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EFFECT OF ERROR IN SPECTRAL MEASUREMENTS OF SOLAR SIMULATORS ON SURFACE RESPONSE

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16. Abstract

An analysis was made to determine the effect of measurement error in spectral distributions of solar simulators. The effect of the error is a change in the calculated total response of a surface (absorptance, reflectance, etc.). Data for six typical spacecraft surfaces and three different solar simulators were used.

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EFFECT OF ERROR IN SPECTRAL MEASUREMENTS OF SOLAR SIMULATORS ON SURFACE RESPONSE

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SUMMARY

An analysis was performed to determine the accuracy requirements of spectral irradiance measurements on solar simulators. The approach used involved calculating the changes in total response (absorptance, reflectance, etc.) as a function of measurement error in spectral irradiance. Measurement error was applied to a spectral irradiance curve by a worst-case error function, which was chosen such that any real measurement error, characterized by the same percent error figure, would result in a smaller change in total response.

Spectral data for the response of six typical spacecraft surfaces and the irradiance of three types of solar simulators were used. Estimates of accuracy requirements for spectral irradiance measurements may be made by comparing the percent change in total response as a function of spectral irradiance error with design tolerance limits of total response. Spectral irradiance data obtained using a grating monochromator and a multifilter radiometer gave substantially equal values of response.

INTRODUCTION

A solar simulator provides radiant energy with characteristics designed to match those of the Sun. One of the more important characteristics of solar radiant energy is its spectral distribution, often called spectral irradiance. This indicates how the radiant energy is distributed along the wavelength scale. Measurements of the spectral irradiance of the simulator are made to determine how closely it matches the spectral irradiance of the Sun.

Attempts to match the power and spectral irradiance of the Sun for laboratory tests of spacecraft and components have led to a great variety of simulator systems. The effects studied under the various types of systems have not been well correlated and often differ from those in space. Part of the problem was caused by the different measurement systems used. This whole problem becomes critical when a new test system costing several million dollars must be designed, and confidence must be had in the results. Therefore, the NASA Lewis Research Center made an analysis of the effect of systematic measurement errors on the total response of surfaces. This analysis and application are described in this report.

Computations were made using a worst-case error analysis to define the measuring accuracy required during simulator evaluation. In order to test the method developed in the analysis, the total responses for six surfaces were calculated for three simulator sources and the Johnson Solar Curve (ref. 1). Two measuring methods were also used.

The accuracy requirements were established by comparing the differences in computed total response of these typical spacecraft surfaces when errors were deliberately introduced into the measured spectral irradiance curves of present-day solar simulators.

SYMBOLS

E	error function, function of wavelength
H	spectral irradiance, function of wavelength
H'	HE, spectral irradiance with error, function of wavelength
R	spectral response, function of wavelength
$\overline{R}$	total response
$\overline{R}'$	total response using spectral irradiance with error
Δ	error figure in E
$\Delta\%$	100Δ
λ	wavelength

THEORY AND ERROR FUNCTION ANALYSIS

Consider a surface exposed to incident solar radiant energy. The surface will reflect, absorb, transmit, or even convert (as in a solar cell) the incident energy. Depending on what the surface is and how it is being used, usually only one surface parameter will be of interest at a time. Examples are the reflectance of a mirror surface or the absorptance of a thermal control surface. Quantities such as reflectance and absorptance will be termed surface response and are, in general, functions of wavelength.

Hence, this discussion deals with spectral surface response or just spectral response. If the incident energy has a spectral irradiance H and the surface has a spectral response R, then the total response is defined as

$$\overline{R} = \frac{\int HR\, d\lambda}{\int H\, d\lambda} \tag{1}$$

where the integration is over the solar wavelength region. This report will only be concerned with applications of H as defined by equation (1).

An inaccurate measurement of spectral irradiance may be expressed by

$$H' = HE \tag{2}$$

where H' is an inaccurate measurement of H and E is an error function, which multiplies the actual irradiance by an error factor. For example, if at some wavelength there is no error in the measurement of H, then E equals 1.0 at that wavelength. If the error were +20 percent, then E equals 1.2 at that wavelength; E is a function of wavelength and may have different values at different wavelengths. The effect of E may be found by comparing calculated values of total response for a surface by using first H and then H' as the incident irradiance. An infinite number of possible error functions exist, and, obviously, only a few of them can be analyzed. Herein, all the error functions will arbitrarily be limited to ±20 percent error or less. This implies that there are no values of E used in this report that are greater than 1.2 or less than 0.8 at any wavelength.

Each error function has a maximum in the form $1 + \Delta_{max}$ and a minimum in the form $1 - \Delta_{min}$. The Δ's are fractional errors, and the largest of the two (in absolute value) is the fractional error which characterizes that error function. For convenience, the symbol $\Delta\%$ (equal to 100Δ) will designate the percentage error. For example, if the largest Δ is 0.15, then that E is a 15-percent error function.

Any error function may now be put in classes, such as 5-percent error functions, 10-percent error functions, and so forth. There are still an infinite number of error functions in each percentage class. Since the effect of a certain percentage error in spectral measurement on the calculated total response of a surface is to be found, a worst-case error function is chosen. The worst-case error function is the one that maximizes the change in response given by

$$\overline{R}' - \overline{R} = \left| \frac{\int HER\, d\lambda}{\int HE\, d\lambda} - \frac{\int HR\, d\lambda}{\int H\, d\lambda} \right| \tag{3}$$

The terms H and R are the measured spectral irradiance and the spectral response for the simulator and surface in question, respectively. A worst-case error then is the E that makes the largest change in calculated total response. Any real error function of the same percentage class would cause less of a change in total response.

Before determining a worst-case error function, first consider a few simple cases. Consider E equal to a constant K. Hence,

$$H' = KH$$

equation (1) is used to calculate R'

$$\overline{R'} = \frac{\int KHR \, d\lambda}{\int KH \, d\lambda}$$

The constant may be taken out of the integrals and canceled. Hence, $\overline{R'} = R$ if $E(\lambda)$ is constant and the error is zero. A similar argument is used to show that any error function multiplied by a constant results in the same total response as just the error function. Hence, any error function may be put in a form such that its maximum is $1 + \Delta$ and its minimum is $1 - \Delta$; that is, Δ_{max} and Δ_{min} are the same, and Δ is the fractional error that characterizes E.

The problem of determining E now reduces to finding an E, consistent with the foregoing, which maximizes the change in total response for a given Δ. Consider an error function E. Let it be 1.0 except in some small wavelength interval $\delta\lambda$, where $E = 1 + \delta E_\lambda$. This error function produces a change in total response of $\delta\overline{R}$:

$$\delta\overline{R} = \frac{\int HR \, d\lambda + \delta E_\lambda H_\lambda R_\lambda \delta\lambda}{\int H \, d\lambda + \delta E_\lambda H_\lambda \delta\lambda} - \overline{R}$$

where

$$\overline{R} = \frac{\int HR \, d\lambda}{\int H \, d\lambda}$$

The subscripts refer to the function evaluated at a particular wavelength λ. Algebraic manipulation is used to obtain

$$\delta\overline{R} = \overline{R}\,\frac{\left(1 + \dfrac{\delta E_\lambda H_\lambda R_\lambda \delta\lambda}{\int HR\ d\lambda}\right)}{\left(1 + \dfrac{\delta E_\lambda H_\lambda \delta\lambda}{\int H\ d\lambda}\right)} - \overline{R}$$

Since $\delta\lambda$ is a small quantity, the terms in parentheses are of the form $1 + \Delta$, where $\Delta \ll 1$. Looking at $(1 + \Delta A)/(1 + \Delta B) = (1 + \Delta A)(1 - \Delta B + \Delta B^2 - \ldots)$ and since ΔA and ΔB are small, all second-order and higher terms are neglected, and $1 + \Delta A - \Delta B$ is obtained. Therefore,

$$\delta\overline{R} = \left(1 + \frac{\delta E_\lambda H_\lambda R_\lambda \delta\lambda}{\int HR\ d\lambda}\right)\left(1 - \frac{\delta E_\lambda H_\lambda \delta\lambda}{\int H\ d\lambda}\right)\overline{R} - \overline{R}$$

or

$$\delta\overline{R} = \overline{R}\left(\frac{\delta E_\lambda H_\lambda R_\lambda \delta\lambda}{\int HR\ d\lambda} - \frac{E_\lambda H_\lambda \delta\lambda}{\int H\ d\lambda}\right)$$

or by more algebraic manipulation,

$$\delta\overline{R} = \frac{\overline{R}\delta E_\lambda H_\lambda \delta\lambda}{\int H\ d\lambda}\left(\frac{R_\lambda}{\overline{R}} - 1\right)$$

Since all the individual terms ($\overline{R}$, H_λ, δ_λ, etc.) are positive, $\delta\overline{R}$ is maximized by making δE_λ the same sign as $(R_\lambda/\overline{R}) - 1$ and by maximizing $|\delta E_\lambda|$. This process may be repeated for all wavelength intervals with the result that

$$E = 1 + \Delta \quad \text{at } \lambda \text{ where } R_\lambda > \overline{R}$$

$$E = 1 - \Delta \quad \text{at } \lambda \text{ where } R_\lambda < \overline{R}$$

Calculating total response using the foregoing E gives a new calculated total response $\overline{R}'$. Hence, the expression $R_\lambda/R' - 1$ will be positive or negative at slightly different wavelengths. By using the same process as that just described, E can be changed slightly again, and a new $\overline{R}'$ $(\overline{R}'')$ can be obtained. This procedure is repeated until there is no further change in total response. In practice, this takes about three or four iterations.

APPLICATIONS AND RESULTS

Responses to Various Irradiances Without Measuring Errors

The range of variation in the total response of surfaces to different irradiances was illustrated by making a few calculations that do not include errors in spectral irradiance measurement. The calculation of a total response using equation (1) requires data for both a spectral irradiance of a source and a spectral response of a surface. Since the problem concerns solar simulators used in testing spacecraft materials, spectral data of actual solar simulators and spacecraft surfaces are used.

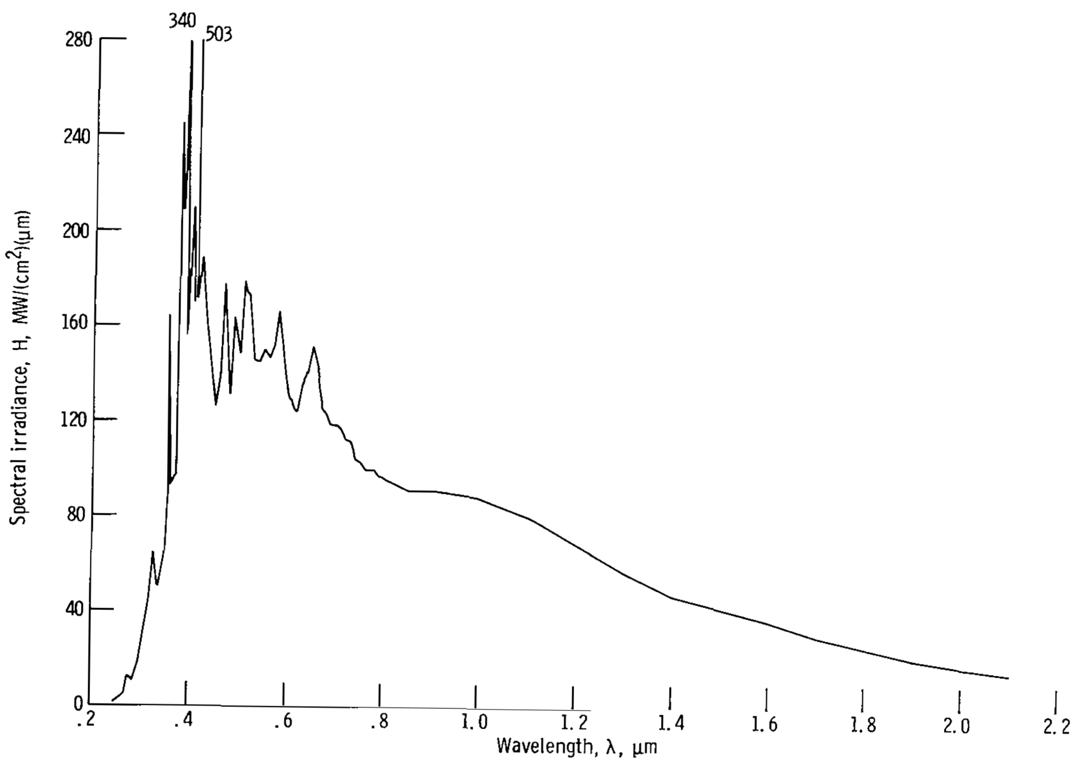

Figure 1. - Spectral irradiance as function of wavelength for carbon arc solar simulator.

Figures 1 to 3 show spectral irradiance as a function of wavelength for three solar simulators, namely, a carbon arc, a xenon lamp, and a mercury-xenon lamp. These data were taken at the Lewis Research Center using a grating monochromator with an integrating sphere. A quartz-iodine lamp was used as a reference standard. (More detailed information on the measuring technique is given in ref. 2.) The spectral irradiance of each source consists of approximately 100 measured points and is converted to a

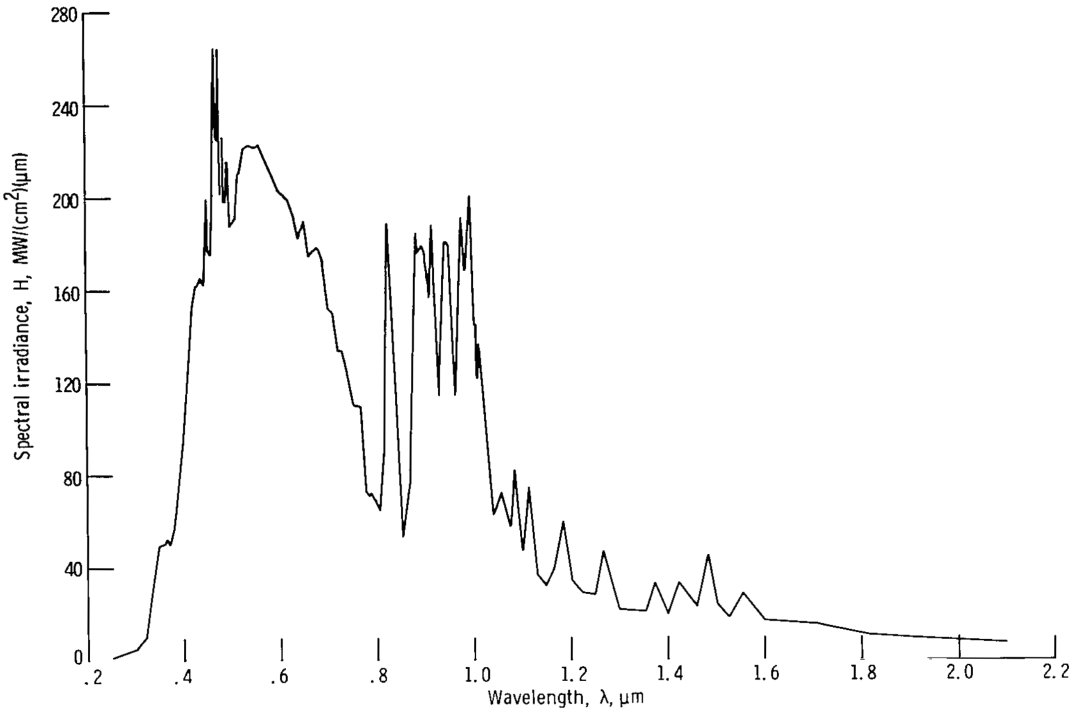

Figure 2. - Spectral irradiance as function of wavelength for xenon lamp solar simulator.

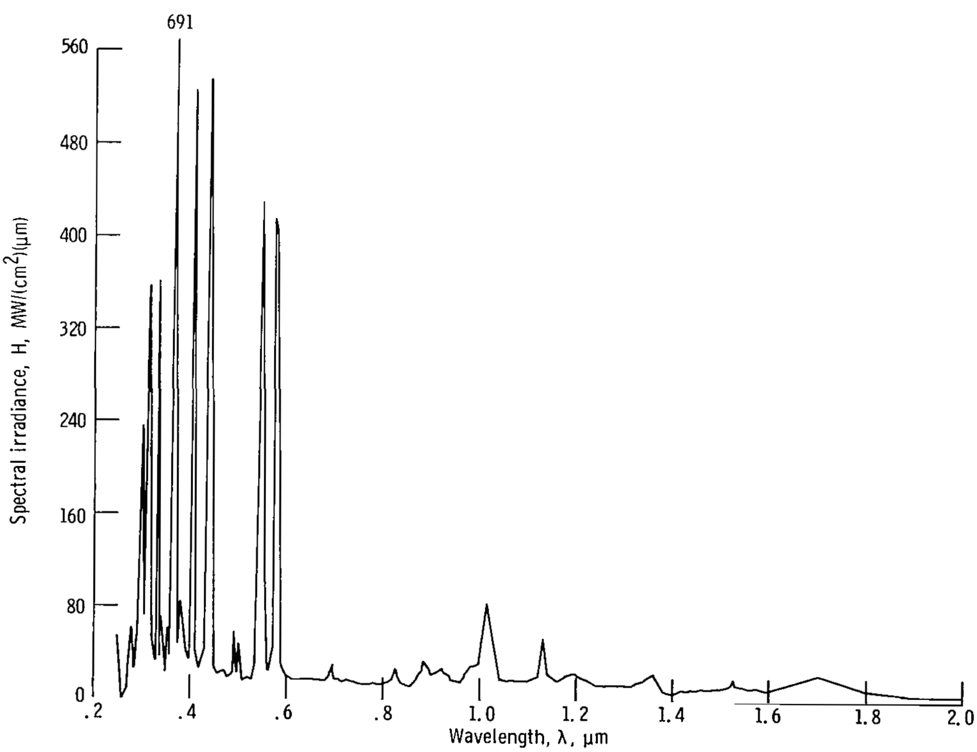

Figure 3. - Spectral irradiance as function of wavelength for mercury-xenon solar simulator.

continuous curve by straight-line interpolation. It should be noted that these are only typical of spectral irradiance curves for these types of simulators. The generally accepted values for the spectral irradiance of the Sun outside the Earth's atmosphere are given by Johnson (ref. 1). Figure 4 shows the Johnson curve with straight-line interpolation between points.

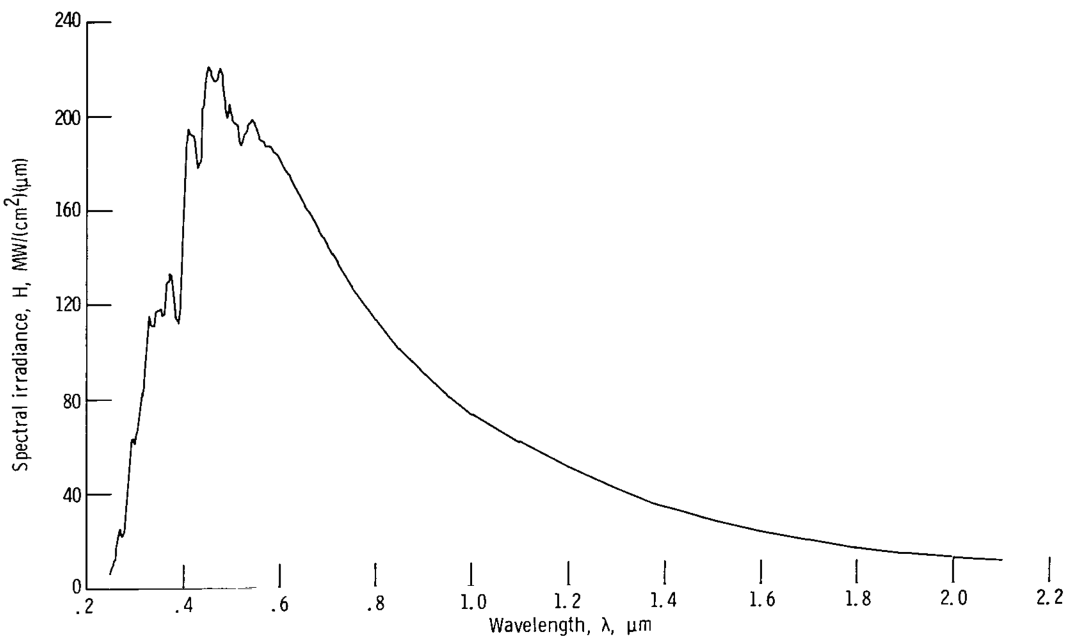

Figure 4. - Spectral irradiance as function of wavelength for Johnson curve.

Calculations were made using the spectral response of surfaces representative of actual spacecraft surfaces. Figures 5 to 10 show spectral response as a function of wavelength for six different surfaces, which were chosen for the maximum variety (more descriptive information can be found in the following references):

(1) Absorptance of unexposed zinc-oxide-pigmented white paint (fig. 5 and ref. 3)

(2) Absorptance of zinc-oxide-pigmented white paint exposed for 7000 equivalent sun hours (ESH) of ultraviolet radiation (fig. 6 and ref. 3)

(3) Absorptance of fused silica with second surface silver (often called the optical solar reflector (OSR)) (fig. 7 and ref. 4)

(4) Absorptance of a solar absorber, infrared reflector (fig. 8 and ref. 5)

(5) Reflectance of a SiO coated aluminum mirror (fig. 9 and ref. 6)

(6) Percent efficiency of a typical silicon solar cell (fig. 10 and unpublished data of R. Hart of Lewis)

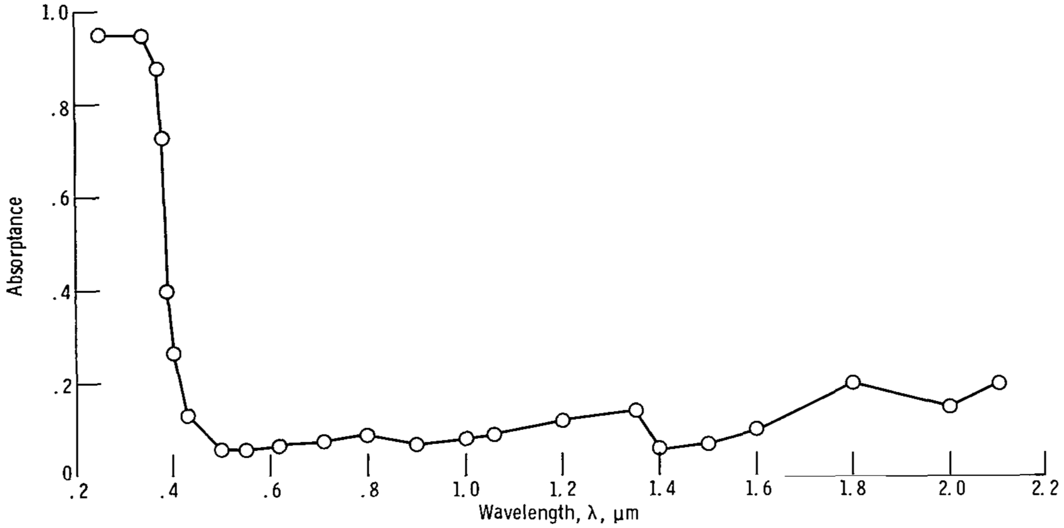

Figure 5. - Absorptance of unexposed white paint as function of wavelength.

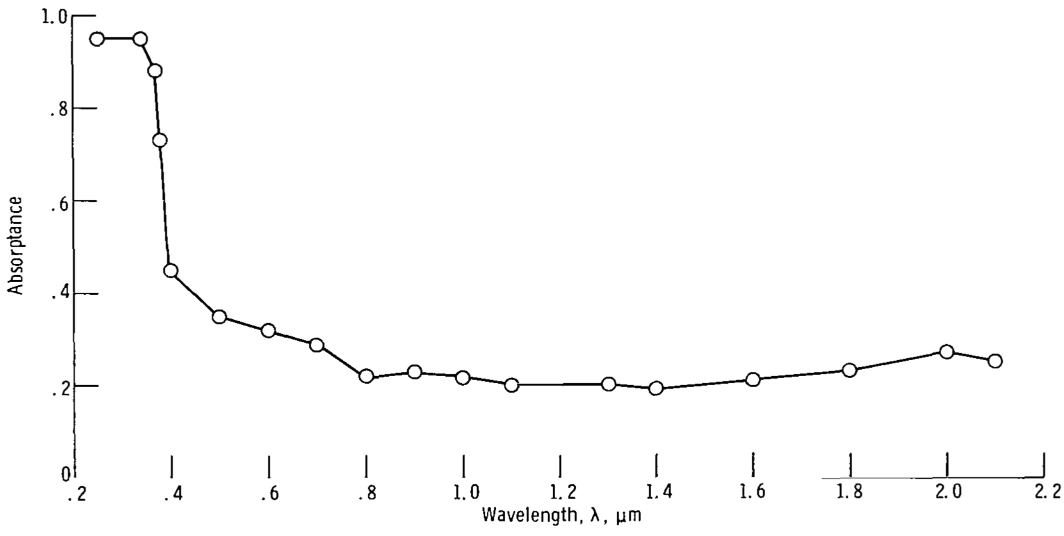

Figure 6. - Absorptance of exposed white paint for 700 equivalent solar hours of ultraviolet light as function of wavelength.

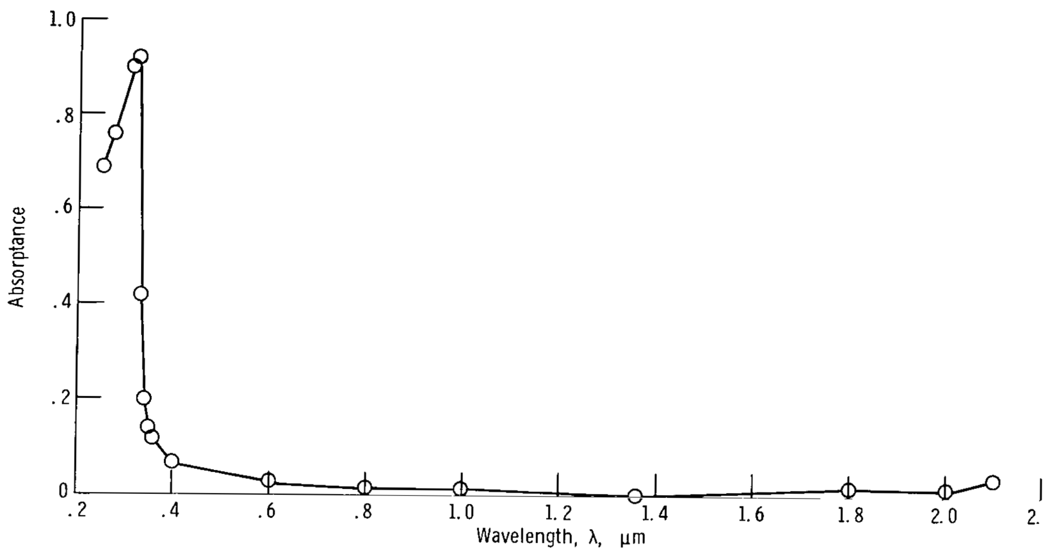

Figure 7. - Absorptance of optical solar reflector as function of wavelength.

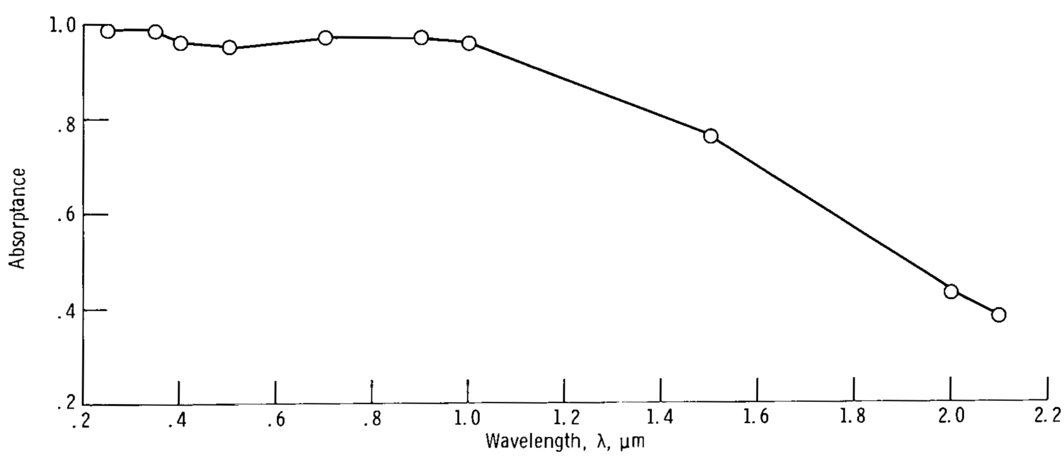

Figure 8. - Absorptance of solar absorber as function of wavelength.

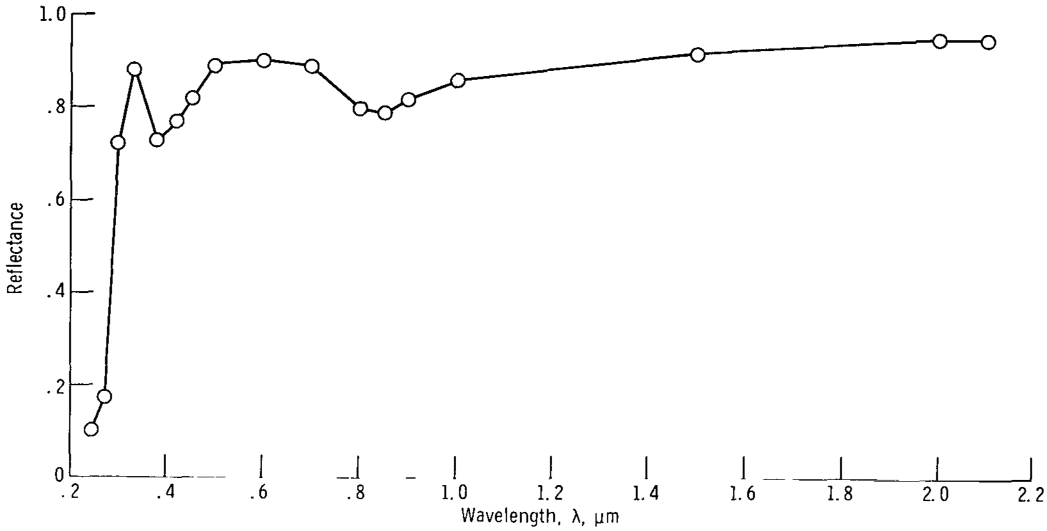

Figure 9. - Reflectance as function of wavelength for aluminum mirror coated with SiO.

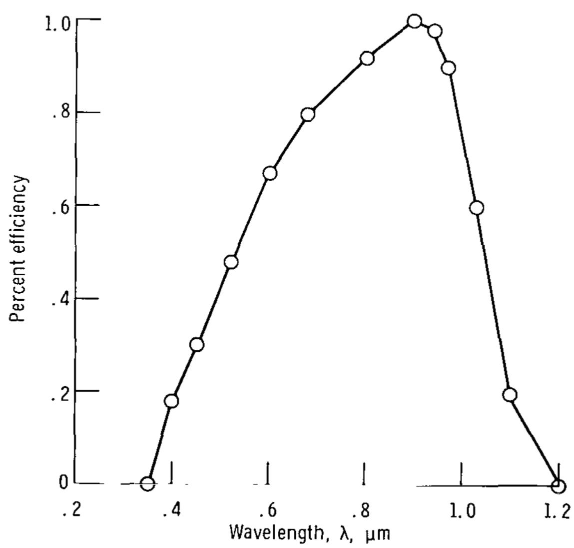

Figure 10. - Percent efficiency as function of wavelength for typical solar cell (response normalized to peak of 1).

TABLE I. - CALCULATED TOTAL RESPONSES AND THEIR PERCENT DEVIATIONS

(a) Percent deviation of total response from total response with Johnson curve for six surfaces

Simulator	Surface						Average of absolute values, percent
	Absorptance of unexposed white paint	Absorptance of exposed white paint	Absorptance of optical solar reflector	Absorptance of solar absorber	Reflectance of aluminum mirror with SiO coating	Response of solar cell	
	Deviation, percent						
Carbon arc	-6	-9	-31	-2	1	-11	10
Xenon lamp	-31	-12	-44	1	1	17	18
Mercury-xenon lamp	100	35	137	0	-2	-36	52

(b) Calculated total responses to various surfaces under different incident irradiance

Incident irradiance	Surface					
	Absorptance of unexposed white paint	Absorptance of exposed white paint	Absorptance of optical solar reflector	Absorbtance of solar absorber	Reflectance of aluminum mirror with SiO coating	Response of solar cell
	Calculated total response					
Carbon arc	0.15	0.31	0.041	0.90	0.86	0.42
Xenon lamp	0.11	0.30	0.033	0.93	0.86	0.55
Mercury-xenon lamp	0.32	0.46	0.14	0.92	0.83	0.30
Johnson curve	0.16	0.34	0.059	0.92	0.85	0.47

Table I(b) shows the calculated total response obtained by using the spectral irradiances and spectral responses as described. These were obtained with the use of equation (1) over the wavelength interval of 0.25 to 2.1 micrometers. An inspection of table I reveals very large differences in the total response of a surface (especially for the white paint and the OSR) under different forms of solar simulation. Table I(a) shows the percent deviation of total response from total response with the Johnson curve for the six surfaces. Also, for each of the three types of simulators, an average percent deviation is calculated. This average is obtained by using the absolute values of the percent deviations for the six different surfaces, and it serves as a rough indication of the match between the Johnson curve and the particular type of simulator. Note that the carbon arc has the lowest deviations, while the mercury-xenon lamp has the largest. These differences generally require that a correction be made to the results of environment tests.

For example, assume that the surfaces of a spacecraft are coated with an unexposed white thermal control paint. The results of an environment test with a xenon lamp solar simulator would generally be a series of temperature measurements for various spacecraft parts. The measured total response must be corrected by a factor 0.16/0.11 (from table I(b)), and the measured temperatures must also be corrected by this factor. However, if the measured spectral irradiance is in error, the corrected total response and the corrected temperatures are also in error.

Responses with Measuring Error in Irradiance

Percent changes in the calculated total response as a function of percent error in spectral irradiance measurement $\Delta\%$ are given in figures 11 to 16. The figures are plotted with $\Delta\%$ ranging only from 0 to 20 percent, with values at nonzero $\Delta\%$ being the largest percent change among either $+\Delta\%$ or $-\Delta\%$. (Negative $\Delta\%$ implies the total response is made as small as possible, while positive $\Delta\%$ maximizes the total response.) In all cases, the absolute value of the percent change in total response is plotted.

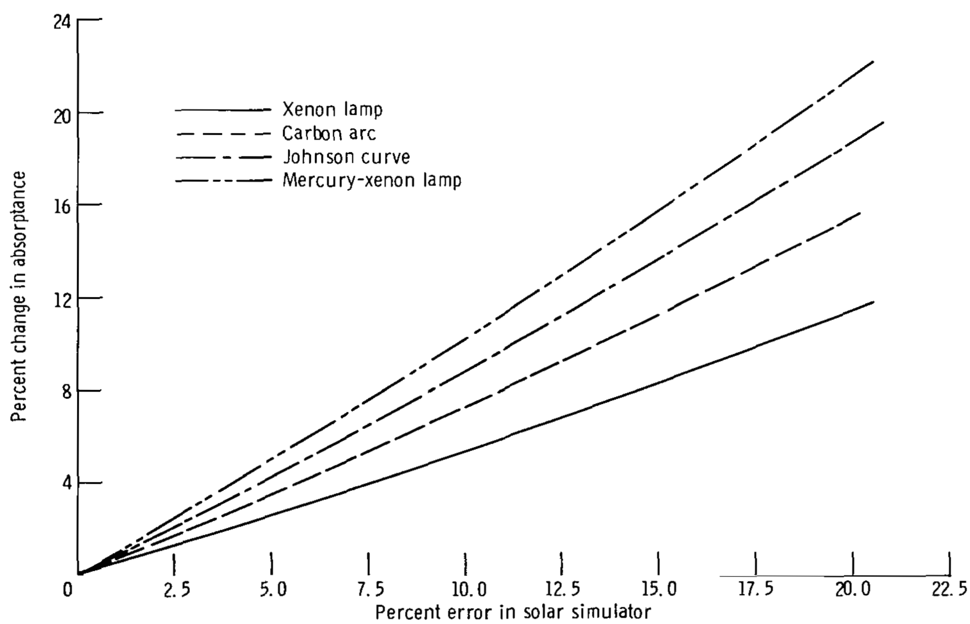

Figure 11. - Percent change in absorptance of unexposed white paint as function of percent error in solar simulator.

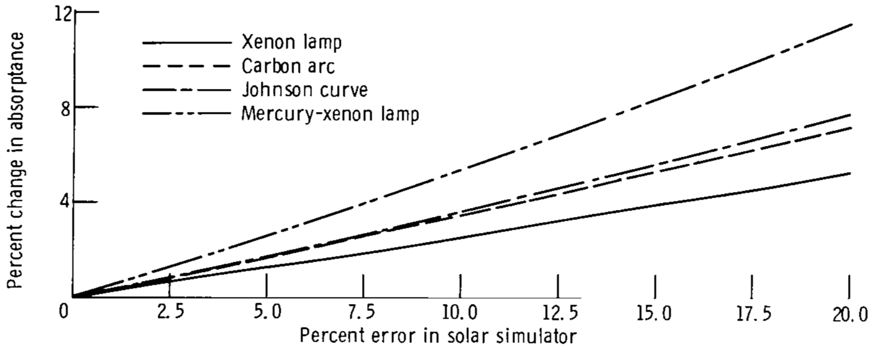

Figure 12. - Percent change in absorptance of exposed white paint as function of percent error in solar simulator.

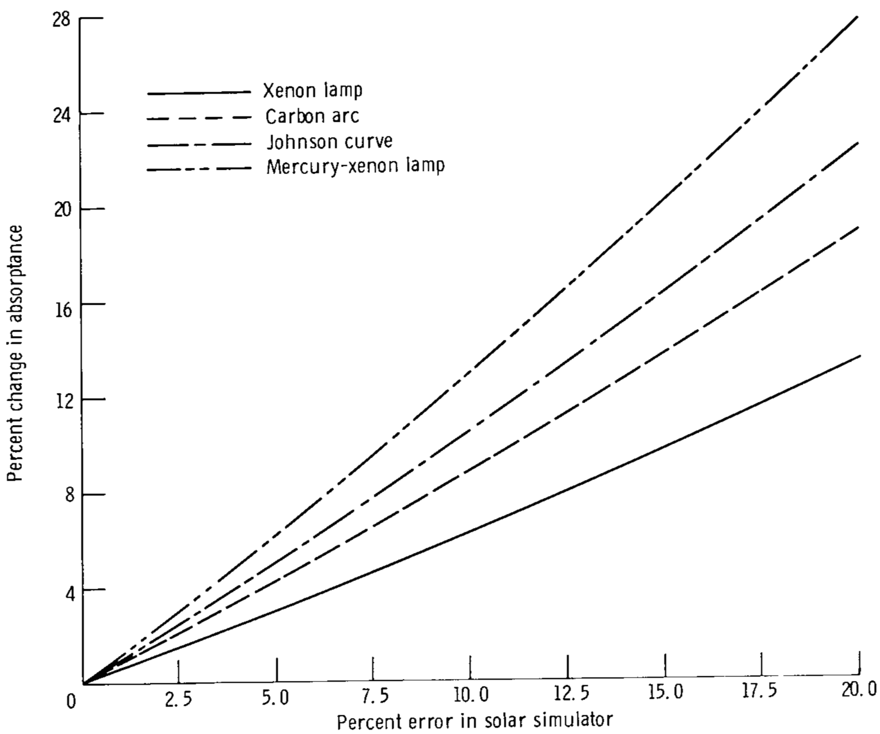

Figure 13. - Percent change in absorptance of optical solar reflector as function of percent error in solar simulator.

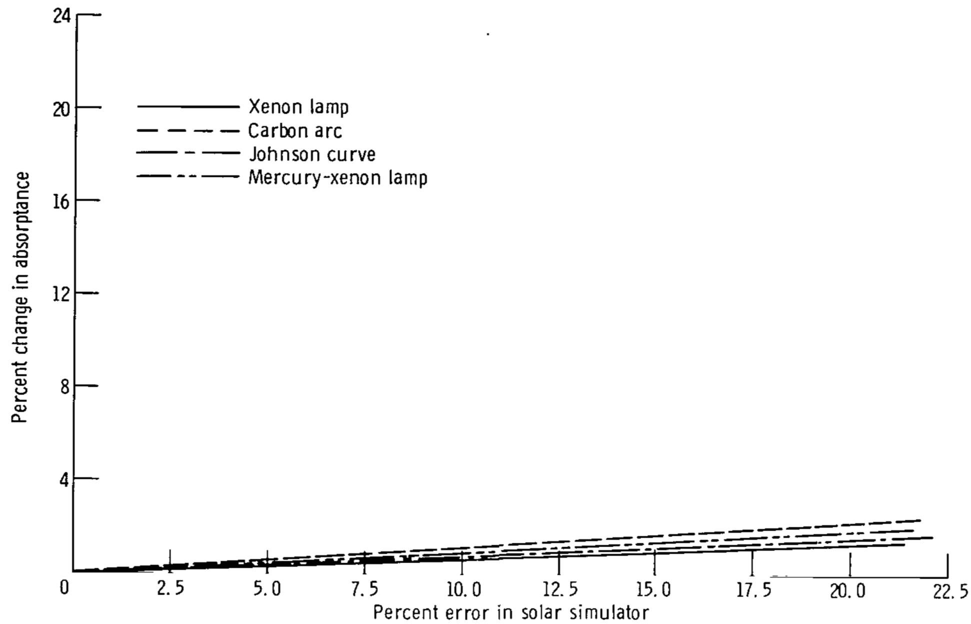

Figure 14. - Percent change in absorptance of solar absorber as function of percent error in solar simulator.

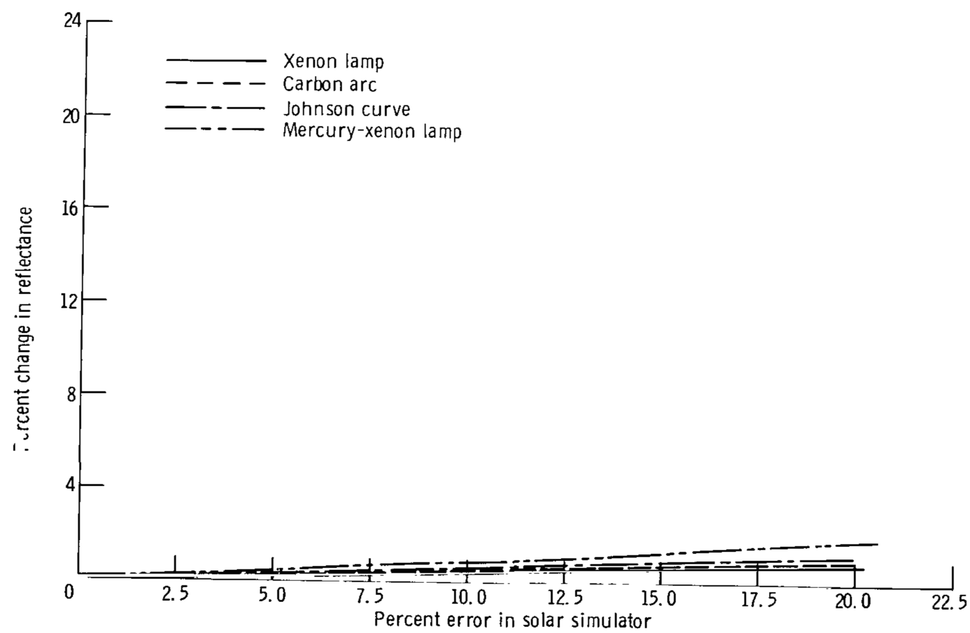

Figure 15. - Percent change in reflectance of aluminum mirror coated with SiO as function of percent error in solar simulator.

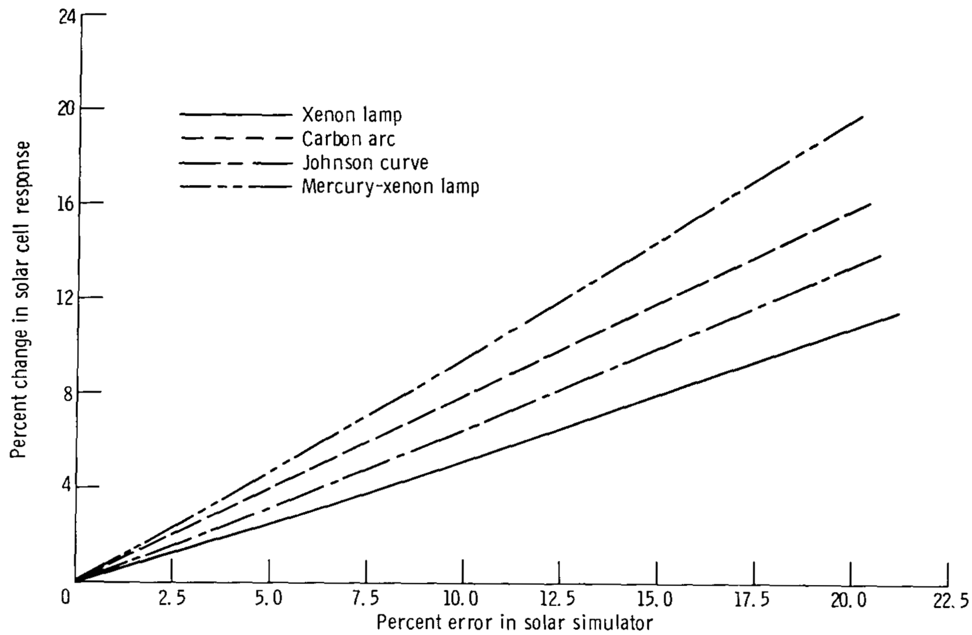

Figure 16. - Percent change in response of silicon solar cell as function of percent error in solar simulator.

Examination of the curves in these figures reveals some similarities. The percent change in total response obviously increases as Δ increases. As a general rule for all six surfaces considered, the mercury-xenon lamp required the most accurate spectral irradiance measurement for a given percent change in response; the xenon lamp required the least accuracy and the carbon arc, an intermediate value. The only exception to this was in the case of the solar absorber, where the carbon arc and the mercury-xenon lamp are interchanged.

The data in figures 11 to 16 may now be used to determine allowable errors for spectral irradiance measurements. For example, consider a white paint surface under a xenon lamp solar simulator. Also assume that the design of the spacecraft dictates that the calculated total absorptance be known within 10 percent. With the use of figure 11, it is seen that an 18-percent-worst-case error in spectral irradiance causes a 10-percent change in absorptance. Hence, any spectral irradiance measurement of the xenon solar simulator (using a similar number of wavelength points) within an 18-percent measurement error will be sufficient. Table II shows the maximum error in spectral irradiance measurements that can be allowed for a 5- or 10-percent error in total response (2 and 5 percent for the silicon solar cell).

The last column of table II shows the ratio of the average measurement error to the total response error. This error ratio was determined by dividing the average of the four measurement errors corresponding to a 5-percent change in total response by

TABLE II. - MAXIMUM ERROR IN SPECTRAL IRRADIANCE FOR

GIVEN ERROR IN TOTAL RESPONSE

Simulator	Surface								Ratio of average measurement error to total response error
	Unexposed white paint		Exposed white paint		Optical solar reflector		Silicon solar cell		
	Given error in total response, percent								
	5	10	5	10	5	10	2	5	
	Maximum error in spectral irradiance, percent								
Carbon arc	7.7	14	14	>20	5.7	11	2.6	6.4	1.7
Xenon lamp	7.4	18	19	>20	7.9	15	3.8	9.4	2.3
Mercury-xenon lamp	5.0	9.7	9.1	18	4.1	7.9	2.1	5.3	1.2

5 percent. With the four surfaces and three sources of table II, the spectral distribution measurement error could be greater than the allowable surface response error by an average factor of 2.3 for the xenon lamp, 1.6 for the carbon arc, and 1.2 for the mercury-xenon lamp.

Examination of the error figures for the other two surfaces (a reflecting mirror and the solar absorber) indicates that very small changes in total response result from spectral irradiance measurement errors as large as 20 percent. Hence, accurate measurements of spectral irradiance are relatively unimportant for tests using the mirror surface and the solar absorber surface. In fact, table I(b) indicates that, even for different types of simulators, the mirror and absorber perform approximately the same. This is attributed to the fact that their spectral responses are nearly flat in the major portion of the solar wavelength range.

In each of figures 11 to 16, there is one more set of data labeled Johnson. These points were obtained using the Johnson curve as a spectral irradiance rather than a measured spectral irradiance of a solar simulator. This Johnson data may be used in two ways:

(1) If a measurement on a solar simulator gives the Johnson curve as a spectral irradiance, the effect on the calculated total response of errors in the spectral measurement could be found.

(2) The second way of looking at the Johnson data is to determine the effect that uncertainties in the actual Johnson curve have on total response. For example, a worst-case 5-percent uncertainty in the Johnson curve results in a 4-percent change in the absorptance of white paint (fig. 11).

Effect of Spectral Resolution

All the calculations discussed so far have used high-resolution monochromator measurements of simulator spectral irradiance. However, spectral irradiance may be measured in a variety of ways. The error effects using different forms of spectral irradiance measurement are now discussed. Another method of measurement utilizes a filter radiometer, which results in a spectrum defined by about 20 points with straight-line interpolation. The irradiance curve was obtained using the data reduction technique of reference 7. This is a much lower resolution curve than a monochromator measurement. The two different measurement techniques were compared by calculating the total response of the six surfaces under the same source measured by the two different systems.

Actual filter measurements were available only for the carbon arc and the xenon lamp. With the use of either the high-resolution monochromator measurement or the low-resolution filter measurement, the calculated total response is almost the same. The largest difference between the total response calculated using the filter radiometer spectrum and the total response using the monochromator spectrum (table I(b)) was 0.004. Hence, a filter radiometer with the data reduction technique of reference 7 gives a spectrum that results in total responses almost identical to those of a higher resolution monochromator measurement of the same solar simulator.

To determine the effects of measurement error in the filter radiometer method, the analysis used with the monochromator spectra was repeated with the filter spectra. The results showed almost identical changes in total response as a function of Δ in the error function. This implies that the same limits of error apply to the filter measurements as apply to the monochromator measurements.

SUMMARY OF RESULTS

The effect of measurement error in the spectral distribution of solar simulators was studied. The effect of the error is to change the calculated total response of a surface. A worst-case error was used which maximizes the change in total response. Any real error in spectral distribution would result in less change in total response. A variety of surface responses and solar simulator distributions were used to obtain the following results:

1. The total response of various surfaces depends on the light source of the solar simulator. With six surfaces and three sources tested, the total response has a fractional deviation from that given by the Johnson curve and averages 10 percent for a carbon arc, 18 percent for a xenon lamp, and 52 percent for a mercury-xenon lamp. This

deviation may be corrected when the spectrum of the source and the surface spectral response are known.

2. The allowable errors in spectral irradiance measurements depend on the spectral response of the surface being irradiated by the solar simulator, the source of energy for the simulator, and the allowed tolerances for total response. With four surfaces and three sources tested, the measurement inaccuracy could be greater than the desired surface response tolerances by an average factor of 2.3 for the xenon lamp, 1.6 for the carbon arc, and 1.2 for the mercury-xenon lamp.

3. Almost identical total responses and accuracy requirements are obtained by using either a high-resolution (≈100 points) monochromator measurement or a low-resolution (≈20 points) filter measurement.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 28, 1970,
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