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OPERATIONAL PERFORMANCE OF A LOW COST,  
AIR MASS 2 SOLAR SIMULATOR

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## OPERATIONAL PERFORMANCE OF A LOW COST, AIR MASS 2 SOLAR SIMULATOR

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### ABSTRACT

A low cost air mass 2 solar simulator is in operation at the Lewis Research Center. It is used in the testing of flat plate collectors for solar energy utilization. The design of the simulator and performance of a small prototype have already been reported. Collector performances have also been determined and reported. This paper will discuss modifications and improvements on the simulator and present the performance characteristics of total irradiance, uniformity of irradiance, spectral distribution and beam subtense angle.

The simulator consists of an array of 143 tungsten halogen lamps hexagonally spaced in a plane. A corresponding array of 143 plastic Fresnel lenses shapes the output beam such that the simulator irradiates a 1.2 m by 1.2 m area with uniform collimated irradiance. (Uniformity -  $\pm 10\%$ , beam subtense angle -  $12^\circ$ )

Since the output of each individual lamp varies with manufacturing tolerances, the uniformity of irradiance can be optimized by proper placement of the lamps in the array. Details are given concerning individual lamp output measurements and placement of the lamps. Data on lamp life and cost are given.

Originally, only the direct component of solar irradiance was simulated. Since the diffuse component may affect the performance of some collectors, the capability to simulate it is being added. An approach to this diffuse addition is discussed.

### INTRODUCTION

In an ongoing program at the Lewis Research Center, flat plate collectors are being tested for

utilization of solar energy. Tests are being conducted both indoors and outdoors. Indoor tests are made for a period of hours and are used to determine collector performance under ideal conditions and are used to evaluate performance changes. Indoor tests are also very useful for making rapid comparisons between several collectors. Outdoor tests are conducted over much longer periods of time and can determine collector performance under changing weather conditions and prolonged use. To make short term tests indoors, we need a controlled environment, including a solar simulator. A low cost Air Mass 2 solar simulator has been designed and a 12 lamp prototype tested at the Lewis Research Center (Ref. 1). A 143 lamp simulator was then constructed and is currently part of a test facility. The performance characteristics have been determined for several collectors (Ref. 2).

This paper gives a review of the design and construction of the simulator, along with the operating characteristics. Data on irradiance levels, uniformity of irradiance, spectral distribution, and subtense angle of the simulator are given. The actual performance of this simulator is compared with the performance of the prototype and the differences are discussed. We also discuss lamp life, lamp and bulb cooling, and long term changes in the simulator output.

As originally designed, the simulator provides only the direct (or near direct) component of incident solar irradiance. For many flat plate collectors, this may be sufficient. However, other collectors may perform differently under diffuse irradiance (hemispherical). Hence, it was decided to add the capability of simulating the diffuse component in addition to the direct component.

### SIMULATOR DESCRIPTION

The solar simulator is located in the indoor test facility at the Lewis Research Center. A view of the facility is shown in figure 1. The 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  $25^\circ$  to  $72^\circ$  from the horizontal to accommodate different collector tilt angles. At the separation distance, the irradiated area is 1.2 by 1.2 meters (4 by 4 ft).

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 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

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coincident with that of its respective lens. The lenses are flat plastic (acrylic) Fresnels having a focal length of 25 cm. (10 in) and a circular groove density of 39.4 lines per cm (100 lines per in). They are commercially available in 17 cm (7 in) squares which are then cut into hexagons measuring 15 cm (6 in) across the flats. The lamps (General Electric Quartzline ELH) are also commercially available and intended for use in film projectors. Rated 300 watts at 120 volts, each lamp consists of a tungsten halogen bulb fixed into a stippled, front surface dichroic coated glass, open ellipsoidal reflector.

Forced air cooling of the lamps is provided by an exhaustor motor with a blower capacity of 2.2 cubic meters per second (4700 ft<sup>3</sup>/min). The direction of the cooling air in the simulator is shown by the air flow arrows in figure 2. Air enters the enclosed simulator between the lenses and lamps through eight air filters. It then enters the lamp plate openings adjacent to each lamp and is redirected with deflecting vanes (figure 3) to pass over the rear reflector surfaces and bases of the lamps. It is finally exhausted to atmosphere through a flexible 0.8 meter (30 in) diameter duct.

Power to the lamps is controlled through two switches at the remote console. Each switch operates a motor driven bank of autotransformers, and the output voltage of each bank is directed to half the lamps of the simulator. Another switch permits the voltage readout of each bank on a common digital voltmeter. A more complete description of the entire simulator is furnished in reference 1. Total cost was less than \$10,800/m<sup>2</sup> (\$1000/ft<sup>2</sup>).

#### OPERATIONAL EXPERIENCE AND IMPROVEMENTS

Since becoming operational, the simulator has accumulated over 150 hours of running time on solar collector tests. Results of tests on 5 collectors have been reported. Operating experience gained during this period indicated certain areas in need of improvements, and modifications were made to upgrade simulator performance. The modifications had to do with (1) lens preparation and mounting, (2) lamp cooling and lamp life, and (3) lamp variation, measurement, and placement. These are described below.

##### Lens Preparation and Mounting

Shortly after becoming operational, several lenses cracked, although two thermocoupled lenses showed no excessive temperature during operation. Cracks developed at the mounting holes and at the outside edges of the lens. Stresses at the hole were eliminated by cushioning with a fabric-reinforced neoprene washer between each screw and the lens. The cracks at the edges originated at small nicks occurring during the cutting of the lenses from the square into its hexagonal shape. New lenses were cut approximately 0.08 cm (1/32 in) oversize, and then sanded to final size. No further cracking occurred.

##### Lamp Cooling and Lamp Life

The lamp manufacturer specifies an average life of 35 hours at rated voltage (120 volts), providing the lamp is operated horizontally. Since life of a tungsten filament lamp is inversely proportional to approximately the 13th power of the voltages, calculated life at 105 volts and 115 volts would be 201 and 61 hours, respectively. Although, calculated life is seldom achieved in practice, it does provide useful approximations. The first set of lamps exhibited failures beginning at 31 hours. Surprisingly, operating at reduced voltage apparently had no effect on life.

The lamps were operated over a range of voltages from 95 to 115 volts. Based on a maximum operating voltage 115 volts the calculated life should be 61 hours when in reality it was much less. The manufacturer recommends that the base temperature of the lamp (at the surface) never exceed 288°C. Thermocouple measurements verified that this temperature was indeed never exceeded. We then returned a number of failed lamps to the manufacturer for inspection. Their analysis indicated too low an operating bulb temperature. Overcooling of the bulb interfered with the tungsten halogen cycle leading to premature failure.

The most expedient solution for our simulator was to reduce fan speed, and thus bulb cooling. Too great a reduction though, could threaten lamp life by increasing base temperature. The motor and fan pulley wheel arrangement was modified and fan speed was reduced. Improvement was noted in the second set of lamps, which showed over 60 hours of life before the first failure. Some thought has been given toward maximizing this particular improvement which would involve measurements relating bulb and base temperatures with exhaustor motor speed (or a damper setting) for different operating lamp voltages. Access to the simulator for this purpose has not been made available as of this writing.

##### Lamp Variation, Measurement and Placement

Initial measurements of total irradiance distribution in the test plane showed uniformity poorer than expected. Several regions of excessive brightness were also in evidence. Determining the cause of the nonuniformity led to the measurement of the relative radiant outputs of each of the 143 lamps through its corresponding lens at a constant voltage setting. This was accomplished by means of a specially built radiometer. The relative readings ranged from 67 to 93, about +16% variation from the average. In addition, five readings were abnormally high, ranging from 103 to 124. Under close examination, these five lamps were found to have one or more turns of the coiled filament electrically shorted and drawing excessive current. These lamps were discarded and replaced.

Subsequent measurements confirmed the +16% spread in lamp differences for each set of 143 lamps used. Shorted filaments have not recurred. These differences were not uncovered during tests on the 12 lamp prototype (Ref. 1) when +5% uniformity of irradiance in the test phase was achieved. Improving uniformity by limiting lamps employed to a narrow band at the center of the deviation

spread is unnecessarily expensive. Because seven lamps contribute to the irradiance at any point in the test plane, redistribution of the lamps in the array can improve the uniformity through averaging. Our solution is as follows: Starting with the lowest measured lamp value we then alternate the highest, the next lowest, etc., lamps in the first row, followed by a row of near average lamps. The third row repeats the first row, and the fourth repeats the second row scheme. The plan is repeated through the last row.

A lamp radiometer was constructed permitting lamp output to be measured without a Fresnel lens and without using the solar simulator. It was a modification of the one used for on-site measurements. The lamp, measured at 95 volts, is marked with its reading for future placement. Premature failure of any lamp in the simulator need only have another lamp of near like reading replace it to retain uniformity.

#### MEASUREMENT PROCEDURES

Measurements were made on the 143 lamp solar simulator except where noted, and in a manner similar to the measurements performed on the 12 lamp prototype (Ref. 1). The solar collector was removed from the test location, and the simulator operated in a normal manner. All measurements were begun and completed between the 10th and 15th hours of lamp life.

Total irradiance was measured on axis and in the test plane. (The test plane is the plane of the solar collector absorber surface at the collector-simulator separation distance of 4.6 meters (15 ft).) Measurements were made at lamp voltages of 90, 95, 100, 105, 110, and 114 volts. Mechanical stops at the autotransformer control banks prevent operation at higher voltages.

The collector support table was used as the rectangular grid for sampling in the 1.2 by 1.2 meter total irradiance distribution plane. The plane was sampled in 15 cm (6 in) increments, using a water-cooled, black, detector having a 2.5 cm (1 in) diameter sensitive surface. In addition, the central square of this plane, measuring 30 cm (12 in) on a side, was sampled in smaller 5 cm (2 in) increments.

A second sampling of the central square was also made in a plane 15 cm (6 in) closer to the simulator. A comparison of these similar areas, from each of the two planes, will give a measure of the change of uniformity with distance.

Spectral energy distribution measurements were obtained with an Eppley Mark V filter radiometer and a set of 12 filters. Measurements were made for lamp voltages of 90, 101, and 114 volts.

Because the outline of the apparent source is not sharply defined, the simulator beam subtense angle, sometimes called collimation angle, was measured by the energy method (Ref. 3). For this purpose, the filter radiometer was used as a total detector with the filter wheel replaced by an aperture wheel. The wheel has apertures with

known view angles from 15° down to 5° in 1° steps.

#### LAMP AND LENS AGING CHARACTERISTICS

Temporal stability (embodying the fidelity of total and spectral irradiance with time) of the simulator can be divided into short (seconds), medium (minutes), and long (hours) term categories. Short term stability which includes voltage transients is of minor importance in solar collector testing. Medium term stability is dependent upon line voltage drift and temperature changes. This also proved of no consequence, since no observable change of irradiance was noted on a strip chart recorder over an interval of 15 minutes. Long term stability is dependent to a great extent upon lamp and lens life and their degradation rate. Since, the indoor test facility has a busy schedule, and the simulator is not readily available for long term tests, measurements were made on lamp and lens aging without using the facility.

To determine lamp degradation rate as a function of lamp life, a new lamp was mounted in an aluminum box having an exhaustor motor and an air deflection vane. The configuration is similar to a one lamp arrangement of the simulator without the lens. The box was mounted to orient the lamp 55° downward from the horizontal. The filter radiometer was positioned in the lamp beam, on-axis and normal to it. Through a well-regulated power supply, the lamp was held constant at 115 volts until lamp failure occurred. Nothing was disturbed during the test. Initial spectral and total irradiance measurements were made during the first hour of lamp operation followed by a measurement at 17 hours, and again at successive 8 hour intervals.

The lamp failed after 53 hours. The total irradiance was constant to  $\pm 1/2\%$  over the life of the lamp. Hence, long term drift of the simulator due to lamp degradation is negligible. The spectral distribution, measured at 1, 17, 25, 33, 41, and 49 hours, showed no change in spectrum during this time interval.

Determination of the extent of lens aging was accomplished by comparing the transmission curves of a randomly chosen new unexposed lens, and a lens removed from the central portion of the simulator. The latter lens had an accumulated radiation exposure time of over 150 hours and was measured immediately following the most recent collector test. Spectral transmissions were measured with a spectroradiometer and integrating sphere. There was no degradation in transmission at any wavelength due to 150 hours of simulator operation. Hence, the long term drift in the simulator due to either the lamp or the lens should be small.

#### RESULTS

Figure 4 is a plot of average total irradiance versus lamp voltage for the simulator. The irradiance ranges from 61 to 105 mw/cm<sup>2</sup> as the voltage varies from 90 to 114 volts. The air mass

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2 level of  $75.7 \text{ mw/cm}^2$  is at approximately 100 volts.

The distribution of total irradiance in the test plane is shown in figure 5. Since the area of the detector is such a small percentage of the area of the test plane (0.03%), we averaged four detector readings to obtain the average irradiance in larger area increments. The test plane is therefore divided into 64 equal squares each 15 cm (6 in) on a side. The average irradiance in each square is given in  $\text{mw/cm}^2$ . The overall average irradiance during the distribution measurement was  $76.2 \text{ mw/cm}^2$ . In figure 5, the areas which are more than +10% from the average irradiance are marked. Note that only 5% of the total area is outside this number.

The volume uniformity is obtained from the two central square irradiance distribution data. The data show that near the test plane the average irradiance increases 1% for each 4 cm closer to the simulator, while the distribution of irradiance remains relatively unchanged.

The spectral distribution of the simulator at 101 volts is given in figure 6. Also plotted in figure 6 is the air mass 2 spectral distribution. Both curves are normalized to a total irradiance of  $75.7 \text{ mw/cm}^2$  for comparison purposes. The simulator gives a fairly good match to the air mass 2 spectrum. The main reason for the good agreement is the reduction of the tungsten lamp's infrared output by the dichroic coating on the lamp reflector.

We also measured the spectral distribution at two other lamp voltages, 90 and 114 volts, in order to determine how much the spectral distribution changed with voltages. Table I shows the percent of irradiance in various wavelength intervals for the simulator at 90, 101 and 114 volts. Also shown in Table I is the distribution for the air mass 2 spectrum. Note that the irradiance shifts some from the infrared to the visible as the lamp voltage is increased. This is expected since the brightness temperature of the lamp increases with voltage. The comparison with the air mass 2 spectrum is fairly good except for the lack of ultraviolet in the simulator.

Another method of comparing spectrums of the simulator and the Sun is to calculate how various surfaces respond when irradiated by the simulator or by the Sun. Three such typical surfaces are:

1. A silicon solar cell (Ref. 4).
2. A silicon oxide coated front surface aluminum mirror (Ref. 5).
3. A solar absorber such as a Tabor surface (Ref. 6).

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

Table II shows the calculated percent efficiency of a silicon solar cell (10.5% under air mass zero conditions), the reflectance of the aluminum mirror, and the absorptance of the Tabor surface when irradiated by the three measured simulator

spectral distributions, and the air mass 2 distribution. Note that all the calculated surface responses are within a few percent of the air mass 2 values. Hence, for tests using these surfaces (or any other surface with a response not strongly dependent on wavelength) the simulator gives a good match of air mass 2. For the solar cell, a change in lamp voltage from 90 to 114 volts results in about a 5% increase in cell efficiency. This is due only to the change in spectrum and should be accounted for in testing such cells. Note that there is a very small change in the calculated absorptance of the Tabor surface as the lamp voltage changes. Hence, little or no correction would be applied in tests using such surfaces.

The simulator beam subtense angle as measured by the change in total irradiance with various aperture sizes is shown in figure 7. The irradiance drops to 95% of the maximum value at approximately  $12^\circ$ , thus defining the subtense angle. This implies that 95% of the incident irradiance is within a  $12^\circ$  cone centered on the normal to the test plane, or within  $\pm 6^\circ$  of the normal.

#### SIMULATION OF DIFFUSE COMPONENT

All of the results described so far are for the direct component of solar irradiance. As mentioned earlier, some collectors might perform differently when a portion of the incident irradiance is diffuse. The diffuse irradiance is that portion which is incident on the test surface at angles other than directly from the Sun. There is some data (Ref. 7) on the angular distribution of the diffuse solar irradiance, but it is not complete. It is obviously very dependent on the cloud cover and atmospheric conditions. This variety of angular distributions can be simulated by adding a diffuser (such as ground glass), a few centimeters (10-20) in front of the test plane. Then all the irradiance incident on the test plane is through the diffuser. Some preliminary tests were made using a ground glass, and also a plastic photographic diffusing screen, as the diffusers. The twelve lamp prototype of reference 1 was used as a simulator.

These tests show that there is a strong direct component through both of the two diffusers. About two-thirds of the incident irradiance is within a full angle of  $30^\circ$  about the normal. Hence, we have a mixture of direct and diffuse irradiance. Further tests with other diffusers will allow us to extend the range of angular distribution of simulated irradiance. Since the total solar irradiance drops as the ratio of diffuse to direct increases, the attenuation of the incident simulator irradiance by the diffuser screen is not a problem.

#### CONCLUDING REMARKS

In comparing the measured results of the large 143 lamp simulator with earlier measurements made on the small 12 lamp prototype, the following differences are noted:

1. The large simulator has more radiant energy output. For example, it requires a lower lamp voltage (100 vs 105) for an equivalent average total irradiance ( $75.7 \text{ mw/cm}^2$ ) in the test plane.
2. The distribution of total irradiance is not as good for the large simulator (compare uniformity of  $\pm 10\%$  vs  $\pm 5\%$ ).
3. The solar subtense angle is greater for the large simulator ( $12^\circ$  vs  $10^\circ$ ).

We attribute these differences mostly to internal scattering of radiation from the reflective surfaces of the simulator. The large model has two important design changes. First, the plate containing the lamps was constructed of aluminum whereas the prototype plate was made of dull steel. The aluminum surfaces lend themselves to reflective action between the lenses and lamp plate. Secondly, the vent hole and deflection vane (aluminum) configuration for cooling the lamps was not in the prototype design. The deflector vane likewise, tends to reflect lamp radiation which is then projected toward the test plane.

This hypothesis was confirmed by measurements made comparing a blackened deflector vane with an unblackened one. The obvious solution is to remove the cause of the unwanted reflections. As time permits, steps will be taken to remedy this condition.

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TABLE I  
PERCENT OF IRRADIANCE IN  
VARIOUS WAVELENGTH INTERVALS

Wave-length Inter-val, $\mu\text{m}$	Simulator lamp voltage			Air Mass 2
	90v	101v	114v	
0.3 - 0.4	0.0%	0.1%	0.2%	2.7%
0.4 - 0.7	41.1	44.6	48.0	44.4
0.7 - 1.0	28.2	27.7	27.2	28.6
1.0 - 2.2	30.7	27.6	24.6	24.3

TABLE II  
CALCULATED RESPONSES OF THREE  
TYPICAL SURFACES TO DIFFERENT  
SPECTRAL IRRADIANCES

Lamp Voltage (Volts)	Silicon Solar Cell (Percent Efficiency)	Al-SiO Mirror (Reflectance)	Tabor Surface (Absorptance)
90	12.4	.88	.87
101	12.7	.88	.88
114	13.0	.88	.88
Air Mass 2	12.6	.86	.90

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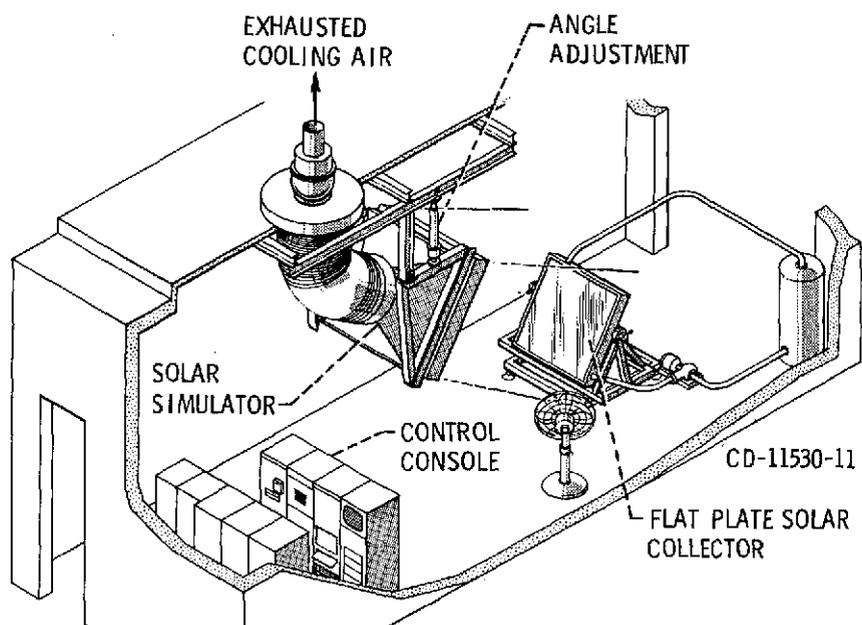


Figure 1. - Indoor test facility.

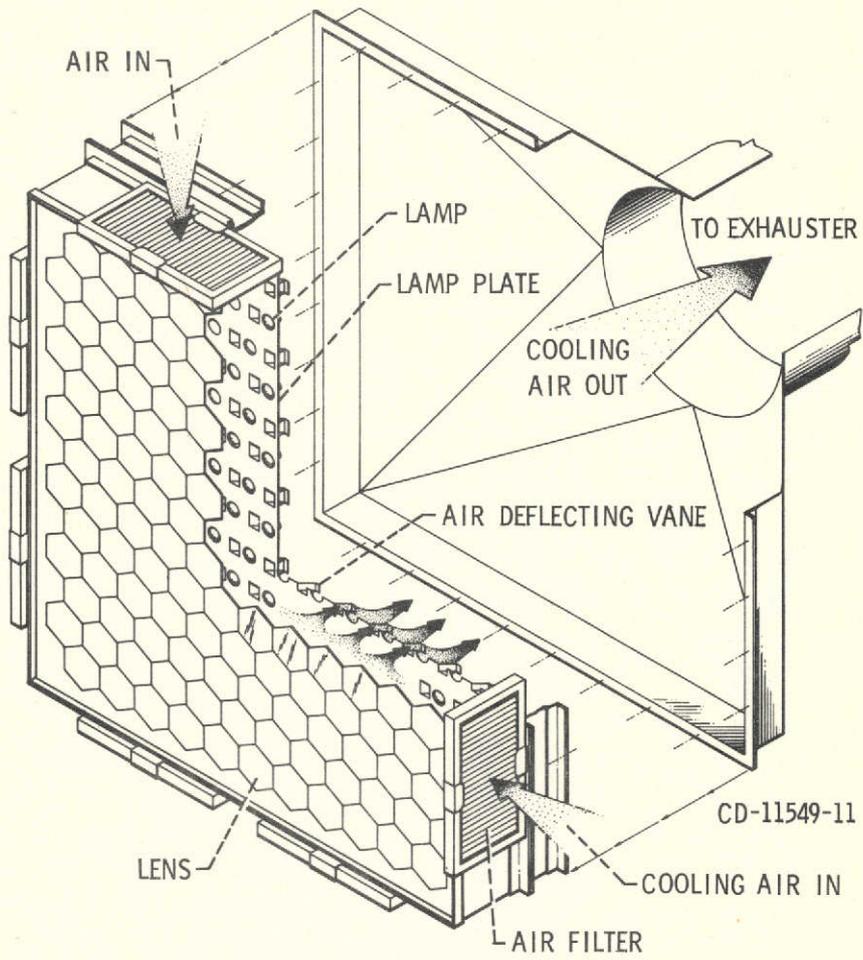


Figure 2. - Solar simulator cut-away view.

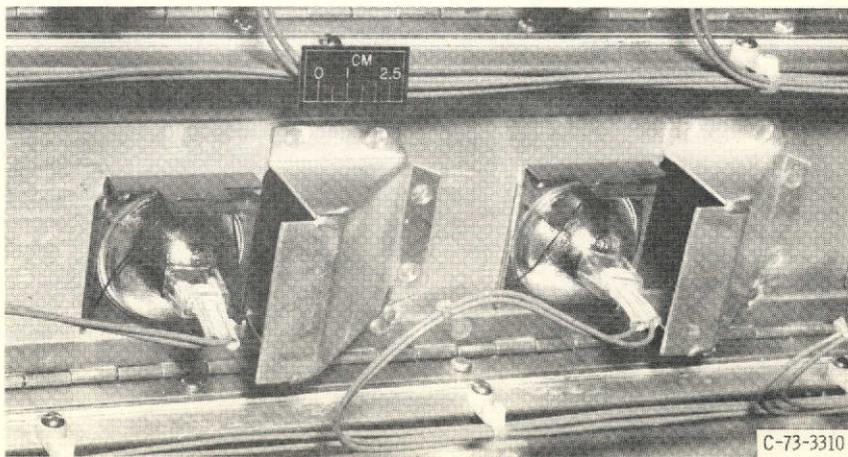


Figure 3. - Air cooling deflection vanes.

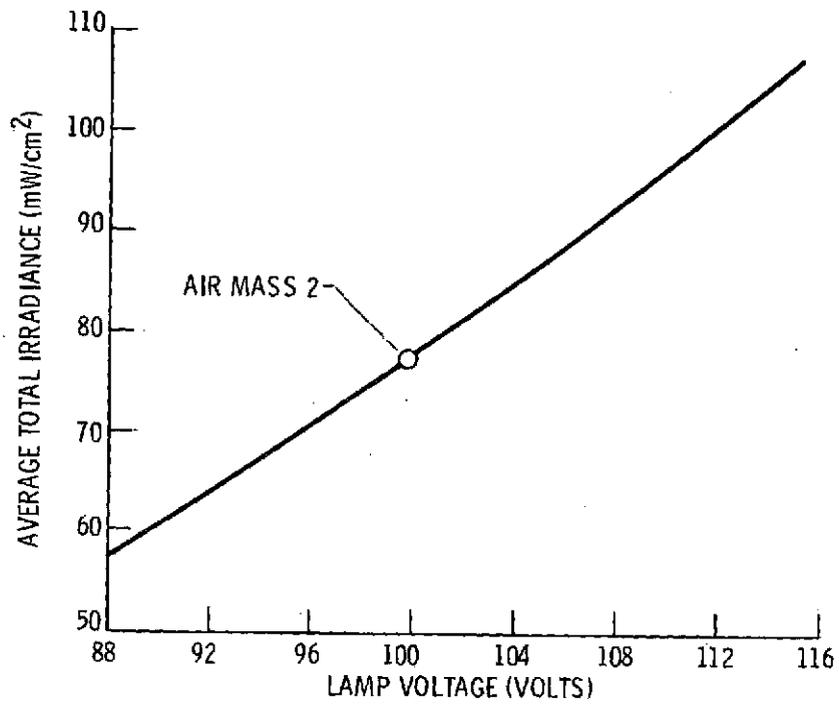


Figure 4. - Average total irradiance as function of lamp voltage.

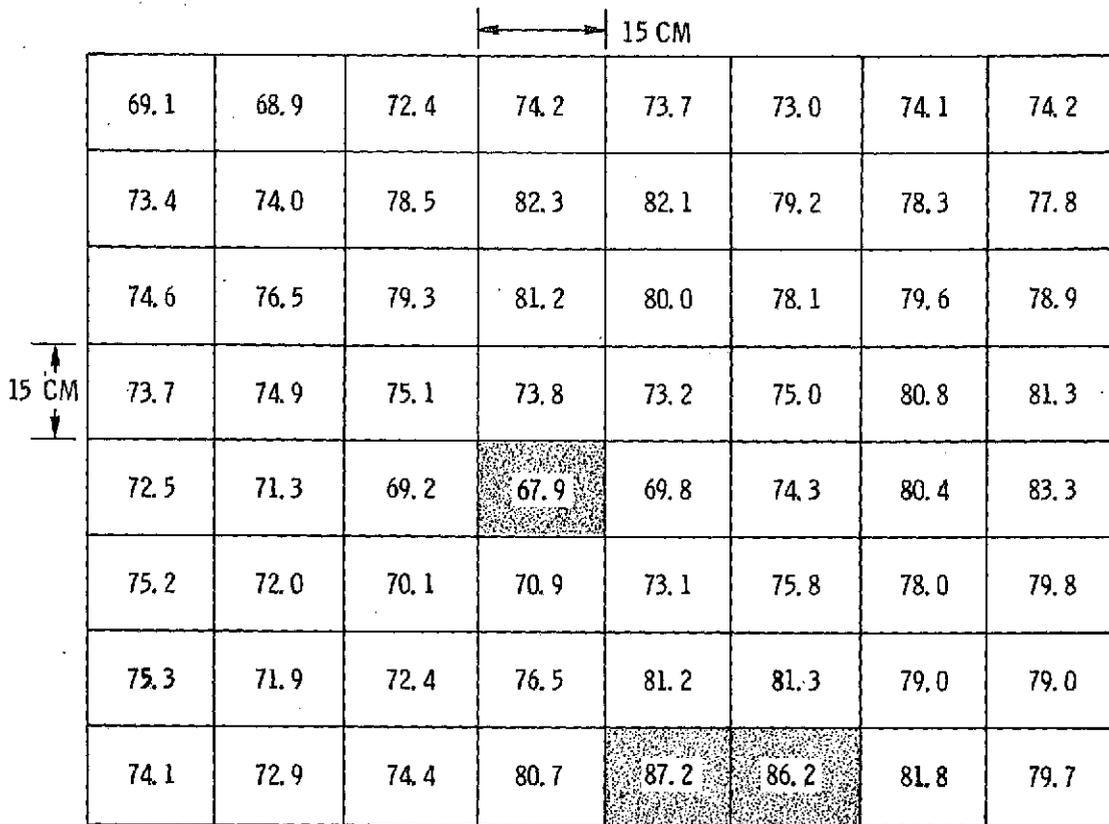


Figure 5. - Distribution of total irradiance.

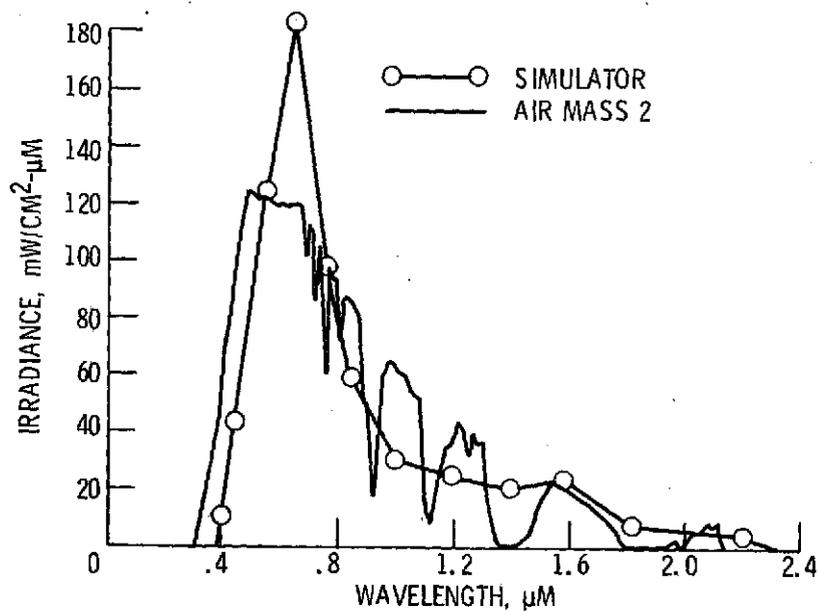


Figure 6. - Variation of spectral irradiance with wavelength.

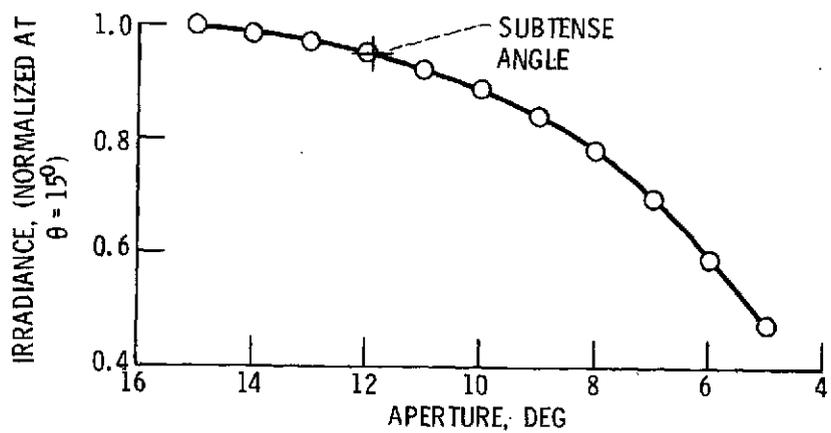


Figure 7. - Variation of total irradiance with aperture.