flick-of-the-thumb lamp ejector using an attached lever arm. This facilitates lamp replacement.

LENSES

The lenses are flat plastic Fresnels (fig. 4), and, like the lamps, are commercially available shelf items (Cryton Optics, Inc.). The plastic is specified as optical grade acrylic. As purchased, they are square, measuring 17.8 centimeters (7 in.) on a side, 0.25 centimeter (0.09 in.) thick, and 25 centimeters (10 in.) in focal length, and have a circular groove density of 39.4 lines per centimeter (100 lines/in.). The diameter of the outermost groove is 15 centimeters (6 in.), with the remaining outer area of the lens clear and ungrooved. The lenses are easily cut into hexagons measuring 15 centimeters (6 in.) across the flats before installation in the simulator's lens holder section. A transmission curve of a randomly chosen lens measured with a spectroradiometer and integrating sphere is shown in figure 5. The losses at the lens must be considered in the calculation of test plane irradiance.

LAMP COOLING

The manufacturer recommends forced-air cooling of the lamps to limit the surface temperature at their base to a maximum of 288° C (550° F). Temperatures greater than this value increases the likelihood of electrode seal destruction and subsequent lamp failure. On the other hand, excessive cooling of the bulb itself may also decrease lamp life by interfering with the tungsten-halogen cycle.

The direction of the cooling air in the simulator is shown by the airflow arrows in figure 2. Air enters the enclosed simulator between the lenses and the lamps through the eight air filters. Filtered air is used to prolong the cleanliness of the optical components. The air then enters the lamp plate square openings adjacent to each lamp, and is redirected with deflecting vanes (fig. 6) to pass over the lamps. The air continues rearward until it is exhausted to the atmosphere by a blower motor. The blower has a capacity of 2.22 cubic meters per second (4700 ft^3/min).

ONE LAMP-LENS COMBINATION

The elementary optical building block for the simulator is one lamp-lens combination. Measurements and calculations based on this optical unit provided the information necessary to design the required multiple lamp-lens array. The optical schematic for this single lamp-lens combination is shown in figure 7.

A hexagonal shaped Fresnel lens is located approximately one focal length from the reimage caustic of the lamp. Measurement of the lamps directed beam power is used to calculate the area of the lens through which the required irradiance is directed to the test plane; that is, the directed beam power divided by the area of the lens should equal the test plane irradiance design goal of 110 milliwatts per square centimeter (lens losses considered). This measurement and calculation determined the 15-centimeter (6-in.) across-the-flat dimension of the hexagonal lens and the resultant 15-centimeter (6-in.) pitch spacing for the multiple lamp-lens array. The distance to the test plane (4.6 m (15 ft)) and the size of the image produced by the lamp near its caustic (approx. 3.18 cm (1.25 in.)) determined the focal length of the Fresnel lens. The distribution of irradiance in the test plane from a single lamp-lens combination is approximately Gaussian over a 55.1-centimeter (21.7-in.) diameter, which gives a calculated beam spread of 9^{o}. Similar patterns from adjacent lamp-lens combinations will combine to improve the distribution of irradiance from the Gaussian. To maintain irradiance uniformity over the entire 1.2 by 1.2 meters (4- by 4-ft) test area, an extra row of lamps and lenses is added on each side of the array to compensate for an edge-effect drop in irradiance. Slight adjustments in the lamp to lens distance can be made to optimize irradiance uniformity of the multilamp array. Figure 8 is a plan view of the 143 lamp-lens array.

The preceding arrangement was designed to satisfy a particular set of test requirements stated earlier, and area scaling is possible with the pitch spacing so determined. However, for the same size test plane, increasing the number of lamp and lens pairs by reducing the pitch spacing of the lamps would result in increased irradiance and improved uniformity. (Vice-versa for less lamps and increased pitch spacing.) Increased costs would then be a factor. Trade-offs in irradiance, uniformity, or subtense angle are options of the designer, depending on the test requirements.

12 LAMP-LENS ARRAY PROTOTYPE

Scaling up the design from a one lamp-lens combination to a 143 lamp-lens combination presents certain problems. For instance, small measurement errors made on the one lamp-lens combination could be multiplied many-fold in extrapolating to a large array. To verify the predicted performance of the 143-lamp simulator, a small prototype was constructed. It consisted of the minimum number of lamps that would validate the extrapolation. Since at least seven lamps contribute radiation to each point in the test plane, a 12 lamp-lens array produces a small area of uniform irradiance. Because of beam divergence, this area will be an approximate equilateral triangle, measuring 15 centimeters (6 in.) on a side. Each apex of the triangle will be located at the center of its own seven lamp-lens hexagon (see fig. 9). This incremental area will be representative of the irradiated area of the full simulator, and total and spectral irradiance measurements confined to this area will be applicable to the full size model.

Measurements made with the 12-lamp prototype indicate that its design and construction followed, for all practical purposes, the one lamp-lens relation designed into the 143-lamp simulator. Therefore, it is expected that the completed 143-lamp simulator will perform as predicted.

MEASUREMENT PROCEDURES

A 12 lamp-lens array prototype was operated, and its performance measured. Measurements were made in accordance with recommended practice for solar simulation (ref. 5). Cooling air was first turned on, and the lamp input voltage was slowly advanced and then kept constant through frequent reference to voltmeter readings. A 15-minute warmup was used to stabilize temperatures before measurements were begun. Two lamp bases had thermocouples clamped to their surfaces. Thermocouples were also attached to two lenses. Thermocouple outputs were measured on a digital voltmeter, and these temperatures were continuously monitored to insure that they did not exceed safe operating limits.

Measurements of the total irradiance and its distribution were obtained by placing in the test plane a water-cooled, black detector which has a 0.9-centimeter (3/8-in.) sensitive surface, a 3-second time constant, and a 150° field of view. The detector was previously calibrated against a National Bureau of Standards irradiance standard. By means of a rectangular grid placed in the test plane, the plane was scanned in 2.54-centimeter (1-in.) increments, and a shutter was used to obtain zero readings. The results were plotted, and isoirradiance lines were traced to indicate the area of uniformity. Detector output was measured using a digital voltmeter. Lamp voltage was measured with a Weston ac-dc voltmeter having a one quarter of 1 percent full scale accuracy. Accuracy of the total irradiance and its uniformity measurements is estimated at better than ±3 percent.

Spectral energy distribution measurements were obtained with an Eppley Mark V filter radiometer and a set of 16 filters. Measurements were made on-axis and in the test plane. Results were computer processed by a procedure developed at Lewis by Wagoner and Pollack (ref. 6). High resolution spectral measurements were also made using a Cary-14 spectroradiometer with an integrating sphere for lamp voltage settings of 90, 105, and 120 volts (fig. 13). Agreement between the high and low resolution spectral measurements when conducted on the spectrum of a tungsten lamp using this technique has been shown by Uguccini (ref. 7) to be better than 2 percent. The accuracy of the high resolution spectra made at different voltages is better than 5 percent.

Because the outline of the apparent source is not sharply defined, the solar beam subtense angle was measured. For this purpose the filter radiometer was used as a total detector with the filter wheels replaced by an aperture wheel. This wheel has apertures of known view angles from 15° down to 5° in 1° steps. The radiometer was then placed in the test plane on-axis and, with lamp power held constant, detector output readings were recorded for each aperture. The subtense angle is determined to be at that aperture where the output has fallen to 0.95 of the maximum value or, alternately, the aperture within which is retained 95 percent of the total energy of the apparent source.

Radiant efficiency is the ratio of delivered test plane power to the total lamp input power. This may be calculated by integrating the power in the test plane area as obtained from average irradiance and uniformity data (beam spill beyond the test plane area not considered) and dividing the test plane power by the average lamp input power.

No attempt was made to measure the prototype for stability of irradiance over the life of the lamps. This will be determined during operation of the full 143-lamp simulator. Calibrations will be made periodically to maintain the simulator as a "standard sun," replacing lamps when necessary. However, considering that most testing will be made at reduced lamp voltage (105 V for air mass 2 irradiance), the dichroic coating should have extended life, as should the lamp's tungsten filament. The plastic lenses should also exhibit minimal degradation as a consequence of the low ultraviolet radiation from the lamps.

RESULTS

Measurements made on the 12 lamp-lens prototype module indicate that the average irradiance in the test plane at rated lamp voltage is in excess of 100 milliwatts per square centimeter (93 W/ft^2). Figure 10 is a plot of average total irradiance against lamp voltage. It shows that in the range of 90 to 120 volts, the irradiance varies from about 55 to 102 milliwatts per square centimeter (51 to 95 W/ft^2).

The total irradiance distribution is uniform to within ±5 percent. This is shown by the isoirradiance line traced on the x-y plot of total detector output readings in figure 11. The incremental area of interest is outlined by the 15-centimeter (6-in.) equilateral triangle. Except for its extreme corners, the triangle lies wholly within the ±5 percent isoirradiance line. Therefore, it is expected that a comparable uniformity will be achieved by the 143-lamp simulator.

The spectral distribution of irradiance of the prototype simulator is shown in figure 12. It was obtained with the filter radiometer, which was described in the measurements section. This measurement was made with lamp voltage maintained at 117 volts. Also shown in figure 12 is the air mass 2 solar curve. The spectral irradiance of the prototype has been normalized so the areas under both curves are equal (75.7 mW/cm^2 = air mass 2). The effect of the dichroic coating on the lamp's reflector is apparent when compared with the spectrum of a tungsten filament lamp. The infrared content of the simulator has been reduced, and a fairly good match in the infrared exists between air mass 2 and the simulator.

In addition to the spectral irradiance measurement at 117 volts (fig. 12), measurements were made at 90, 105, and 120 volts using the Cary-14 spectroradiometer to determine the effect of varying lamp voltage on spectral distribution. These three measurements were made using an older set of lenses on the prototype. They have a slightly lower transmission than the lenses used in the final design of the simulator and on the prototype for data of figure 12. Since these measurements were intended only to determine the change in spectral irradiance with voltage, the slightly different lenses should have no effect on the results. Figure 13 shows the 90-, 105-, and 120-volt spectral curves, which are normalized so that the areas under the curves are equal (75.7 mW/cm^2). Inspection of the curves indicates the expected shift of spectral irradiance from the infrared (>1 μm) to the visible as the lamp voltage is increased. Table I shows the percent of total irradiance within various wavelength bands for all four measured spectral distributions. Similar data for the air mass 2 curve is also given in table I.

A useful method (refs. 8 and 9) of determining how well a solar simulator's spectral distribution matches the Sun is to calculate how various surfaces respond when irradiated by the simulator and by the Sun. Three such typical surfaces could be

(1) A silicon solar cell (ref. 9)

(2) A silicon oxide coated, front surface aluminum mirror (ref. 10)

(3) A solar absorber such as a Tabor surface (ref. 11).

The references denote the source for the spectral surface data used in calculating the response.

Table II shows the calculated efficiency of a silicon solar cell (10.5 percent under AM0 conditions), reflectance ρ of a silicon oxide coated aluminum mirror, and the absorptance α of a Tabor surface under radiant flux with the spectral distribution of air mass 2, and the four measured spectral irradiances of the simulator prototype.

The data in table II may be interpreted by using an example. Suppose an array of silicon solar cells was being tested using the simulator at a lamp voltage of 105 volts. The output of the cells, per unit of incident irradiance, will be about 7 percent higher ((13.7 - 12.6)/12.6) from the simulator irradiance than from air mass 2 irradiance. This 7-percent increase is due solely to the imperfect spectral match between air mass 2 and the simulator. Surfaces that have "flatter" spectral characteristics, such as the mirror and absorber of table II, exhibit much less change in reflectance or absorptance under different spectra. Thus, for solar collector applications, the spectrum may be assumed constant over the voltage range cited.

The solar beam subtense angle was measured with the radiometer and multiple aperture wheel, as described in the measurements section. The irradiance varied with the aperture size as shown in figure 14. A drop in irradiance to the 95-percent level, defining the subtense angle, occurs at 9.6°.

The radiant efficiency of the 143-lamp simulator can be determined from the total irradiance measurements on the 12-lamp prototype. The average irradiance at rated voltage of 120 volts was 102 milliwatts per square centimeter. This will be uniform over the test plane of 1.44 square meters (16 ft^2) for a total of 1490 watts. Total input power is 42.9 kilowatts (143 lamps at 300 W/lamp). Hence, the efficiency will average about 3.5 percent.

COSTS

The capital cost for the construction of the 143-lamp solar simulator is approximately \$11 400 without and \$14 400 with the inclusion of several automatic control features. On a basis of cost per irradiated area, the cost is about \$7500 per square meter (\$700/ft^2) without and \$9700 per square meter (\$900/ft^2) with the control features. The controls, such as motor driven autotransformers, remote control of the tilt angle of the simulator, and timed automatic power reduction to complete shut-down are convenience items. They add nothing to the improvement of output parameters of the simulator, and, for strict adherence to the low cost goal, they may be omitted. Unit costs of the basic components of the simulator, which are the lamps, lamp holders, lenses, and exhauster motor, are respectively, \$5.40, \$0.57, \$7.00, and \$500.00.

The capital cost of the air mass 2 simulator may be compared with costs of air mass zero simulators purchased competitively by Lewis over the past 10 years. Although specifications and tolerances may vary, the costs, ranging from \$133 000 per square meter (\$12 400/ft^2) to \$291 000 per square meter (\$27 000/ft^2), are still from 18 to 40 times the cost of the air mass 2 simulator described in this report.

Generally, the closer the simulator duplicates the Sun, the higher the costs. A description of such an air mass 2 simulator is given in the literature by Benning (ref. 12). This system modifies a commercially available air mass zero simulator by additional filtering, including a water filter. Reported measurements of the spectral distribution indicate a fairly good match of the air mass 2 spectrum. Its cost (estimated at \$223 000/m^2 (\$30 000/ft^2)) is comparable to that given for air mass zero simulators. Therefore, a unit that covers a comparable area (1.44 m^2 (16 ft^2)) would be many times the cost of the subject simulator.

On the other hand, Norman (ref. 13) describes a low-cost AM0 simulator for thermal vacuum testing of a space vehicle in a large environmental chamber requiring an irradiated area of 18.6 square meters (200 ft^2). The radiation source uses 736, 1000-watt, 120-volt tungsten iodide lamps with integral lenses, but without dichroic coated reflectors. No effort is made to tailor the spectrum to the Sun, but suggestions for future improvement are noted. Total cost of the simulator is given as less than \$10 800 per square meter (\$1000/ft^2).

Finally, a few lamps and lenses may be used to irradiate small areas to test coatings and surfaces in an air mass 2 environment. Again, the interest lies in a simulator constructed in the simplest manner and at a minimum cost. Universities and small experimental groups where manpower is available but funds are limited have expressed an interest in a simple construction, low-cost simulator. The 12 lamp-lens prototype is such a simulator. (See figs. 15 to 17.) It is constructed of 1.9-centimeter (3/4-in.) plywood, except for the metal plate that holds the lamps. The lamp holes can be punched or drilled. The outline of the lens array is cut out of the plywood, and the lenses are fastened over the hole. A screw is placed at each trijunction of the lens corners to form an assembled array. A 0.8-meter (30-in.) diameter fan blows directly on to the lamps from the rear. Autotransformers control the input voltage. Variations of this construction may be left to the ingenuity of each user.

SUMMARY OF RESULTS

A low-cost air mass 2 solar simulator for testing flat-plate solar collectors was developed at the Lewis Research Center. It consists basically of 143 tungsten halogen lamps each with a corresponding plastic Fresnel lens. The simulator irradiates an area of 1.2 by 1.2 meters (16 ft^2) from a distance of 4.6 meters (15 ft) from the lenses. Area coverage can be scaled up or down by addition or deletion of lamp-lens combinations. (The present design will not simulate the diffuse component of sky radiation, but consideration is being given for the inclusion of this feature.) A 12-lamp-lens prototype was constructed, and its output parameters were measured to verify the predicted performance of the simulator. It should be noted that the complete simulator has been assembled, installed in the indoor test facility (fig. 1) and operated, but its performance has not yet been measured as of this writing. The characteristics of the simulator from measured results on the prototype are as follows:

Radiation source:	
Number of lamps	143
Type of lamp	tungsten halogen
Lamp voltage, V	120
Lamp wattage, W	300
Test plane size, m^2 (ft^2)	1.44 (16)
Total irradiance (continuously variable), mW/cm^2	55 to 100
Total irradiance distribution, percent	±5
Solar beam subtense angle, deg	9.6
Spectral irradiance distribution	Near air mass 2
Cost, dollars	14 400
Cost per area, dollars/m^2 (dollars/ft^2)	9700 (900)

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 28, 1974,
502-25.

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TABLE I. - PERCENT ENERGY

IN WAVEBANDS

Wavelength, Δλ, μm	Lamp voltage				Air mass 2
	90	105	120	117	
	Prototype lenses				
	Old	Old	Old	New	
	Percent energy				
0.3 - 0.4	0.4	0.8	0.7	0.3	2.7
0.4 - 0.7	44.1	48.0	50.8	48.4	44.4
0.7 - 1.0	31.0	30.4	30.0	29.5	28.6
1.0 - ---	24.5	20.8	18.5	21.8	24.3

TABLE II. - RESPONSES OF THREE TYPICAL SURFACES

TO SPECTRAL IRRADIANCE

Lamp voltage, V	Prototype lenses	Silicon solar cell, percent efficiency	Al-SiO mirror reflectance, ρ	Tabor surface absorptance, α
90	Old	13.4	0.87	0.90
105	Old	13.7	.87	.90
120	Old	13.8	.87	.91
117	New	13.4	.87	.90
Air mass 2		12.6	.86	.90

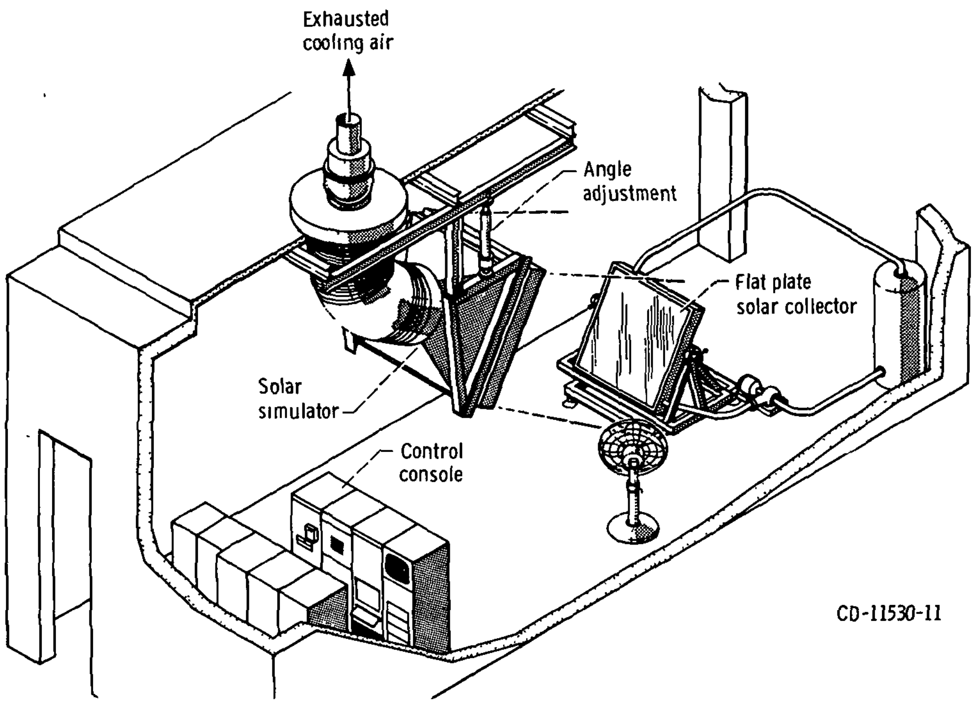

Figure 1. - Indoor test facility.

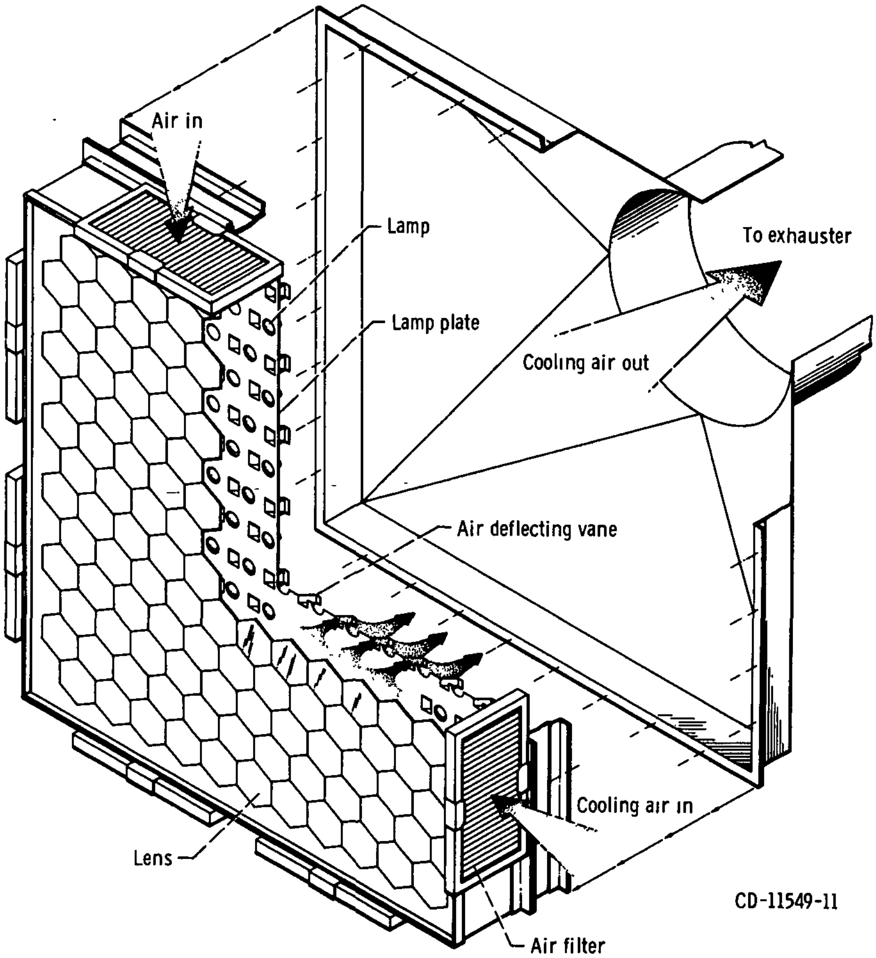

Figure 2. - Solar simulator cut-away view.

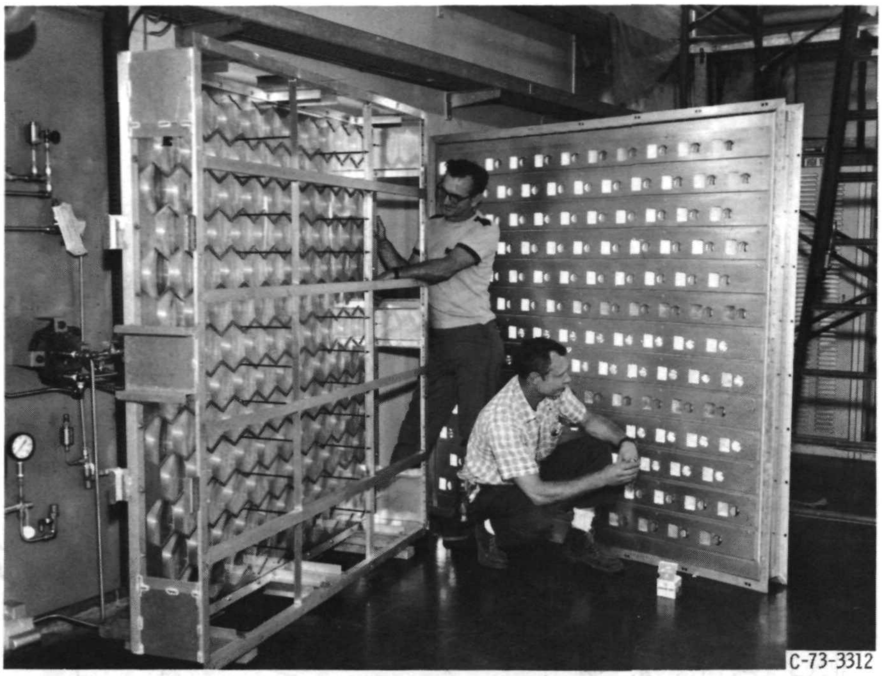

Figure 3. - Lens and lamp sections before assembly.

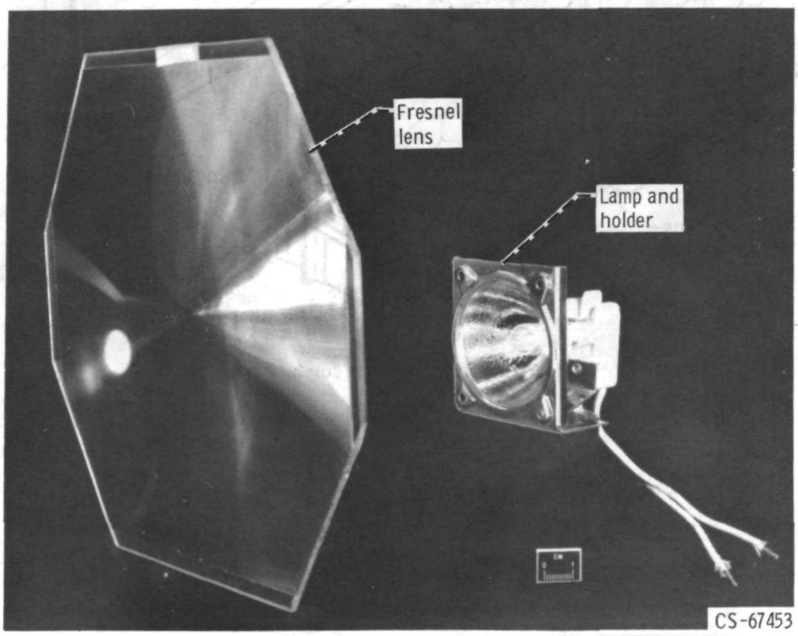

Figure 4. - Lens, lamp, and lamp holder.

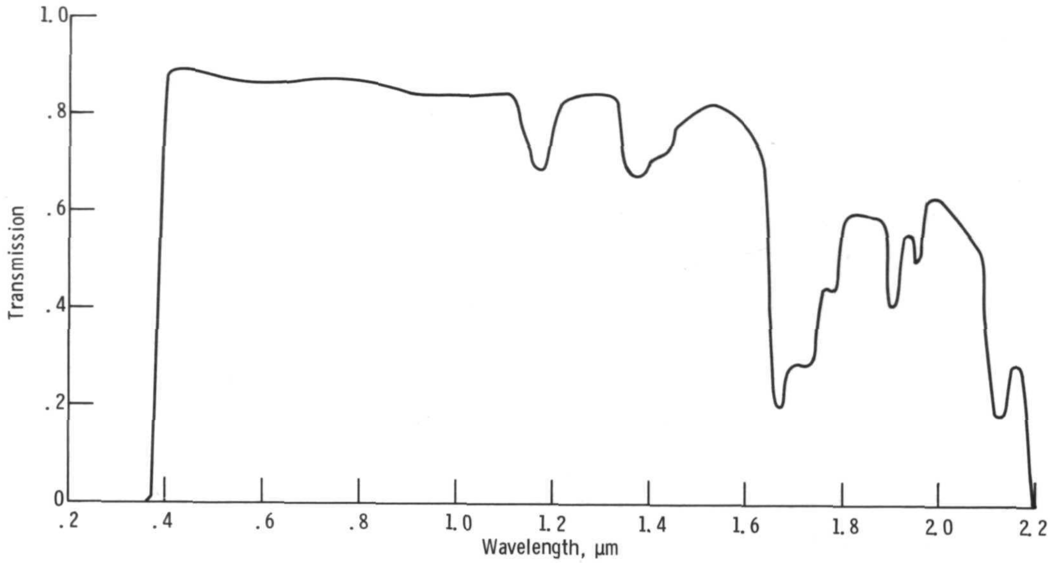

Figure 5. - Transmission of plastic Fresnel lens.

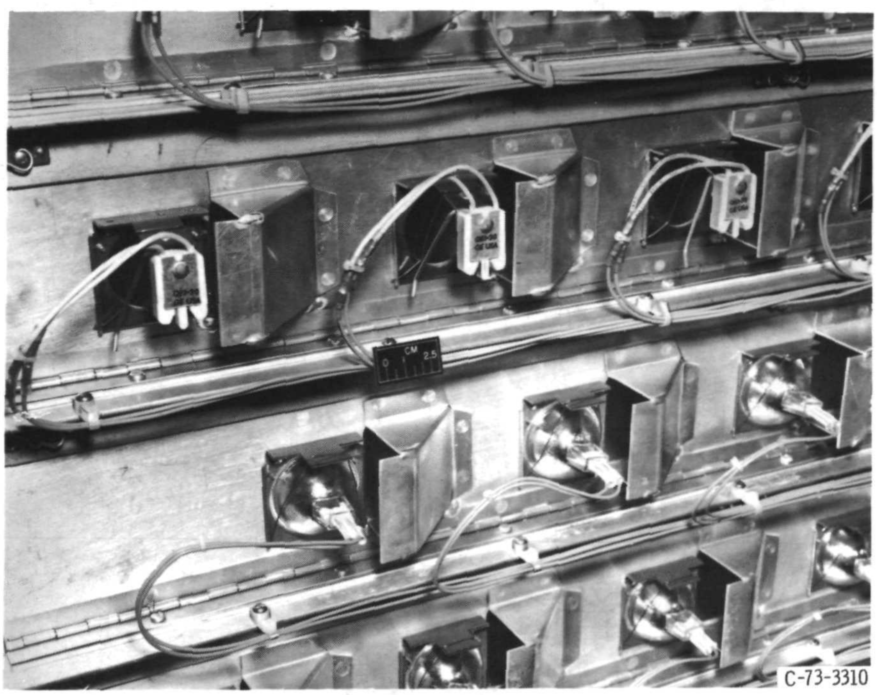

Figure 6. - Air cooling deflecting vanes at lamps.

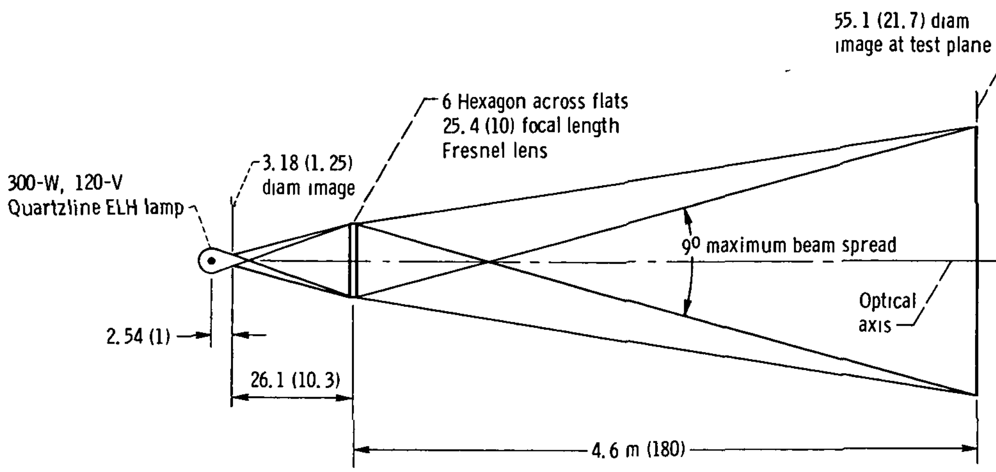

Figure 7. - Optical schematic of single lamp and lens. (All dimensions in cm (in.) unless otherwise noted.)

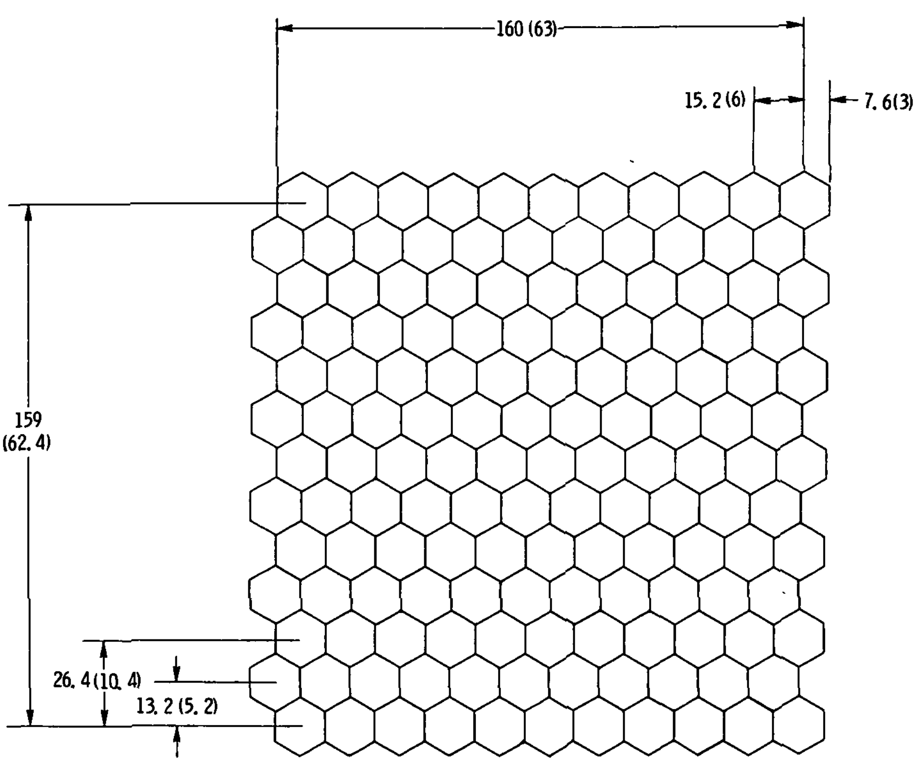

Figure 8. - 143-Lamp-lens array.

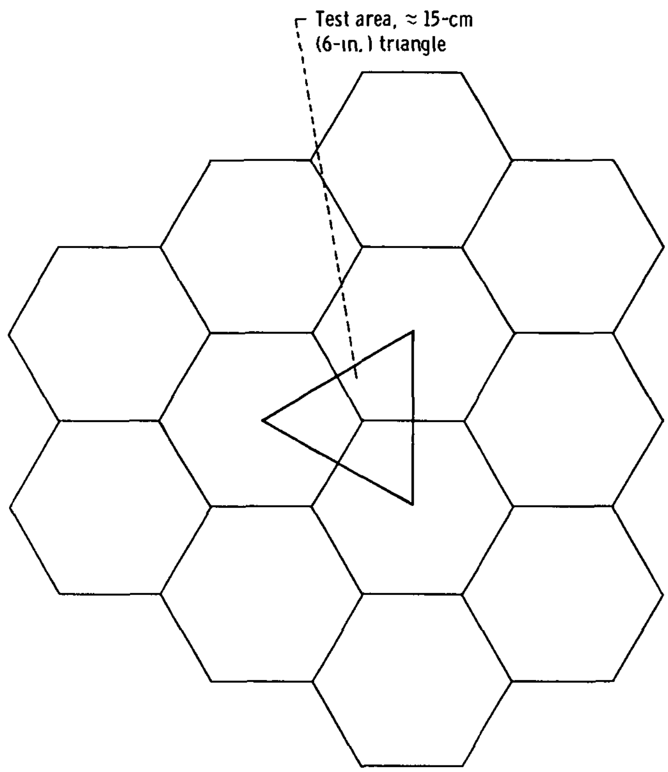

Figure 9. - 12-Lamp-lens array.

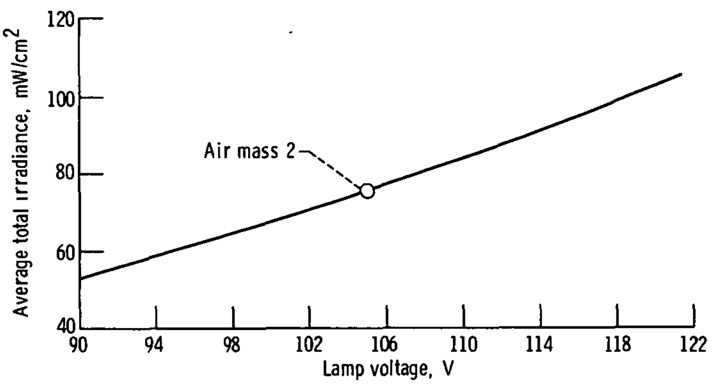

Figure 10. - Average total irradiance as function of lamp voltage.

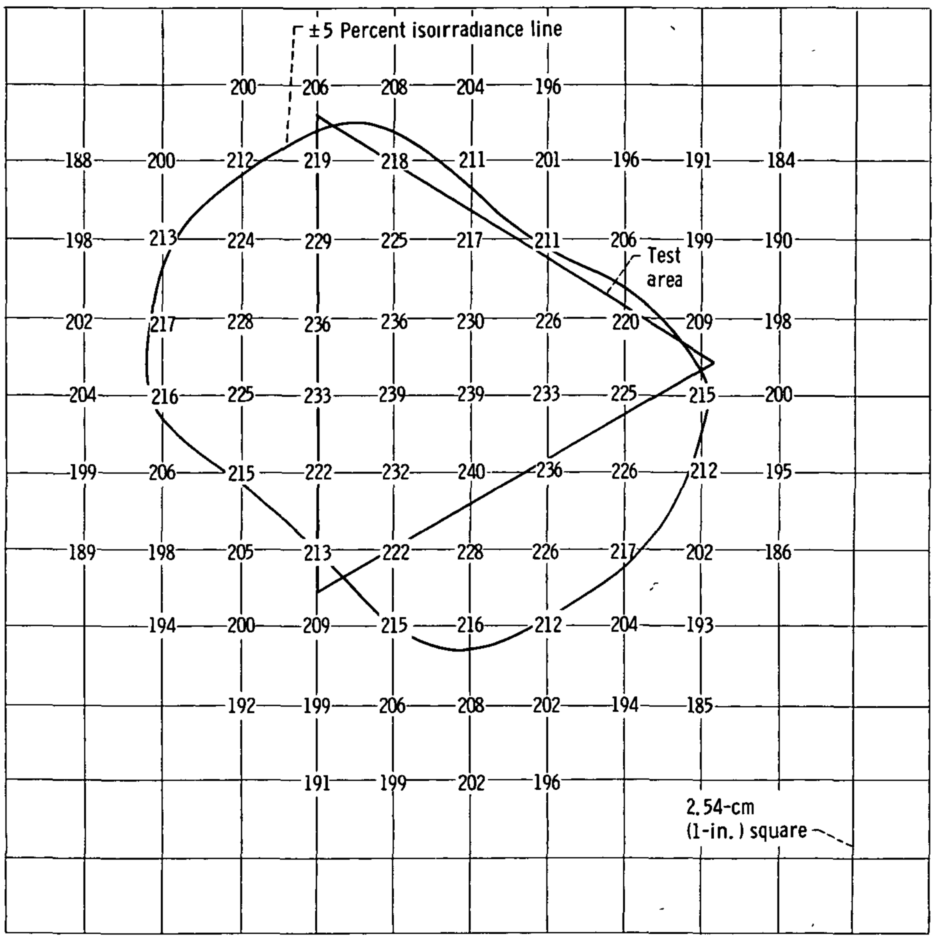

Figure 11. - Distribution of total irradiance in test plane

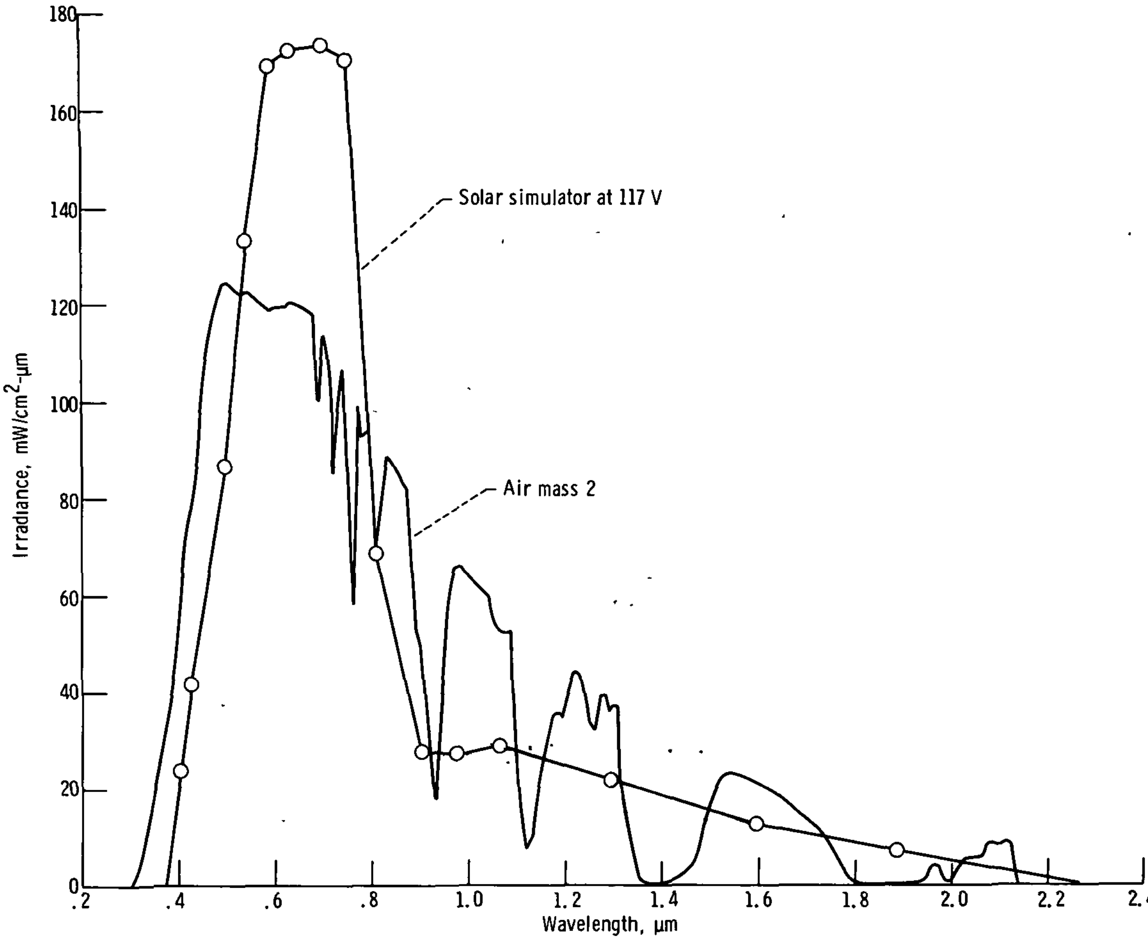

Figure 12. - Variation of spectral irradiance with wavelength.

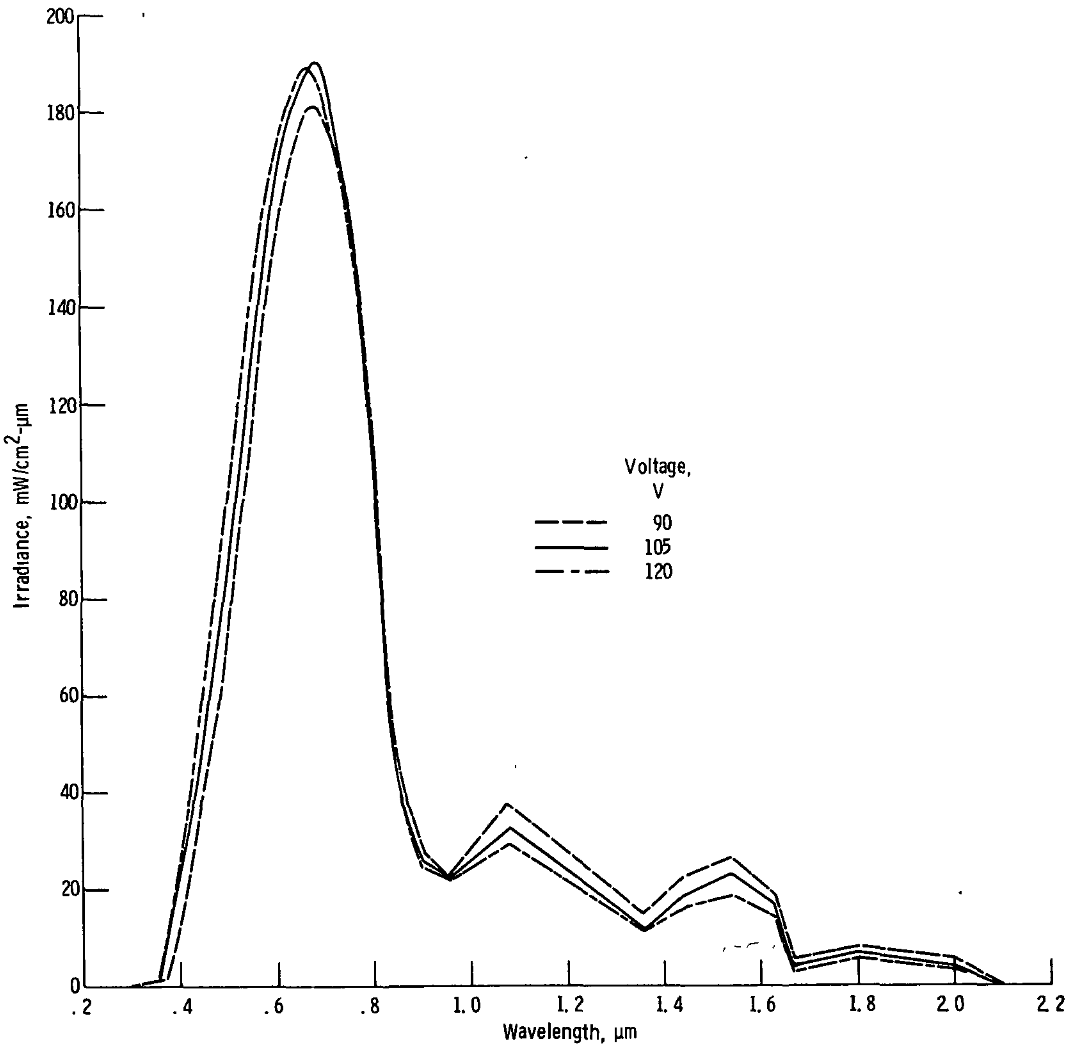

Figure 13. - Variation of spectral irradiance with wavelength at three voltages.

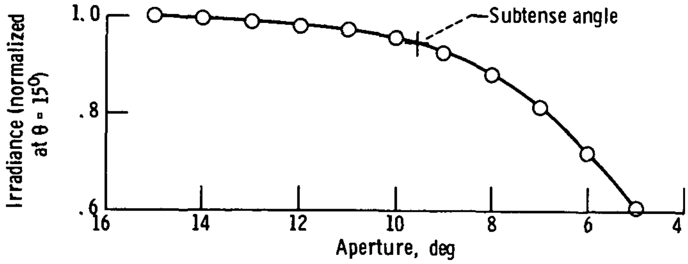

Figure 14. - Variation of total irradiance with aperture.

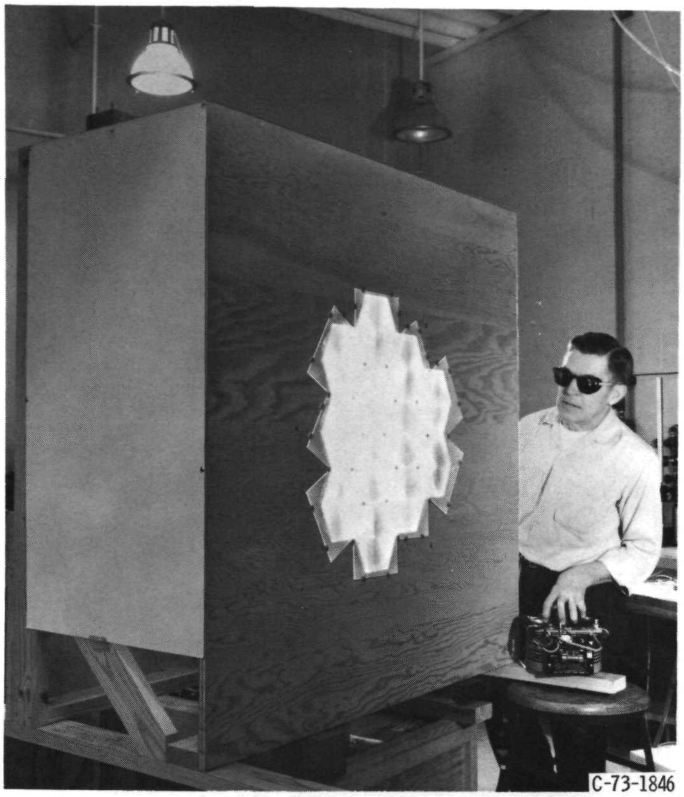

Figure 15. - Front view of prototype.

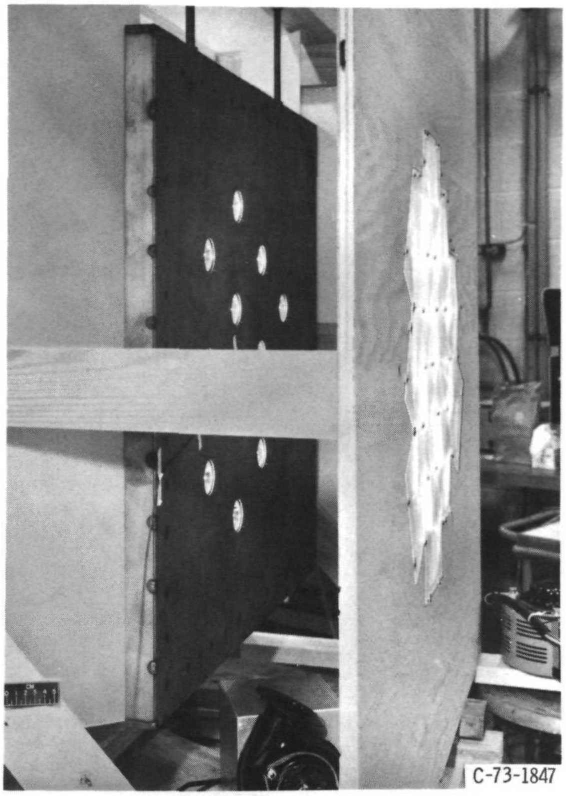

Figure 16. - Side view of prototype.

Figure 17. - Rear view of prototype.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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