Standard Practice for
Solar Simulation for Thermal Balance Testing of Spacecraft[1]

This standard is issued under the fixed designation E491; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 *Purpose:*

1.1.1 The primary purpose of this practice is to provide guidance for making adequate thermal balance tests of spacecraft and components where solar simulation has been determined to be the applicable method. Careful adherence to this practice should ensure the adequate simulation of the radiation environment of space for thermal tests of space vehicles.

1.1.2 A corollary purpose is to provide the proper test environment for systems-integration tests of space vehicles. An accurate space-simulation test for thermal balance generally will provide a good environment for operating all electrical and mechanical systems in their various mission modes to determine interferences within the complete system. Although adherence to this practice will provide the correct thermal environment for this type of test, there is no discussion of the extensive electronic equipment and procedures required to support systems-integration testing.

1.2 *Nonapplicability*—This practice does not apply to or provide incomplete coverage of the following types of tests:

1.2.1 Launch phase or atmospheric reentry of space vehicles,

1.2.2 Landers on planet surfaces,

1.2.3 Degradation of thermal coatings,

1.2.4 Increased friction in space of mechanical devices, sometimes called "cold welding,"

1.2.5 Sun sensors,

1.2.6 Man in space,

1.2.7 Energy conversion devices, and

1.2.8 Tests of components for leaks, outgassing, radiation damage, or bulk thermal properties.

1.3 *Range of Application:*

1.3.1 The extreme diversification of space-craft, design philosophies, and analytical effort makes the preparation of a brief, concise document impossible. Because of this, various spacecraft parameters are classified and related to the important characteristic of space simulators in a chart in 7.6.

1.3.2 The ultimate result of the thermal balance test is to prove the thermal design to the satisfaction of the thermal designers. Flexibility must be provided to them to trade off additional analytical effort for simulator shortcomings. The combination of a comprehensive thermal-analytical model, modern computers, and a competent team of analysts greatly reduces the requirements for accuracy of space simulation.

1.4 *Utility*—This practice will be useful during space vehicle test phases from the development through flight acceptance test. It should provide guidance for space simulation testing early in the design phase of thermal control models of subsystems and spacecraft. Flight spacecraft frequently are tested before launch. Occasionally, tests are made in a space chamber after a sister spacecraft is launched as an aid in analyzing anomalies that occur in space.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E259 Practice for Preparation of Pressed Powder White Reflectance Factor Transfer Standards for Hemispherical and Bi-Directional Geometries

E296 Practice for Ionization Gage Application to Space Simulators

E297 Test Method for Calibrating Ionization Vacuum Gage Tubes (Withdrawn 1983)[3]

E349 Terminology Relating to Space Simulation

2.2 *ISO Standard:*

ISO 1000-1973 SI Units and Recommendations for the Use of Their Multiples and of Certain Other Units[4]

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[1] This practice is under the jurisdiction of ASTM Committee E21 on Space Simulation and Applications of Space Technology and is the direct responsibility of Subcommittee E21.04 on Space Simulation Test Methods.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

[4] Withdrawn.

2.3 *American National Standards:*[5]

ANSI Y10.18-1967 Letter Symbols for Illuminating Engineering

ANSI Z7.1-1967 Standard Nomenclature and Definitions for Illuminating Engineering

ANSI Y10.19-1969 Letter Symbols for Units Used in Science and Technology

3. Terminology

3.1 *Definitions, Symbols, Units, and Constants*—This section contains the recommended definitions, symbols, units, and constants for use in solar simulation for thermal balance testing of spacecraft. The International System of Units (SI) and International and American National Standards have been adhered to as much as possible. Terminology E349 is also used and is so indicated in the text. Table 1 provides commonly used symbols.

3.2 *Definitions:*

3.2.1 *absorptance* (α_e, α_v, α)—ratio of the absorbed radiant or luminous flux to the incident flux (E349) (Table 1).

3.2.2 *absorptivity of an absorbing material*—internal absorptance of a layer of the material such that the path of the radiation is of unit length (E349).

3.2.3 *air mass one (AM1)*—the equivalent atmospheric attenuation of the electromagnetic spectrum to modify the solar irradiance as measured at one astronomical unit from the sum outside the sensible atmosphere to that received at sea level, when the sun is in the zenith position.

3.2.4 *air mass zero (AM0)*—the absence of atmospheric attenuation of the solar irradiance at one astronomical unit from the sun.

3.2.5 *albedo*—the ratio of the amount of electromagnetic radiation reflected by a body to the amount incident upon it.

3.2.6 *apparent source*—the minimum area of the final elements of the solar optical system from which issues 95 % or more of the energy that strikes an arbitrary point on the test specimen.

3.2.7 *astronomical unit (AU)*—a unit of length defined as the mean distance from the earth to the sun (that is, 149 597 890 ± 500 km).

3.2.8 *blackbody (USA),Planckian radiator*—a thermal radiator which completely absorbs all incident radiation, whatever the wavelength, the direction of incidence, or the polarization. This radiator has, for any wavelength, the maximum spectral concentration of radiant exitance at a given temperature (E349).

3.2.9 *collimate*—to render parallel, (for example, rays of light).

3.2.10 *collimation angle*—in solar simulation, the angular nonparallelism of the solar beam, that is, the decollimation angle. In general, a collimated solar simulator uses an optical component to image at infinity an apparent source (pseudo sun) of finite size. The angle subtended by the apparent source to the final optical component referred to as the collimator, is defined as the solar subtense angle and establishes the nominal angle of decollimation. A primary property of the "collimated" system is the near constancy of the angular subtense angle as viewed from any point in the test volume. The solar subtense angle is therefore a measure of the nonparallelism of the beam. To avoid confusion between various scientific fields, the use of solar subtense angle instead of collimation angle or decollimation angle is encouraged (see *solar subtense angle*).

3.2.11 *collimator*—an optical device which renders rays of light parallel.

3.2.12 *decollimation angle*—not recommended (see *collimation angle*).

3.2.13 *diffuse reflector*—a body that reflects radiant energy in such a manner that the reflected energy may be treated as if it were being emitted (radiated) in accordance with Lambert's law. The radiant intensity reflected in any direction from a unit area of such a reflector varies as the cosine of the angle between the normal to the surface and the direction of the reflected radiant energy (E349).

3.2.14 *dispersion function* (X/λ)—a measure of the separation of wavelengths from each other at the exit slit of the monochromator, where X is the distance in the slit plane and λ

TABLE 1 Commonly Used Symbols

Symbol	Quantity	Definition Equation or Value	Unit	Unit Symbol
Q	radiant energy, work, quantity of heat		joule	J
Φ	radiant flux	$\Phi = dQ/dt$	watt (joule/second)	W, Js^{-1}
E	irradiance (receiver) flux density	$E = d\Phi/dA$	watt per square metre	$W \cdot m^{-2}$
M	radiant exitance (source)	$M = d\Phi/dA$	watt per square metre	$W \cdot m^{-2}$
I	radiant intensity (source)	$I = d\Phi/d\omega$	watt per steradian	$W \cdot sr^{-1}$
		ω = solid angle through which flux from source is radiated		
L	radiance	$L = dI/(dA \cos\theta)$	watt per steradian = square metre	$W \cdot sr^{-1} \cdot m^{-2}$
		θ = angle between line of sight and normal to surface dA		
τ	transmittance	τ = Φ, transmitted/Φ, incident	none	
$\tau(\lambda)$	spectral transmittance	$\tau(\lambda)$ = Φ(λ), transmitted/Φ(λ), incident	none	
ρ	reflectance (total)	ρ = Φ, reflected/Φ, incident	none	
εH	emittance (total hemispherical)	εH = M, specimen/M, blackbody		
α	absorptance	α = Φ, absorbed/Φ, incident	none	
α_s	solar absorptance	α_s = solar irradiance absorbed/solar irradiance incident	none	

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[5] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

is wavelength. The dispersion function is, in general, different for each monochromator design and is usually available from the manufacturer.

3.2.15 *divergence angle*—see *solar beam divergence angle*(3.2.60).

3.2.16 *electromagnetic spectrum*—the ordered array of known electromagnetic radiations, extending from the shortest wavelengths, gamma rays, through X rays, ultraviolet radiation, visible radiation, infrared and including microwave and all other wavelengths of radio energy (E349).

3.2.17 *emissivity of a thermal radiator* ε, $\varepsilon = M_{e,th}/M_e(\varepsilon = 1)$—ratio of the thermal radiant exitance of the radiator to that of a full radiator at the same temperature, formerly "pouvoir emissif " (E349).

3.2.18 *emittance* (ε)—the ratio of the radiant exitance of a specimen to that emitted by a blackbody radiator at the same temperature identically viewed. The term generally refers to a specific sample or measurement of a specific sample. Total hemispherical emittance is the energy emitted over the hemisphere above emitting element for all wavelengths. Normal emittance refers to the emittance normal to the surface to the emitting body.

3.2.19 *exitance at a point on a surface (radiant exitance) (M)*—quotient of the radiant flux leaving an element of the surface containing the point, by the area of that element, measured in $W \cdot m^{-2}$ (E349) (Table 1).

3.2.20 *field angle*—not recommended (see *solar beam subtense angle*).

3.2.21 *flight model*—an operational flight-capable spacecraft that is usually subjected to acceptance tests.

3.2.22 *flux (radiant, particulate, and so forth)*—for electromagnetic radiation, the quantity of radiant energy flowing per unit time; for particles and photons, the number of particles or photons flowing per unit time (E349).

3.2.23 *gray body*—a body for which the spectral emittance and absorptance is constant and independent of wavelength. The term is also used to describe bodies whose spectral emittance and absorptance are constant within a given wavelength band of interest (E349).

3.2.24 *incident angle*—the angle at which a ray of energy impinges upon a surface, usually measured between the direction of propagation of the energy and a perpendicular to the surface at the point of impingement or incidence.

3.2.25 *infrared radiation*—see *electromagnetic spectrum* (E349).

3.2.26 *insolation*—direct solar irradiance received at a surface, contracted from incoming solar radiation.

3.2.27 *integrating (Ulbrecht) sphere*—part of an integrating photometer. It is a sphere which is coated internally with a white diffusing paint as nonselective as possible, and which is provided with associated equipment for making a photometric measurement at a point of the inner surface of the sphere. A screen placed inside the sphere prevents the point under observation from receiving any radiation directly from the source (E349).

3.2.28 *intensity*—see *radiant intensity.*

3.2.29 *irradiance at a point on a surface* E_e, E; $E_e = d\Phi_e/dA$—quotient of the radiant flux incident on an element of the surface containing the point, by the area of that element measured in $W \cdot m^{-2}$ (E349) (Table 1).

3.2.30 *irradiance, mean total* ($\bar{E}$)—the average total irradiance over the test volume, as defined by the following equation:

$$\bar{E} = \int_v E(r,\theta,z)\,dV \Big/ \int_v dV \qquad (1)$$

where:

$\bar{E}(r,\theta,z)$ = total irradiance as a function of position (Table 1).

3.2.31 *irradiance, spectral [*E_λ *or* $E(\lambda)$*]* —the irradiance at a specific wavelength over a narrow bandwidth, or as a function of wavelength.

3.2.32 *irradiance, temporal*—the temporal variation of individual irradiances from the mean irradiance. The temporal variations should be measured over time intervals equal to the thermal time constants of the components. The temporal stability of total irradiance can be defined as:

$$E_t = \pm 100\left[\left(\Delta E_{t\,(\min)} + \Delta E_{t\,(\max)}\right)/2\bar{E}\right] \qquad (2)$$

3.2.33 *irradiance, total*—the integration over all wavelengths of the spectral irradiance.

3.2.34 *irradiance, uniformity of*—uniformity of total irradiance can be defined as:

$$E_u = \pm 100\left[\left(E_{(\min)} + E_{(\max)}\right)/2\bar{E}\right] \qquad (3)$$

where:

E_u = uniformity of the irradiance within the test volume, expressed as a percent of the mean irradiance,
$E_{(\min)}$ = smallest value obtained for irradiance within the test volume, and
$E_{(\max)}$ = largest value obtained for irradiance within the test volume.

Uniformity of irradiance values must always be specified together with the largest linear dimension of the detector used.

3.2.35 *Lambert's law*—the radiant intensity (flux per unit solid angle) emitted in any direction from a unit-radiating surface varies as the cosine of the angle between the normal to the surface and the direction of the radiation (also called Lambert's cosine law). Lambert's law is not obeyed exactly by most real surfaces, but an ideal blackbody emits according to this law. This law is also satisfied (by definition) by the distribution of radiation from a perfectly diffuse radiator and by the radiation reflected by a perfectly diffuse reflector. In accordance with Lambert's law, an incandescent spherical blackbody when viewed from a distance appears to be a uniformly illuminated disk. This law does not take into account any effects that may alter the radiation after it leaves the source.

3.2.36 *maximum test plane divergence angle*—the angle between the extreme ray from the apparent source and the test plane. This applies principally to direct projection beams where it is equivalent to one half the projection cone angle (see Fig. 1).

3.2.37 *natural bandwidth*—the width at half height of a radiation source emission peak. It is independent of instrument spectral bandwidth, being an intrinsic property of the radiation source.

3.2.38 *penumbra*—see *umbra*.

3.2.39 *Planck's law*—a law giving the spectral concentration of radiant exitance of a full radiator as a function of wavelength and temperature. For the total radiation emitted (unpolarized):

$$M(\lambda,T) = c_1\lambda^{-5}\left(e^{c2\lambda T} - 1\right)^{-1} \tag{4}$$

where:

M = spectral concentration, W·m^{-2};
λ = wavelength, m; and
T = absolute temperature, K.

The constants are:

$$c_1 = 2\pi\, hc^2 = 3.741\,844 \times 10^{-16}\ \mathrm{W\cdot m^{-2}} \tag{5}$$

$$c_2 = hc/k = 1.438\,833 \times 10^{-2}\ \mathrm{m\cdot K}$$

where:

h = Planck's constant,
c = velocity of light in vacuum, and
k = Boltzmann constant.

NOTE 1—It is recommended that the constant c_1 is always used with the meaning noted above. The numerical constants applicable to other aspects of the radiation emitted are shown below. They should be designated c_1 multiplied by an appropriate factor.

πhc^2 = $c_1/2$ (for the exitance of the polarized radiation)
$2hc^2$ = c_1/π (for the radiance of the nonpolarized radiation)
hc^2 = $c_1/2\pi$ (for the radiance of the polarized radiation)
$8\pi hc$ = $4c_1/c$ (for the energy per unit volume of the nonpolarized radiation

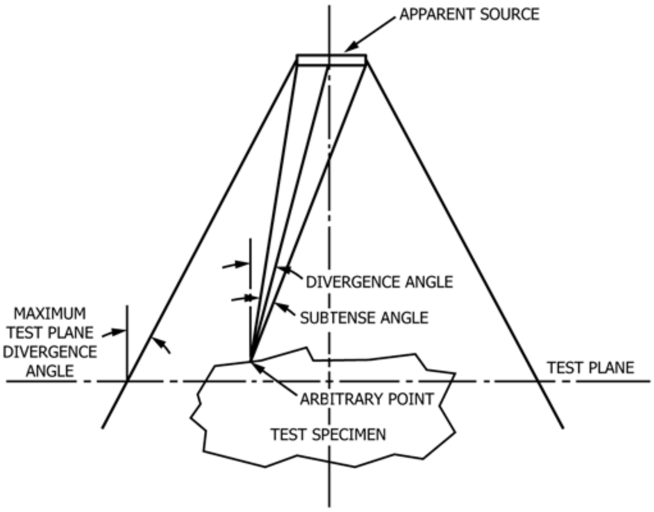

FIG. 1 Solar Subtense and Divergence Angles

3.2.40 *prototype model*—a spacecraft or subsystem that is used for development or qualification test. This is an accurate reproduction of actual space hardware and is identical or nearly identical to the flight model.

3.2.41 *pyranometer*—an instrument that measures the combined solar irradiance and diffuse sky irradiance. The pyranometer consists of a recorder and a radiation-sensing element which is mounted so that it views the entire sky.

3.2.42 *pyrheliometer*—an instrument that measures the direct solar irradiance, consisting of a casing which is closed except for a small aperture through which the direct solar rays enter, and a recorder unit.

3.2.43 *Angstrom compensation pyrheliometer*—an instrument developed by K. Angstrom for the measurement of direct solar irradiation. The radiation receiver station consists of two identical manganin strips whose temperatures are measured by attached thermocouples. One of the strips is shaded, whereas the other is exposed to sunlight. An electrical heating current is passed through the shaded strip so as to raise its temperature to that of the exposed strip. The electric power required to accomplish this is a measure of the solar irradiance.

3.2.44 *radiance (in a given direction, at a point on the surface of a source or receptor, or at a point in the path of a beam)*—quotient of the radiant flux leaving, arriving at, or passing through an element or surface at this point, and propagated in directions defined by an elementary cone containing the given direction by the product of the solid angle of the cone, and the area of the orthogonal projection of the element of surface on a plane perpendicular to the given direction (E349) (Table 1). Symbol: L_e, L; $L_e = d^2\Phi/(d\omega dA \cos\theta)$; measured in W·sr^{-1}m^{-2}.

3.2.45 *radiant flux* (φ)—radiant power, power-emitted, transferred, or received as radiation, measured in W (E349) (Table 1).

3.2.46 *radiant flux (surface)density at a point of a surface*—quotient of the radiant flux at an element of the surface containing the point, by the area of that element (also see *irradiance and radiant exitance*), measured in W·m^{-2} (E349).

3.2.47 *radiant intensity of a source, in a given direction (I)*—quotient of the radiant flux leaving the source propagated in an element of solid angle containing the given direction, by the element of solid angle measured in W · sr^{-1} (E349) (Table 1).

NOTE 2—For a source that is not a point source: The quotient of the radiant flux received at an elementary surface by the solid angle which this surface subtends at any point of the source, when this quotient is taken to the limit as the distance between the surface and the source is increased.

3.2.48 *radiation, monochromatic*—radiation at a single wavelength, and by extension, radiation of a very small range of frequencies or wavelengths.

NOTE 3—Use of the adjective "spectral." When certain properties, such as absorptance or transmittance, and so forth, are considered for monochromatic radiation, and they are functions of wavelength (or frequency or wavenumber, and so forth), the term may be preceded by the adjective "spectral" or by the property symbol followed by the subscript λ, or both; example: spectral transmittance $\tau(\lambda)$ (E349).

3.2.49 *radiometer*—instrument for measuring irradiance in energy or power units (E349).

3.2.50 *radiometry*—measurement of the quantities associated with irradiance (E349).

3.2.51 *reflection*—return of radiation by a surface without change frequency of the monochromatic components of which the radiation is composed (E349).

3.2.52 *reflection, diffuse*—reflection in which, on the microscopic scale, there is no specular reflection (E349).

3.2.53 *reflection, mixed*—partly specular and partly diffuse-reflected (E349).

3.2.54 *regular (specular)reflection* —reflection without diffusion in accordance with the laws of optical reflection (E349).

3.2.55 *resolution*—a qualitative term relating to the fidelity of reproduction of the natural band (both in height and width). An emission peak is said to be completely resolved when the observed band is practically identical to the natural band. Fig. 2 shows the relationship between resolution (observed peak height/true peak height) and the ratio of spectral bandwidth to natural bandwidth. Note that when this ratio is small, the deviation from true peak height is small, the fraction being 99.6 % at a ratio of 0.1.

3.2.56 *reflectance* (ρ)—ratio of the reflected radiant or luminous flux to the incident flux (E349) (Table 1).

3.2.57 *reflectivity*—reflectance of a layer of material of such a thickness that there is no change of reflectance with increased thickness (E349).

3.2.58 *slit width*—the physical width of a monochromator slit opening. In general, all slits should be equal in width at all times. The exit defines the wavelength bandwidth directed to the detector. The energy incident upon the detector varies as the square of the slit width.

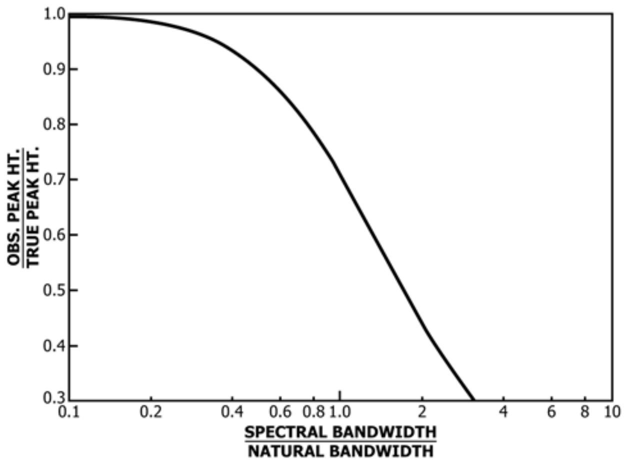

FIG. 2 Relationship of Peak Height to Spectral Bandwidth/Natural Bandwidth Ratio

3.2.59 *solar absorptance* (α_s)—the ratio of the absorbed solar flux to the incident solar flux (Table 1).

$$\alpha = \int_0^\infty \alpha(\lambda)E(\lambda)d\lambda / \int_0^\infty E(\lambda)d\lambda \qquad (6)$$

3.2.60 *solar beam divergence angle*—the angle measured from a line extending from the center of the apparent source to an arbitrary point in the test volume and to a line parallel to the principal axis of the solar beam (see Fig. 1).

3.2.61 *solar beam incident angle*—the angle measured from a line extending from the center of the apparent source to an arbitrary point on the test specimen and the surface normal at that point.

3.2.62 *solar beam subtense angle*—that angle subtended by the maximum dimension of the apparent source at an arbitrary point on the test specimen (see Fig. 1).

NOTE 4—The terms "collimation angle" and "field angle" are sometimes used for "subtense angle." The term "subtense angle" is preferred.

3.2.63 *solar constant*—the total solar irradiance at normal incidence on a surface in free space at the earth's mean distance from the sun (1 AU).

NOTE 5—The current accepted value of 1AU is 1353 ± 21 $W \cdot m^{-2}$ and is subject to change.

3.2.64 *space environment simulation*—a laboratory duplication of one or more of the effects of the space environmental parameters on a spacecraft, components, or materials. The natural environmental parameters include vacuum-pressure, particulate radiation, electromagnetic radiation, and meteroid radiation. Induced environmental parameters include vibration, shock, and acceleration. The effects can include thermal balance, heat transfer, material property change, operational/mechanical subsystem problem, and subsystem functional testing.

3.2.65 *spectra, line*—the spontaneous emission of electromagnetic radiation from the bound electrons as they jump from high to low energy levels in an atom. This radiation is essentially at a single frequency determined by the jump in energy. Each different jump in energy level, therefore, has its own frequency and the net radiation is referred to as the line spectra. Since these line spectra are characteristic of the atom, they can be used for identification purposes.

3.2.66 *spectropyrheliometer*—an instrument that measures the spectral distribution of direct solar irradiance.

3.2.67 *spectroradiometer*—an instrument for measuring the spectral concentration of radiant energy or radiant power, also called "spectrometer" (E349).

3.2.68 *spectrum, continuous*—a spectrum in which wavelengths, wavenumbers, and frequencies are represented by the continuum of real numbers or a portion rather than by a discrete sequence of numbers (see *spectra*). For electromagnetic radiation, it is a spectrum that exhibits no detailed structure and represents a gradual variation of intensity 0 with wavelength from one end to the other, such as the spectrum from an incandescent solid.

3.2.69 *spectral filter*—an optical component that is spectrally selective, or any optical component that rejects radiation in spectral regions to shape the resulting spectral distribution.

3.2.70 *Stefan-Boltzmann law*—the relation between the radiant exitance of a blackbody radiator and its temperature.

$$M = \sigma T^{4} \tag{7}$$

where the constant of proportionality (σ) is called the Stefan-Boltzmann constant and has a value of $5.669\,61 \times 10^{-8}$ W · m^{-2} K^{-4}.

3.2.71 *subtense angle*—see *solar beam subtense angle*.

3.2.72 *test volume, simulator*—the total volume within the space environmental chamber that can simulate the desired effects.

3.2.73 *test volume, spacecraft*—the volume occupied by the spacecraft within the space simulation chamber throughout the duration of the test. Unless otherwise specified, test volume is meant to mean spacecraft test volume.

3.2.74 *thermal analytical model*—a mathematical model of the thermal characteristics of a spacecraft that is usually solved using a computer.

3.2.75 *thermal balance test*—a test or series of tests conducted upon a spacecraft or model to determine the temperatures in space under normal or extreme operating conditions. Both transient and equilibrium conditions can be simulated.

3.2.76 *thermal radiator*—source-emitting by thermal radiation (E349).

3.2.77 *thermopile*—a transducer for converting thermal energy directly into electrical energy, composed of pairs of thermocouples which are connected either in series or in parallel.

3.2.78 *transmission*—passage of radiation through a medium without change of frequency of the monochromatic components of which the radiation is composed (E349).

3.2.79 *transmittance (τ)*—ratio of the transmitted radiant flux to the incident flux (E349) (Table 1).

3.2.80 *ultraviolet radiation*—see *electromagnetic spectrum* (E349).

3.2.81 *umbra*—the darkest part of a shadow in which light is completely cut off by an intervening object. A lighter part surrounding the umbra, in which the light is only partly cutoff, is called *penumbra*.

3.2.82 *visible radiation*—see *electromagnetic spectrum* (E349).

3.3 *Commonly Used Constants*—The values of the physical constants presented below are taken from Refs (**1**) and (**2**).[6] The constants are subject to change and the latest available supplied by the National Bureau of Standards should be used.

Symbol	Constant	Value
c	velocity of light in vacuum	$2.997\,925 \cdot 10^{8}$ m·s^{-1}
h	Planck's constant	$6.626\,196 \cdot 10^{-34}$ J · s
c_1	first radiation constant	$3.741\,844 \cdot 10^{-16}$ W· m^{2}
c_2	second radiation constant	$1.438\,833 \cdot 10^{-2}$ m · K
b	Wien displacement constant	$2.899\,78 \times 10^{-3}$ m·K
σ	Stefan-Boltzmann constant	$5.669\,61 \times 10^{-8}$ W · m^{-2} · K^{-4}

4. Summary of Practice

4.1 Thermal balance testing of spacecraft can be performed in many ways. The specific methods depend upon such items as the spacecraft design, the characteristics of the available simulator, the mission requirements, the cost, and the schedule. Therefore, it is not desirable or possible to include all thermal balance tests in one test method.

4.2 This practice defines terms, discusses test requirements and instrumentation, and reviews general procedures, safety, and maintenance. The test, instrumentation, and thermal engineers must provide the detailed test method that will satisfy their particular requirements and they must be fully aware of the effects of the necessary deviations from the ideal.

5. General Considerations

5.1 The use of solar simulation for thermal balance testing of spacecraft imposes a number of specific technical requirements and methods. The general considerations covered here relate more to the philosophical bases of the various thermal balance tests rather than to their specific implementation.

5.2 A space program can be said to have its own unique characteristics and problems and the same can be said for each test facility. The characteristics of both the facility and the test item must be considered in the definition of the thermal balance tests. First, however, one must establish the purpose of the test and determine what must be proved or verified. Second, one may devise an excellent test program assuming no monetary, schedule or facility limitations. Finally, one may recognize the restraints and establish a set of meaningful compromises.

5.3 This section is separated into four parts:

5.3.1 Purposes or reasons for performing thermal balance tests. Each test rationale is related to a specific model of the spacecraft; that is, the thermal control model, the qualification model, or prototype, and the acceptance or flight model. On each of these the test is performed for a slightly different reason.

5.3.2 *Ideal Thermal Balance Test Program*—This is the program that would be performed if there were no restraints, such as cost, schedule, and facility limitations. This ideal test is also described in terms of thermal control model, prototype model, and flight model spacecraft.

5.3.3 Tradeoff considerations that should be examined before establishing the final test program, and typical test configurations.

5.3.4 Definition and content of the selected program.

5.4 *Purpose of Thermal Balance Testing*—The severity of the space thermal environment demands a thorough verification of the thermal design of the spacecraft and its subsystems. To do this, a number of spacecraft models are tested within a given program. Usually these include a thermal control model,

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[6] The boldface numbers in parentheses refer to the list of references at the end of this practice.

a prototype, and one or more flight models. In each of these test exposures there are specific, but slightly different reasons, for performing the test.

5.4.1 *Thermal Control Model (Development Test)*—The purpose of the thermal balance test of the thermal model is to obtain empirical data relating to the spacecraft thermal properties. These data are in the form of temperature measurements provided by temperature transducers distributed throughout the spacecraft. In some cases, as many as several hundred locations are monitored. During the test exposure various spacecraft operational modes may be simulated as well as external thermal inputs from solar, earth, and lunar simulators. The test item normally has dummy electronic assemblies which provide a simulation of the mass and thermal dissipation of the actual units. Both passive and active thermal control techniques are tested in this manner. The data derived from the thermal control model test may be used to refine the mathematical model, if one exists, or may be used directly by the thermal analyst to assess the adequacy of the thermal design.

5.4.2 *Prototype (Qualification Test)*—The configuration of the spacecraft used for qualification testing is closely representative of that of the flight vehicle. The thermal balance test performed on this model gives the opportunity, once again, to verify the thermal design and also to evaluate any changes made due to thermal model test results. The test method here includes exposure of the spacecraft to as realistic a space environment as possible and also, perhaps, to some unrealistic but readily definable thermal environments. The accurate simulation of the space environment allows a determination of in-space operating temperatures. The thermal inputs that do not simulate space conditions may be used in some cases to determine the spacecraft thermal response. Perhaps the most important aspect of the qualification test is the verification of spacecraft functional operation while all components are at, or near, their in-space thermal conditions (both transient and steady-state).

5.4.3 *Flight Model (Acceptance Test)*—The thermal balance test on a flight spacecraft provides assurance of satisfactory operation in space. The purpose of the test is to indicate any deficiencies, either functional or thermal, that may only be recognizable under thermal-vacuum conditions. Frequently, this test is the final check of the thermal systems and spacecraft functional performance before launch.

5.5 *The Ideal Thermal Balance Test Program*—It is desirable to outline a test program that will satisfy all test objectives, and provide the highest possible confidence in the reliability of the spacecraft. This idealistic planning may be done without considering many of the normal restraints such as cost, schedule, and facility limitations. However, when the restraints are imposed, the compromises, as discussed in 5.6, tend to highlight those areas where deviations from this ideal have been made. The method of implementation and the test results will be different for each model of the spacecraft, since the test exposure is specifically arranged to satisfy the desired objectives.

5.5.1 *Thermal Control Model Test*—The design of the ideal thermal control model spacecraft test includes two test concepts. One of these test concepts involves the accurate simulation of all significant characteristics of the space environment, the orbital conditions, and the precise control of spacecraft operational modes. Since this concept leads to test results that match the response that would be obtained under real space flight conditions, an analytical (mathematical) thermal model may not be necessary. A second test concept involves a known deviation from accurate simulation of all significant characteristics. A prime purpose of this test is frequently the verification of the thermal analytical model. Often arbitrary test conditions may be more accurately controlled and more reproducibly established than the true space environment can be simulated. These known thermal inputs may then be inserted as forcing functions for a computer run of the analytical model, thus providing a basis for the prediction of in-chamber temperatures. The success of these predictions establishes the validity of the analytical model. The arbitrary test-condition exposures need not replace an accurate orbital simulation, but often are performed in addition to it. The ideal thermal control model test conditions should have no unknown thermal inputs. Among the things that should be known are the differences between the solar simulator and the real in-space sun, thermal radiative emission, and reflection from chamber walls (even at liquid nitrogen temperatures).

5.5.2 *Prototype (Qualification) Test*—The prototype spacecraft is normally used for qualification tests. Typically it is near flight configuration, with all subsystems capable of performing their normal functions. The ideal qualification test will include some test exposures that are identical to those used on the thermal control model. This provides a further verification of the thermal design, particularly of any parts of the thermal subsystem modified as a result of thermal control model testing. The most significant result of the qualification spacecraft test exposure is proof of the functional performance of all spacecraft subsystems, in addition to the thermal subsystem. To achieve this end, and to demonstrate system design margins, an environment is produced that thermally stresses all systems more severely than they will be stressed by the anticipated space conditions. In conjunction with the thermal stresses, functional design margins are also verified by operation at high and low bus voltages and at various input signal threshold conditions.

5.5.3 *Flight Model (Acceptance) Test*—The final thermal balance test is performed on flight spacecraft before launch. The ideal test is one in which the simulated conditions are representative of all of those that will be experienced in flight. Extreme hot, cold, and transient conditions should be simulated as well as nominal operations. Again, the functional design margin, as represented by bus voltage and control signal tolerances, is demonstrated concurrently with the verification of the thermal design. Ideally, this would be a long duration test, and would include numerous temperature cycles from hot to cold extremes. This technique has a relatively high probability of exposing infant mortalities and marginal operations due to component parameter drift.

5.6 *Tradeoff Considerations*—It is not usually possible to have as complete and rigorous a test program as the one described in 5.5. Among the restraints to be considered are the costs, in terms of money and schedule, and, as detailed in

Section 7, the characteristics and limitations of the existing test facilities, as well as the nature of the spacecraft and its mission parameters.

5.6.1 *Cost and Schedule*—The cost per hour to operate a major environmental test facility must enter into each decision about the duration of test exposures. The more desirable long duration tests are much more costly. Costs include not only the environmental test facilities personnel and materials, but also the supporting spacecraft personnel and data reduction activities. On flight spacecraft the space simulation test comes very late in the integration sequence. At this time in a space program there is usually a considerable schedule urgency to meet a launch date commitment. These cost and schedule factors must be examined in terms of reliability as well as spacecraft requirements. For example, there are specific technical factors in addition to the subjective view that a longer test is a better test. The thermal time constant of the spacecraft, that is, the time required to reach an equilibrium condition under a given set of thermal inputs, establishes a minimum duration for thermal design verification. For qualification and acceptance spacecraft, this may be further extended by the minimum length of time required to perform a complete spacecraft functional test.

5.6.2 *Facilities*—The test facility itself provides the major influence on test tradeoffs and configuration. The size of the available chamber, the method of loading it (that is, top, bottom, side, and so forth), and the direction of incidence of the solar simulator beam, are all important factors. Among other things, these tend to determine the basic geometry of the support fixture. The fixture design is also influenced by spacecraft orbital characteristics such as spin rate and sun angles, and by thermal influences, including conduction errors into and out of the fixturing and shadowing from various sources. The solar-simulator characteristics must be thoroughly understood to allow proper test evaluation. Major factors are spectrum, total-beam irradiance, uniformity of irradiance in the total test volume, solar beam divergence angle, and temporal variations. These factors, together with recommended tradeoffs, are discussed in 7.2 and 7.5.

5.6.3 *Spacecraft and Mission Parameters*—Each spacecraft and each mission presents unique characteristics which must be considered in the design of the test exposure. For attitude-stabilized planet-oribiting spacecraft, the orientation with respect to run and planet has considerable thermal influence. The altitude of the orbit determines the amount of albedo and earth emission that must be simulated or accounted for. The structure of the spacecraft also has an effect in the amount of self-shadowing by appendages and solar paddles. Along this same line there may be extraneous heat sources. An example is the use of nuclear generators for power sources on deep-space missions. There are some spacecraft, or spacecraft subsystems, in which the test item surface temperature is so high (for example several hundred degrees Fahrenheit) that it may be necessary to use a liquid nitrogen temperature cold wall in the chamber. All of these things are considered in the tradeoffs which lead to a optimum test design. 7.3 and 7.4 cover the subject in more detail.

5.7 *Final Test Definition*—The final test plan should be evaluated in terms of test adequacy after careful consideration of the objectives and facility capabilities. In the case of the thermal control model test, the evaluation consists of assessing the fidelity of the space simulation and the completeness and accuracy of the instrumentation. The qualification and acceptance tests pose a somewhat more complex problem since all subsystems must be tested. A matrix of test objectives, facility characteristics, and spacecraft and mission parameters may be prepared to assist in the final test definition. For a complete systems integration test, this matrix is very complex and certainly is beyond the scope of this recommended practice. However, a matrix is provided in 7.6 for the thermal balance testing phase only. The final test definition is a pyramid formed by the many materials tests, subsystem tests, and supporting analysis which all provide confidence in meeting the overall objectives. Several examples of test facility configurations are given to illustrate special conditions which may influence the test design.

5.7.1 *Variable Solar Flux Vector*—Most spacecraft do not maintain a constant orientation with respect to the sun. The change in altitude may occur at the orbital period, seasonally, during spacecraft maneuvers, or at other times depending upon the mission profile. The simulation of different solar flux angles may be accomplished by physically moving the spacecraft to the desired position within the stationary solar beam. In some instances, especially with spin-stabilized spacecraft, the mechanical complexity of producing a variable-spin axis handling fixture precludes this approach. An equally effective test method uses a movable mirror to redirect the solar beam to the desired angle. Tests have been successfully performed in this manner using plane mirrors up to 100 ft^2 in area. The use of a remotely positionable mirror frame may permit the stimulation of summer, equinox, and winter incident angles on a spinning, geosynchronous spacecraft without returning the chamber to atmospheric pressure.

5.7.2 *Stationary Test of Spinning Spacecraft*—It is sometimes necessary to perform a stationary test on a spacecraft that is designed to spin in orbit. An example of this is a communications satellite on which the transponders must be connected to the test equipment by waveguides or coaxial cables, which precludes the use of sliprings. This thermal balance test may be accomplished by a circumferential tungsten lamp array.

5.7.3 *Combined Solar Sources*—A combination of tungsten or infrared sources may have to be used in conjunction with a spectrally accurate source if the high quality source does not irradiate a large enough area. Whenever this technique is used, it is essential to consider all of the effects of the differences between the sources in spectrum, subtense angle, and divergence angle. These aspects are discussed more thoroughly in 7.1 and 8.5.1.

6. Safety Considerations

6.1 *Purpose*—The purpose of this section is to recommend procedures that will help to ensure the safety of persons (including casual observers) associated with the use, operation, and maintenance of solar simulators.

6.2 *Scope*—Potential hazards are discussed in terms of what they are, their damage or consequences, and their exposure rates and times (where applicable). The hazards have been categorized into mechanical, chemical, electrical, radiation, thermal, and miscellaneous hazards. The prevention of hazards and the protection and care of the victims are also discussed. Only those hazards and injuries peculiar to solar simulation are included.

6.3 *General Instructions:*

6.3.1 Whenever a solar simulator, laser, or similar equipment is being operated, suitable warning signs should be clearly displayed at all entrances to the work area. A complete list of safety procedures appropriate to the facility should be clearly and prominently displayed.

6.3.2 Every person who may be operating in the work area should be informed to the hazards involved, safety precautions to be taken, and supervisory or medical personnel to be contacted in case of accidents. All operational personnel should be required to observe appropriate safety measures at all times. Experienced personnel should provide an example for new employees and visitors by observing rules of safety.

6.3.3 Most large industrial facilities and government installations employ medical and safety personnel. The expertise of these departments should be used. Local, state, or Federal safety requirements differ, and the safety officer or industrial hygienist is in the best position to be informed regarding these standards, which should include periodic checkups. Cooperation between operational and safety personnel should be supported and encouraged whenever possible.

6.4 *Safety Consciousness*—The keys to an effective safety program are awareness of special and ordinary hazards, common sense, and safe working habits. A person who is aware of the hazards of a particular job (without being overly cautious) is less likely to be hurt than one who thinks that safety procedures are unimportant or designed for less knowledgeable people. Awareness and common sense together compose safety consciousness, the opposite of the feeling, "it can't happen to me." A few rules to increase safety consciousness are:

6.4.1 Read the safety handbook, and also learn all the special hazards and necessary safety precautions relating to the equipment or material.

6.4.2 Become familiar with the equipment used and the material or item on which work is being done.

6.4.3 Be alert for any unsafe conditions in the work area and correct them or bring them to the attention of supervisors or the safety representative.

6.4.4 Learn the proper exit route in case of fire or other danger.

6.4.5 Learn where first aid kits, fire extinguishers, and other safety equipment are located.

6.4.6 Use the "buddy system" described as follows: The "buddy system," long established for hazardous situations in industry and elsewhere, is designed to provide immediate help in case of accidents and, in most cases, will help to avoid serious accidents. Its prime purpose is to ensure that no person works alone on a dangerous job; there is always a "buddy" to help in case of danger or accident.

6.5 *First Aid*—A knowledge of first aid on the part of as many persons as possible is an essential part of any safety program. All personnel involved in potentially hazardous operations should be acquainted with the basic principles of first aid; indeed it would be desirable for all personnel to have such knowledge. In addition, it is essential that certain key personnel in each operation have a thorough grounding in first aid techniques, particularly those relating to the special hazards of their own jobs. Appropriate first-aid texts are referenced (Refs 3-9).

6.6 *Discussion of Hazards:*

6.6.1 *Mechanical Hazards*—Mechanical hazards involve those hazards which could produce physical injury to personnel or equipment. They can be caused by exploding high-pressure lamps, implosion of vacuum windows, falls, ruptures, high-pressure systems, structural hazards, lifting and handling, rotating machinery, and so forth.

6.6.1.1 *Exploding High-Pressure Lamps*—A compact arc lamp, when in use, is at a high internal pressure. The 20- and 30-kW lamps carry approximately 3 atm cold and 10 to 15 atm when hot. Pressures in small lamps are considerably higher. The lamp is subject to failure at any time, and the damage to both equipment and personnel can be extreme. Proper shielding and safety precautions must be considered to protect personnel when observing and handling these high-pressure lamps. Recent tests indicate that the small lamps (up to 5 kW) are in many cases more dangerous then large lamps (20 to 30 kW). If depressurization of the lamps (see Ref (7)) is not possible, they must be kept in their protective covers until the last possible moment. Safety glasses are a necessity whenever lamps are being handled. The presence of a safety cover around a lamp should not build one into a sense of overconfidence. Protective clothing, suitable for handling these lamps, is necessary.

6.6.1.2 *Implosion of Vacuum Windows*—Because of excessive expansion (from the heating of a vacuum window by the solar beam), improper cushioning, or impact, and so forth, glass view windows, solar entrance ports, or bell jars might implode. Any vacuum implosion can impart considerable velocity to the pieces of material involved. These may receive sufficient energy to pass through the center of the implosion and continue out the other side as an outward-bound projectile. Such projectiles can pass through glass windows and injure anyone nearby. Adequate provision for window expansion and keeping window surfaces clean of contaminants will minimize the hazards. Screens or shields around *all* glass ports are necessary to protect observers and operators from injury.

6.6.2 *Chemical Hazards*—A chemical hazard is any hazard that has the capacity to produce personal injury or illness through indigestion, inhalation, or absorption through any body surface. Many of the chemicals, solvents, and metals used in solar simulation testing have known toxic properties, and standard handbooks on toxic materials can be contacted for easy reference. Accidents involving toxic materials often can leave the victim blinded or disfigured for life. Toxic materials associated with solar-vacuum simulation testing are ozone, mercury, cadmium, and carbon arc fumes. Nontoxic but suffocating gases include nitrogen. Gases heavier than air will accumulate near the floor and low areas, while gases lighter than air (for example, N_2) will accumulate near the ceiling or elevated areas. Areas where gases accumulate should be recognized as hazardous and the proper ventilation should be provided.

6.6.2.1 *Ozone—*Ozone is produced by exposing oxygen in the air to ultraviolet light. It is a strongly oxidizing gas which attacks metal and rubber rapidly. In humans, ozone primarily affects the respiration system. Exposure of short duration to air concentrations of ozone in excess of a few tenths of a part per million (ppm) can cause discomfort to exposed individuals in the form of a headache and dryness of the throat and the mucous membranes of nose and eyes. The industrial limit for an 8-h exposure is set at 0.1 ppm. Ozone is detectable by smell; however, it is a subtle hazard in that personnel working in an area where ozone is being introduced have a tendency to miss early detection of the gas. Personnel entering an ozone-contaminated area from a different environment have much greater sensitivity and can smell the health hazard. If personnel think that they smell ozone, they should contact the safety officer and leave the area. The safety officer should measure the ozone concentration in the area and determine if a hazard exists.

6.6.2.2 *Mercury—*Many types of high-pressure short arc lamps use mercury in combination with other gases. If the mercury enters the laboratory environment through lamp explosions or other means, a definite safety hazard exists. Suitable mercury detectors should be installed in locations where the possibility of mercury contamination exists. Although it is a metal, mercury evaporates at ordinary room temperature, and its volatility is rapidly augmented by relatively small temperature increases. An exploding mercury lamp is particularly dangerous because the entire content is released as vapor; therefore, a considerable quantity may be inhaled in one or two breaths by someone nearby. If a lamp-explosion spillage should occur, the area involved should be sprinkled generously with sulfur power. Allow the sulfur to remain for at least 1 h so that it can react with the mercury, then scrape the contaminated sulfur and dispose of it in a sealed container. Good housekeeping practices are very important in the control of mercury both in the simulator and the adjoining areas. While liquid mercury can be absorbed through the skin, its effect on the body is unclear. Therefore, skin contact should be avoided whenever possible and protective clothing should be worn. Symptoms of mercury poisoning are not immediately detectable and may not show up until several years later. Some symptoms are chronic nervousness, restlessness, and shaky handwriting. Acute symptoms can be bloody discharges, abdominal pains, and so forth.

6.6.2.3 *Cadmium—*Cadmium is used as a protective plating on iron and steel articles, as an ingredient in many solders, and frequently as a pigment in yellow, orange, and red paints. Welding, soldering, or any high-temperature heating of cadmium or cadmium-plated parts can produce toxic fumes.

6.6.2.4 *Carbon Arc Fumes—*The burning of carbon arcs produces toxic fumes. Adequate ventilation in the form of a hood or open system exhausting to the outside of the building must be provided.

6.6.2.5 *Nitrogen—*Nitrogen is commonly used to purge simulators of oxygen to minimize the production of ozone and to backfill chambers to minimize condensation of moisture on cold surfaces. The hazard connected with gaseous nitrogen is that pure nitrogen will cause rapid anoxia. Complete deprivation of oxygen for 5 min can cause death. Anoxia usually is insidious and one is not aware of anything wrong until one is on the verge of collapse. Thus, it is extremely important to prevent conditions in which anoxia may occur. Adequate ventilation should precede the entering of simulators or facilities where nitrogen is used. Oxygen-concentration monitors must be used when backfilling large chambers with gaseous nitrogen to ensure that a safe level of oxygen (>18 %) exists before personnel enter the facility.

6.6.3 *Electrical Hazards—*Solar simulators require large amounts of electrical power and use this power in many diverse circuits. The circuits range from high-voltage incoming supply lines rated at many kilowatts, to control circuits operating at small fractions of a watt but still using dangerous voltages. Several types of electrical hazards should be considered. These include dangers from high voltage, high current, improper insulation, grounding, and so forth. A good healthy respect for these hazards will both improve the operation of the system as well as protect the personnel. Before installing a new system or modifying an existing one, the local, state, and Federal codes should be studied to ensure operation and maintenance of a safety system. Several of the more important hazards are listed below.

6.6.3.1 *High Voltage—*Potentials of 75 kV or more are used to ignite the various types of short arc lamps used in solar simulators. This voltage is produced by step-up transformers and can be lethal if not handled properly. Lead lengths should be kept as short as possible and personnel should not touch and must be well clear of any part of the circuit during ignition.

6.6.3.2 *Open Circuit Voltages—*Potentials in the range from 75 to 400 V are available as open circuit-power supply voltages prior to the ignition of the lamps or carbon arcs. Again, these voltages can be lethal if they interact with the body. Heavy insulation should be used on all power supply leads and no terminals should be left exposed. Maintenance personnel should be aware that these power supplies use large capacitors which can retain large charges long after the power has been turned off. These capacitors should always be discharged before any maintenance is attempted.

6.6.3.3 *High Current—*The high-powered lamps used for solar simulation require from 50 to several hundred amperes. It is important, therefore, that adequately sized cables be used to transmit this high current. With this much current, even small contact resistances can result in the formation of considerable heat. Good ventilation is important, particularly where cables must be run through small crevices. Alignment tools must be electrically insulated.

6.6.4 *Radiation Hazards—*One of the most serious hazards associated with the operation of short arc lamps and carbon arcs such as those used in solar simulators is the intense optical radiation which they emit. This radiation has wavelengths that range from 0.2 µm in the ultraviolet to about 2.5 µm in the infrared. The most physiologically damaging wavelengths, however, lie in the ultraviolet and visible regions. Several types of potential hazards are discussed in the following paragraphs and suggestions are made for preventing or minimizing the danger to personnel.

6.6.4.1 *Erythema*—Erythema is a condition that closely resembles sunburn and affects exposed skin surfaces. This condition can be caused by exposure to ultraviolet energy emitted from almost every type of light source used in solar simulation. It is a particularly important problem when working with mercury, mercury-xenon, xenon, and carbon arc sources. The most damaging wavelengths lie below approximately 0.32 µm. Like sunburn, erythema is not immediately detected by the victim, but appears several hours later. The table below indicates the relative effectiveness as referenced to λ = 0.297 µm of various wavelengths in producing erythema:

Wavelength, µm	Relative Effectiveness
0.240	0.95
0.250	0.90
0.260	0.65
0.270	0.15
0.280	0.05
0.290	0.30
0.297	1.00
0.300	0.96
0.310	0.10

Depending on the irradiance associated with the lamp used, an exposure of only a few minutes is sufficient to produce a very painful and possibly severe case of erythema. Fortunately, the prevention of this hazard is relatively simple. Erythema cannot occur if the skin is not exposed. Therefore, this hazard can be avoided by covering all skin areas with a heavy cloth material. When this cannot be done, a good commercial suntan preparation or an industrial skin cream shall be applied to all exposed skin surfaces. This includes face, neck, hands, and so forth. These precautions apply both to operational personnel and visitors.

6.6.4.2 *Conjunctivitis*—Conjunctivitis is an inflammation of the mucous membranes covering the eye. This condition is caused by exposure of the eye to ultraviolet energy with wavelengths below 0.320 µm. These wavelengths correspond roughly to those wavelengths mentioned for erythema. However, the effectiveness of the various wavelengths is somewhat different. This danger is, again, not easily detected at the time of exposure. After a few hours, the victim experiences a feeling likened to having hot sand under the eyelids. This sensation can be extremely painful and last for many hours or days. If the condition does not disappear within a few hours, a qualified physician should be consulted. To eliminate or minimize this danger, all personnel who may have an opportunity to view either the direct or reflected (stray) radiation from high-intensity arc lamps should be required to wear dark sunglasses or goggles. The sunglasses or goggles should preferably be made of glass and should provide dark side shields to prevent light from entering the side of the eye. These precautions should be observed by operational and visiting or occasional personnel.

6.6.4.3 *Retinal Burns*—A third type of hazard involves the possibility of severe burns to the retinas of the eyes. The damage caused by such burns is particularly dangerous and may be irreversible. The eye is an excellent optical-imaging system and good vision depends upon the ability of the eye to image energy on the retina. Images so produced are transduced into heat by absorption in the pigment structure of the retina and the pigmented choroid lying immediately behind the retina. If sufficient heat is produced, a burn may result. Unfortunately, such burns often occur in the area of the fovea centrales which is responsible for acute central vision. In such cases, the victim may experience a severe loss of visual acuity which may seriously impair ability to read or perform other tasks requiring high visual resolution. The threshold exposure required to produce such burns is a function of several factors, including length of exposure, radiance, and size of the light source, irradiance at the eye, transmission of the various ocular components of the eye, retinal image area, and so forth. Therefore, there is no widespread agreement on what should constitute a threshold exposure value. However, note that permanent retinal damage has been caused by viewing solar eclipses, atomic fireballs, laser beams, and arc lamps. Because of this potential danger, special and conscious care should be taken by all personnel to avoid viewing the arc of any discharge or arc lamp. Dark glasses or goggles should be worn by all personnel when exposed to the radiation of any of these lamps. If anyone does accidentally view the arc and the after-image lasts for more than a few minutes, he should consult a physician.

6.6.4.4 *Laser Burns*—Many laboratories have adopted the practice of using small gas continuous wave (cw) lasers for aligning optical systems, including solar simulators. The total output power of these lasers is generally 1 mW or less. The laser is a particularly useful tool for optical alignment because of its excellent collimation and high intensity. These advantages may also be disadvantageous in terms of personnel safety. The problems involved are similar to those outlined in 6.6.4.3 for retinal burns. The energy from a laser is concentrated in a very narrow beam with relatively high energy density, easily capable of damaging the delicate eye components. This is true for reflected as well as direct laser radiation. Special goggles are available from some lasers which reject most of the energy at certain laser wavelengths. These goggles transmit well in other regions of the visible spectrum so that operating personnel will not be hampered by the dark goggles which would otherwise be required. If these special goggles are not available, then operational and visiting personnel should wear dark goggles with at least a No. 7 shade. All personnel should avoid viewing the beam directly. If anyone does accidentally view the beam directly, and the after-images linger for more than a few minutes, a physician should be consulted.

6.6.5 *Thermal Hazards*—While the fire hazard for solar simulators is not high, the complex electrical apparatus and high solar energies do present fire and personnel burn problems. The high currents required to operate the light sources can produce excessively high temperatures if high contact resistances are encountered. Lenses or reflective surfaces that absorb an excessive amount of energy will also become extremely hot. Excessively cold temperatures also pose a hazard when using cryogenic fluids. Types of thermal hazards could include fire as a result of faulty power supply or excessive contact resistance, personnel burns as a result of the handling of hot components (including the light source), and the implosion of ports as a result of increased absorption of the solar entrance window. The use of liquid nitrogen to make gaseous nitrogen or to produce a simulated space environment is also a potential hazard.

6.6.5.1 *Excessive Heating of Vacuum Windows*—A number of solar simulator windows have imploded as a result of excessive expansion or a change in physical properties. Adequate provision for window expansion and keeping window surfaces free of contaminants will minimize these hazards. Screens or shields around all glass ports are necessary to protect observers and operators from injury.

6.6.5.2 *Liquid Nitrogen*—Liquid nitrogen (LN_2) is also commonly used near solar simulator systems, both as a cooling medium for simulator components and as the thermal fluid for simulating the temperature conditions of extraterrestrial space. The principal hazard of LN_2 is its extremely low temperature (77 K) (−320°F); however, it also can cause explosions if contained and allowed to warm in a closed volume. The low temperature of LN_2 will cause burns (frostbite) when it comes in contact with the skin. Therefore, body, head, and face protection must be worn. Insulated gloves (manufactured synthetic fibers or heavy leather) should be worn but these must be loose-fitting to enable quick removal should LN_2 get down inside the glove. Clothing should be of such a nature as to prevent LN_2 from collecting anywhere on it (for example, wear cuffless trousers). Personnel working with LN_2 must be made thoroughly familiar with its properties and proper handling techniques.

6.6.6 *Miscellaneous Hazards:*

6.6.6.1 *Discarding of High-Pressure Lamps*—Before discarding high-pressure lamps, the pressure should be relieved by drilling the lamp near the neck using a special lamp-holding fixture. This fixture will protect the operator in case of lamp explosion. Lamps containing mercury must never be deposited in trash containers. They should be returned to the manufacturer or disposed of by the plant safety officer. Before drilling the lamps, condense the xenon by placing the bulb in contact with LN_2 (a plastic or styrofoam dish is suitable).

6.6.6.2 *Emergency Lighting*—Emergency lighting should be available in case of power failure to allow personnel to evacuate the area. In large vacuum chambers, emergency lighting is particularly important.

6.6.6.3 *Emergency Alarms*—Power-disrupt switches and alarms should be placed in strategic locations within and without facilities to allow persons to stop an operation detrimental to personnel working in the area and to hear emergency signals. Vacuum-disrupt switches inside large facilities are a necessity.

7. Thermal Characteristics and Test Requirements

7.1 *Thermal Sensitivity of Spacecraft*—An ideal thermal balance test of a spacecraft would simulate precisely the thermal and radiation environment of space. No solar simulator, vacuum chamber, or cold shroud simulate space perfectly. Furthermore, some spacecraft are more sensitive to errors in simulation than others. The factors that make spacecraft more sensitive to errors are discussed in this section and are specified in 7.3.

7.1.1 *Materials of the Spacecraft:*

7.1.1.1 The materials used on any spacecraft surface that has a view of the solar simulator or chamber shroud should have the same thermal response during test as in space. The most important properties are the absorptance (α) and thermal emittance (ε) and their ratio (α/ε).

7.1.1.2 The absorptance, α, of a surface determines how much of the incident irradiance is absorbed. The remainder is reflected. The absorptance is defined as:

$$\alpha = \int_0^\infty \alpha(\lambda)E(\lambda)d\lambda / \int_0^\infty E(\lambda)d\lambda \quad (8)$$

where:

$\alpha(\lambda)$ = spectral absorptance of the material,
$E(\lambda)$ = spectral irradiance (amount of flux as a function of wavelength) of the source, and
λ = wavelength.

Since $E(\lambda)$ for a solar simulator will, in general, be different than for the sun, α will be different. Some materials show a lesser change than others and the former are more desirable from a simulation standpoint. Note that material properties might vary from sample to sample depending on quality control.

7.1.1.3 In general, different thermal coatings will be used on a spacecraft to achieve a desirable temperature range. A typical high α/ε material is gold plating. It absorbs relatively well in the ultraviolet and visible range (where the solar irradiance is strong) and has a low emittance. As a result, a gold-plated component will retain heat. Second-surface mirrors have the opposite effect since they have a low α/ε.

7.1.1.4 If a spacecraft were coated with only one material, an adjustment of the simulator irradiance could be used to match the absorbed simulated solar irradiance to that of the sun's irradiance. With a variety of surfaces, this is not possible in most cases. There have been cases in which special thermal coatings have been applied to the specimen to correct for a poor solar simulator spectral irradiance. If this is not done and the mismatch is severe, the thermal analyst will have difficulty reconciling the data.

7.1.1.5 The emittance, ε, of a thermal coating is the ratio of the thermal energy radiated as a result of its own temperature to that emitted by a blackbody radiator. The emittance of a specific sample seldom causes simulation problems because this property is a function of the material temperature and varies only slowly with temperature. However, with a certain set of circumstances (low emittance of a small component at low temperature), the thermal conductance of the residual gas in the chamber may become relatively high compared to the emission from the surface. In most cases, a pressure of 1×10^{-5} torr is low enough. However, an isolated (insulated) aluminized component at low temperature that is, at 100K, $\varepsilon = 0.02$, requires a pressure of 1×10^{-7} torr if the conductive heat transfer is to be kept at 1 % of the emission (see Figs. 4–11 in Ref. (**10**)).

7.1.2 *Construction of Spacecraft:*

7.1.2.1 Spacecraft are extremely diverse in their geometrical complexity and variety. Some are of closed design, being little more than enclosed cubes, cylinders, spheres, octahedrons, and so forth. Others have appendages, cavities, solar panels, antenna arrays, and so forth.

7.1.2.2 Geometrical complexity makes a spacecraft sensitive to solar simulation that has a large divergence angle and subtense angle. The shadows cast by antennae, solar panels, and so forth are misplaced when there is a divergence angle. A subtense angle that is too large will cause the shadows to be fuzzy. Surfaces aligned parallel or nearly parallel to the sun's rays may receive appreciable side lighting when there should be little or none. There may be appreciable error even with simple closed construction such as a sphere when irradiated by a diverging beam through a small window. In this case, the point of tangency of the rays is too far forward (closer to the solar source) and the sides of the test object will be too cold.

7.1.3 *Type of Thermal Control System*—A spacecraft with an active thermal control system can offset some of the spacecraft's thermal sensitivity compared to a passive thermal control system. Internal electrical heaters with thermostats can be used successfully if the electrical requirements are not high. Polished aluminum louvers that open up to expose high-emittance surfaces have been used. If the spacecraft thermal designers can reduce the number of thermal coatings or use more spectrally flat surfaces, this will reduce the sensitivity and simplify the space simulation requirements.

7.1.4 *Spacecraft Motion Relative to the Sun*—Spacecraft may operate during the mission with one axis directed at the sun, or slowly or rapidly rotating with respect to the sun. In planetary orbits, the albedo and thermal emission from the planet may provide a significant and varying thermal input. It is generally necessary to rotate the test specimen in the space chamber to simulate rotation relative to the sun (exceptions are the use of a cage of infrared lamps, thermal blankets, and so forth). If the rotation is fast enough, it reduces the thermal sensitivity to nonuniform solar beam irradiance, at least in a plane normal to the axis of rotation. If the rotation is very slow, there may be no benefit. In fact, it may make analysis more difficult because of the changing thermal inputs to various surface nodes as they sweep through regions of changing irradiance.

7.1.5 *Thermal Analytical Model*—An adequate thermal analytical model in essence simplifies the requirement for fidelity of the solar simulation test. A prime objective of the solar simulation test is the verification of this analytical model. The class of simulator is quite flexible as long as it permits this verification. Temperatures for other aspects or missions, variations in space thermal inputs, and electrical power dissipations, and so forth can be predicted with a high degree of assurance if the mathematical model has been found adequate.

7.2 *Solar Simulator Characteristics That Affect Thermal Response of Spacecraft or Test Specimen*—The characteristics of a solar simulator that can affect the thermal response of a spacecraft or test specimen are discussed in 7.2.1 – 7.2.9. The thermal design engineer and the simulator operator will determine the effect each characteristic may have upon the test requirements and specify the proper requirements for each characteristic.

7.2.1 *Test Volume Dimensions*—The test volume includes, as a minimum, all the space occupied by the spacecraft or test specimen for the duration of the test. When motion of the spacecraft or test specimen occurs during the test, all portions of the test volume which are occupied during such motion must be included in the test volume.

7.2.2 *Mean Total Irradiance:*

7.2.2.1 The mean total irradiance ($\bar{E}$) within the test volume is:

$$\bar{E} = \left(\int_{\upsilon} E(r,\theta,z)\,\mathrm{d}V\right)/\left(\int_{\upsilon}\mathrm{d}V\right) \tag{9}$$

where:

$\bar{E}$ = mean total irradiance within the test volume,

$E(r, \theta, z)$ = irradiance at a position within the test volume, and

$\int_{\upsilon} dV$ = volume integral of the test volume.

7.2.2.2 Irradiance must be determined by use of a detector with finite dimensions. The dimensions of such detectors are discussed in Section 8. However, the largest linear dimension of such detectors may not exceed the linear dimensions of the smallest part of the spacecraft or test specimen which exhibits a different thermal response than its immediate surroundings. The mean total irradiance must be equal to the test requirements for the duration of the test.

7.2.3 *Uniformity of Total Irradiance Throughout Test Volume:*

7.2.3.1 The uniformity of total irradiance throughout the test volume is a measure of the deviations of individual irradiances from the mean value of total irradiance for all positions within the test volume. The procedures developed within this field are such that the most uniformly irradiated systems will have a low number value for uniformity. In accordance with this practice, uniformity of irradiation is defined as shown in Eq 10.

$$Eu = \pm 100\left[\left(\Delta E_{\min} + \Delta E_{\max}\right)/2\ \bar{E}\right] \tag{10}$$

where:

E_u = uniformity of the irradiance within the test volume, expressed as a percent of the mean irradiance,

$\Delta E_{\min}$ = mean irradiation minus the smallest value obtained for irradiance within the test volume, and

$\Delta E_{\max}$ = largest value obtained for irradiance within the test volume minus the mean irradiance. A perfect system would have a value of uniformity of total irradiance of zero.

7.2.3.2 Uniformity of irradiance values must always be specified together with the largest linear dimension of the detector used. Measurements of the irradiance should be made at a sufficient number of positions within the test volume to ensure, within a stated degree of certainty, that the extreme values of ΔE are included. Iso-irradiance plots are desirable for most tests. These plots should show 1 % deviations from the mean irradiance for Class A systems, 2 % deviations from the mean irradiance for Class B systems, and, 5 % deviations from the mean irradiance for Class C systems.

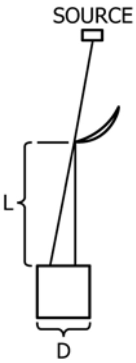
7.2.4 *Temporal Stability of Irradiance Throughout Test Volume*—The temporal stability of the irradiance throughout the test volume for the duration of the test can be defined similarly to the uniformity of irradiance. The stability of irradiance is the temporal variation of individual irradiances from the mean irradiance. The temporal variations should be measured over time intervals equal to the thermal-time constants of the components. In practice, one position in each portion of the test volume which is irradiated by different sources of radiant flux or different optical systems must be monitored. For each position monitored, a maximum and minimum value of irradiance will be obtained. An equation of the form of Eq 10 can then be used to determine the stability of irradiance during the test.

$$E_t = \pm 100\left[\left(\Delta E_t(\min) + \Delta E_t(\max)\right)/2\bar{E}\right] \quad (11)$$

7.2.5 *Solar Beam Divergence Angle:*

7.2.5.1 The solar beam divergence angle is a measure of the nonparallelism of the irradiance in the test volume. It is defined in Section 4. The divergence angle is the most important simulator characteristic from the standpoint of spacecraft construction. Actually, the subtense, divergence, and maximum divergence angles (see Section 4) are quite different and have different effects on a spacecraft. Use of the single column "Solar Beam Divergence Angle" in Table 2 is an attempt to

TABLE 2 Test Requirements

Spacecraft Characteristics	Solar Simulator Characteristics						
	Uniformity of Irradiance	Stability of Irradiance	Divergence Angle	Spectrum	Reflected Irradiance	Environment Temperature	Chamber Pressure
Rotation:							
Random tumbling	C	B	C		C	C	
Fast single axis rotation	B	A	A		A	B	
No rotation or slow rotation:							
High-conductivity structure	B	A			B	C	
Low-conductivity structure	A	A			A	B	
Construction:							
Incident angle:[A]							
Planar surface, incident angle ≃0°			C		C	C	
Incident angle <20°			B		C	B	
Incident angle 20 to 35°			A		B	B	
Incident angle 35 to 55°			2A		A	A	
Incident angle 55 to 70°			3A		A	A	
Incident angle 70 to 80°			4A		A	A	
Incident angle 80 to 85°			5A		A	A	 SOURCE L D
Depth of irradiated components:[A,B]							
Depth <5 % of beam diameter			C				
Depth 5 to 10 % of beam diameter			B				
Depth 10 to 15 % of beam diameter			A				
Depth <1 m			2A				
Depth <2 m			3A				
Depth <4 m			4A				
Depth <8 m			5A				
Shadowing appendages:[A]							
$D < 0.2L$			C				
$0.2L < D < 0.4L$			B				
$0.4L < D < 0.7L$			A				
$0.7L < D < 1.4L$			2A				
$1.4L < D < 3L$			3A				
$3L < D < 6L$			4A				
$6L < D < 12L$			5A				
Spectral Sensitivity:							
One coating or all flat coatings				C			
$\Delta\alpha_i/\alpha_i > 0.04$[C]				B			
Has both UV and IR preferential absorbers				A			
Pressure Sensitivity (test component 1-m diameter):							
$\varepsilon_m \sim 1$, $T \geq 300$ K							C
$\varepsilon_m \geq 0.2$, $T \geq 300$ K							B
$\varepsilon_m \geq 0.03$, $T \geq 250$ K							A

[A] Stationary or slowly rotating spacecraft.

[B] Use maximum test plane divergence angles for direct projection systems, measured change in irradiance with depth for well-collimated systems.

[C] Use of electric heaters assumed.

simplify matters by considering the most important aspects of these characteristics.

7.2.5.2 Direct projection systems generally have a much larger divergence angle than well-collimated systems. Projection systems frequently have a divergence angle of 3° or more at the edge of the test plane. On the other hand, solar simulators with large internal collimating mirrors may have divergence angles of less than 1⁄8 of a degree throughout the test volume. With this system, a traverse of the beam perpendicular to the solar axis will show that the apparent source moves with (follows) the traverse. The apparent source always maintains a line of sight to any point in the test volume very nearly parallel to the solar axis.

7.2.5.3 Table 2 contains a section, "Construction-Depth of Irradiated Components," dealing with the depth of the test object (dimension of the test object parallel to the solar axis). A simple relationship exists between irradiance and depth with a direct projection system. The irradiance decreases inversely proportional to the base area of the cone of rays defined by twice the maximum divergence angle. Divergence angle Classes A, B, and C in Table 3 are for use with direct projection systems.

7.2.5.4 No simple relationship exists between the irradiance and the very small divergence angles of a well-collimated system. Here the divergence angle is generally a result of spherical or other aberrations of the optics. Divergence angle Classes 2A through 5A in Table 4 are to be used with these systems. In particular, the "Depth of Irradiated Components" section of Table 2 requires actual measured values of irradiance change with depth.

7.2.6 *Spectrum:*

7.2.6.1 The spectrum of a solar simulator is determined from spectral irradiance measurements. The wavelength interval for such measurements should include all wavelengths which are pertinent to the test. In general, the wavelength interval from 250 to 2500 nm will be sufficient. The actual interval to be used will depend upon the materials of the spacecraft or test specimen which is tested. In some cases, the interval beyond 2500 nm is very important. The simulator operator and thermal analyst should determine if this wavelength region is important for each test performed and obtain spectral data over the wavelength region required.

7.2.6.2 The irradiance per measured wavelength interval (bandwidth), $E\lambda$, is compared to the currently accepted values for the air mass zero solar irradiance (AM0SI) for the same bandwidth. This yields a ratio of solar simulator irradiance (SSI) to air mass zero solar irradiance as:

$$\text{Ratio} = E_{\lambda}(\text{SSI})/E_{\lambda}(\text{AMOSI}) \qquad (12)$$

7.2.6.3 Table 5 lists the requirements for Class A and Class B spectrum in terms of the ratio of SSI to AM0SI for bandwidths within these intervals. The table divides the spectrum into four large wavelength intervals in the column titled "Wavelength Interval." These intervals should be used for tests in which all of the materials of the spacecraft or test specimen exhibit a linear absorptance as a function of wavelength, that is, when the absorptance of the material of the spacecraft or test specimen has a constant value throughout the indicated wavelength interval or varies linearly over the wavelength interval. Then only four determinations of spectral irradiance need be made, one determination for each wavelength interval. The values obtained are then compared directly to the values in the column titled" AM0SI per Interval'' by use of Eq 12. A ratio for each interval is thus obtained. This ratio is then compared to the tolerances shown in the column titled "Ratio per Bandwidth."

7.2.6.4 When the spacecraft or test specimen is composed of materials that have absorptances which vary strongly within the wavelength intervals or have absorption peaks or other nonlinearities, a more detailed spectral comparison is necessary. In these cases, each wavelength interval must be divided into an additional number of bands which are indicated in the column titled "Number of Bands." The number of bands is such that resolution of 10 nm is obtained from 250 to 700 nm, 50 nm is obtained from 700 to 1000 nm, and 100 nm is obtained from 1000 to 2500 nm. These measurement bandwidths are indicated in the column titled "Measurement Bandwidth." The ratio of the solar-simulator irradiance to the air mass zero solar irradiance for each of the bands within each wavelength interval is then obtained using Eq 12. These values are compared to the values for AM0SI per band which are given in the standard air mass zero solar spectral irradiance table. The ratio for each band within a wavelength interval is then compared to the ratio indicated in the column of Table 5 titled "Ratio per Bandwidth." When the ratio tolerances per bandwidth coincide with the tolerances shown in Table 3 for Class A solar simulation for two thirds of the bands within each wavelength interval, the spectral correlation of the SSI to AM0SI is sufficient to classify the spectrum as Class A. Similarly, for Class B, eight of the eleven bandwidths must fall within the ratio per bandwidth indicated.

7.2.6.5 Uniformity and temporal stability of spectral irradiance can be determined in a manner discussed in 7.2.3 and 7.2.4, the only difference being that each bandwidth of irradiance pertinent to the test must be compared using a wavelength dependent form of Eq 10 and 11. These characteristics may be

TABLE 3 Classification Characteristics of Solar Simulators

Test Volume Characteristics	Class A	Class B	Class C	See Section
Uniformity of irradiance, E_u	3 %	5 %	>5 %	7.2.1, 7.2.2, 7.2.3
Stability of irradiance, E_t	1 %	3 %	>3 %	7.2.4
Solar-beam divergence angle[A]	<2°	<4°	>4°	7.2.5
Spectrum	Table 5	Table 5	all others	7.2.6
Reflected irradiance	<2 % of incident	<5 % of incident	>5 % of incident	7.2.7
Radiation-environment temperature	<80K[B]	≤100K	>100K	7.2.8
Chamber pressure	10^{-6} torr	10^{-5} torr	$<10^{-4}$ torr	7.2.9

TABLE 4 Classification Characteristics of Solar Simulators

Test Volume Characteristics	Class 5A	Class 4A	Class 3A	Class 2A	See Section
Solar beam divergence angle	0.125°	0.25°	0.5°	1°	7.2.5
Change in *E* with depth (%/m)	0.3	0.5	1	2	7.2.5

TABLE 5 Spectral Irradiance Tolerances for Class A and Class B Solar Simulation

Wavelength Interval	Measurement Bandwidth	Number of Bands	AM0SI per Interval	Ratio per Bandwidth
		Class A		
NOTE—Two thirds of the bandwidths in each interval must fall within the ratio tolerances indicated.				
250–400 nm	10 nm	15	115 $W \cdot m^{-2}$	0.60–1.40
400–700 nm	10 nm	30	516 $W \cdot m^{-2}$	0.80–1.20
700–100 nm	50 nm	6	306 $W \cdot m^{-2}$	0.60–1.40
1000–2500 nm	100 nm	15	363 $W \cdot m^{-2}$	0.60–1.40
Total		66	1300 $W \cdot m^{-2}$	
		Class B		
NOTE—Eight of the bandwidths must fall within the ratio tolerances indicated.				
250–400 nm	50 nm	3	115 $W \cdot m^{-2}$	0.35–1.65
400–700 nm	100 nm	3	516 $W \cdot m^{-2}$	0.50–1.50
700–1000 nm	150 nm	2	306 $W \cdot m^{-2}$	0.35–1.65
1000–2500 nm	500 nm	3	363 $W \cdot m^{-2}$	0.20–1.80
Total		11	1300 $W \cdot m^{-2}$	

important for some tests and should be considered by the thermal design engineer in such cases.

7.2.7 *Reflected Irradiance*—The radiant flux incident upon a spacecraft or test specimen that does not originate from the first pass of radiant flex through the optical system is termed reflected irradiance. This may be flux reflected from the spacecraft or test specimen back to the collimator and then back to the spacecraft. It can also originate from reflections of the irradiance flux upon the surface at the side or beyond the spacecraft or test specimen which is then reflected back onto the spacecraft. The quantity and direction of reflected irradiance should be determined after the spacecraft or test specimen is mounted into position in the test chamber. Care must be exercised in these measurements to ensure that the presence of the detector within the test volume has a negligible effect.

7.2.8 *Radiation Environment Temperature*—The thermal-radiant exitance of the surfaces that surround the spacecraft or test specimen must be determined. The uniformity of the radiant exitance as well as the direction of each surface that departs significantly from the mean must also be determined. This energy may be expressed in terms of the equivalent temperature of a blackbody that would supply the same radiant exitance, or:

$$\varepsilon \sigma T_a^{\ 4} = 1.0 \sigma T_e^{\ 4} \tag{13}$$

where:

T_e = blackbody or equivalent temperature and
T_a = actual shroud temperature.

Since most shrouds have a black surface (with high absorptance and emittance) to minimize reflectance of the solar beam, the actual temperature measured will be close to the equivalent blackbody temperature. However, if a low-emittance shroud is used, a higher actual temperature may then be used. This T_a can be obtained from the relation:

$$T_a = T_e \varepsilon^{-\frac{1}{4}} \tag{14}$$

where T_e is the radiation environment temperature given in Table 3.

7.2.9 *Chamber Pressure*—The pressure level within the test volume should be monitored with gages placed so that the pressure levels at the spacecraft or test specimen may be determined. Gages shall be used in accordance with Recommended Practices E296.

7.3 *Characterization of Spacecraft or Test Specimen*—The designs of spacecraft have been very diversified to accomplish a wide variety of missions. Mission requirements and the state of the art dictate a multitude of design approaches including:

(1) Spinning, tumbling, slowly rotating, or stabilized spacecraft;

(2) Variation in shapes, sizes, appendages;

(3) Variations in thermal design, passive and active, flat or spectrally sensitive coatings, conductive or insulating surfaces; and

(4) Terminal conditions (distance from the sun, planetary radiation).

An attempt to classify spacecraft by listing all combinations of the above would yield an unmanageably large list. Therefore, the important spacecraft factors above are taken individually, where possible, and each is compared to the space simulator-characteristics most closely related to it. The spacecraft characteristics below are listed vertically in Table 2. The simulator characteristics from 7.5 are listed horizontally on the chart. To obtain the final classifications of the simulator, add all of the classifications required for the various spacecraft characteristics.

Frequently, thermal balance tests and systems tests are run simultaneously in a space chamber. A combined test may change the environmental requirements. One example of a thermal balance test is one that is run in a space chamber with mocked-up structure and components equipped with resistors to simulate the true components' electrical dissipation. These test items are generally called "thermal control models'' or TCMs. A system integration test would not be possible on a TCM.

A system integration test is one that is run with all spacecraft flight systems installed and operating so that possible interactions between the systems can be studied. A systems integration test can be run at ambient laboratory conditions. However, running this type of test in a space chamber is generally preferred because the space temperatures and pressure conditions are more accurately simulated and electronic and mechanical failures may occur under these conditions that would not occur under ambient conditions.

Another important factor affecting the simulator-spacecraft relationship is the existence or lack of a thermal analytical model (see also 7.4). The notations on Table 2 assume there is no analytical model to correct temperature errors. This not only yields a simulation with accurate temperatures but provides for a good systems integration test. Ordinarily, an analytical model could not correct the performance of electronic and mechanical systems subjected to erroneous temperatures, especially if temperature limits are exceeded. The existence of an analytical model reduces the simulator requirements for a purely thermal balance test but is of little assistance in a systems integration test.

7.3.1 *Spacecraft Rotation*—Spacecraft rotation relative to the sun is an important variable. Rotation is also important for orbiting spacecraft if the spacecraft surfaces are exposed to high irradiance of planetary albedo and thermal emission. Nonuniformities of irradiance in a test chamber will cause errors in thermal input. Highly conductive spacecraft surfaces will minimize these errors. Categories listed in Table 2 include:

7.3.1.1 Random tumbling of the spacecraft at a rate that is fast compared to the thermal time constant of the surface materials.

7.3.1.2 Single axis rotation that is fast compared to the thermal time constant of the surface materials. This motion will tend to average out nonuniform irradiance except at the intersections of the rotational axis and the spacecraft surface.

7.3.1.3 Nonrotating spacecraft, those rotating around the line-of-sight to the sum, or rotation that is slow compared to the thermal time constant of the surface materials.

7.3.2 *Spacecraft Construction*—The spacecraft geometry is an important factor in its sensitivity to solar simulation inaccuracies.

7.3.2.1 *Incident Angle*—Surfaces with small incident angles are less sensitive to solar beam divergence angle (see 7.2.5).

(1) A planar or two-dimensional surface, irradiated at normal incidence. This type of test article is ordinarily insensitive to solar subtense and divergence angle. An example is a solar panel irradiated at normal (zero) incidence to the solar beam axis.

(2) A surface incident angle <20°.
(3) A surface incident angle between 20 and 35°.
(4) A surface incident angle between 35 and 55°.
(5) A surface incident angle between 55 and 70°.
(6) A surface incident angle between 70 and 80°.
(7) A surface incident angle between 80 and 85°.

7.3.2.2 *Depth of Irradiated Components*—A diverging-beam solar simulator will provide lower irradiance to test surfaces that are farther from the source. The maximum divergence angle is the half angle of the cone of rays. This angle is used on Table 2 for diverging beams. Actual measured changes in irradiance with depth in the test volume must be used with simulators using collimating mirrors as the final optical element.

(1) Diverging Beams:

(a) The extreme limits of the projection of all irradiated surfaces on the solar beam axis are less than 5 % of the solar beam diameter,
(b) 5 to 10 %, and
(c) 10 to 15 %.

(2) Simulators with Collimating Mirrors:

(a) Depth <1 m,
(b) Depth <2 m,
(c) Depth <4 m, and
(d) Depth <8 m.

7.3.2.3 *Shadowing Appendages*—Shadows cast on a surface from an appendage, such as a solar panel, will not be properly simulated if the subtense and divergence angles of the beam are greater than those of the sum. A large subtense angle casts a large penumbra but otherwise the shadow is properly located. High thermal-conductance spacecraft skin reduces the error. A large divergence angle casts a shadow displaced from the correct position. For simplification, only divergence angle is considered. Table 2 uses simplified geometrical criteria between D, the distance between an appendage and the test component shadowed, and L, the dimension of the component shadowed perpendicular to the shadow line. These criteria are subject to the following qualifications:

(1) The projection of the shadow-edge solar ray onto the test plane is perpendicular to the shadow line. If not, Dshould be multiplied by the sine of this angle.

$$\Delta l / L \simeq \Delta a / A \quad (15)$$

where:

Δl = displacement of shadow, distance normal to shadow line,
L = characteristic dimension, that is, diameter of test component shadowed normal to the shadow line,
Δa = change in area shadowed as a result of shadow displacement Δl, and
A = area of the shadowed component projected on the test plane.

This expression merely ensures that the percentage error in the area shadowed is proportional to the percentage error in the shadow line displacement. For components of circular cross section or of unusual shapes, a correction for the area shadowed may be necessary.

The chart classifications, subject to these qualifications, are:

(1) $D < 0.2L$
(2) $0.2L < D < 0.4L$
(3) $0.4L < D < 0.7L$
(4) $0.7L < D < 1.4L$
(5) $1.4L < D < 3L$
(6) $3L < D < 6L$

(7) $6L < D < 12L$

7.3.3 *Spectral Sensitivity* (see 7.1.1):

7.3.3.1 Irradiated surfaces are of one type of coating or of several spectrally flat coatings.

7.3.3.2 $\Delta\alpha_i/\alpha_i \geq -0.04$. In accordance with 7.5.3.2, the minus sign will produce overheating of a component in a space chamber. Electrical heaters can be used to remedy underheating.

7.3.3.3 A variety of coatings, some that preferentially absorb at ultraviolet and some at infrared wavelengths.

7.3.4 *Pressure Sensitivity*—The residual gas pressure must be kept low enough so that the thermal conductance is negligible compared to radiative heat transfer. The criterion used is that the conductive heat transfer is 1 % or less of the radiative heat transfer. Spacecraft components at low temperatures and low emittance have low radiative emission. In these cases, the ratio of conduction to emission tends to get larger requiring a lower chamber pressure to maintain a 0.01 ratio. For $\varepsilon_m D_m \leq 1.0$ (ε_m is emittance, D_m is component characteristic dimension in metres) and an 80K cold shroud, the categories below and pressures given in 7.6 are valid (**10**). For intermediate values, radiation increases as $\varepsilon_m T^4$, conduction as pressure to the first power.

7.3.4.1 $\varepsilon_m \sim 1$, $T \geq 300$K

7.3.4.2 $\varepsilon_m \geq 0.2$, $T \geq 300$K

7.3.4.3 $\varepsilon_m \geq 0.03$, $T \geq 250$K

7.4 *Types of Spacecraft or Test Specimen Tests:*

7.4.1 *Thermal Tests to Verify Thermodynamic Analytical Models*—These tests of spacecraft or test specimens can tolerate a less perfect simulation because the variations in simulator performance from conditions extant in space can be added to the analytical model as variables. Spacecraft or test specimens for which an adequate thermal analytical model has been developed can, in general, receive an adequate test with any class of solar simulator characteristics specified in 7.5.1.

7.4.2 *Thermal Tests to Verify Thermal Balance When an Inadequate Thermodynamic Model Exists:*

7.4.2.1 In contrast to the adequate thermodynamic model described in 7.4.1, most spacecraft testing is done when the analytical model is not complete in all respects. A complete model covers the thermodynamics of all errors of simulation, all inputs and outputs for various missions and modes, shadows, view factors, reflections and multiple interreflections of both internal and external packages, and steady-state and transient radiation and conductive heat transfer. With a spacecraft of even moderate complexity, this is a monumental task. Thus, the category of *inadequate thermodynamic model*, covers most spacecraft.

7.4.2.2 Obviously, this category cannot be quantified. A thermal analyst who is familiar with both the performance of the space simulator and the space mission can do a great deal to adapt the analytical model to the simulator deficiencies.

7.4.3 *Test To Verify Thermal Balance When No Thermodynamic Model Exists*—If no model exists, several or all of the following factors would normally be present: short schedule, low budget, simple and easy mission, few innovations, experienced spacecraft designers. If the design and mission are simple and the thermal analysts are experienced, an unsophisticated simulator might suffice. However, for complicated designs without an analytical model, the ultimate in simulator characteristics would generally be required as shown in the chart in Table 2. Also, the very important systems integration test normally conducted before flight should be done under conditions as similar to space as possible (see 7.3).

7.5 *Solar Simulator Requirements for Spacecraft or Test Specimen Tests:*

7.5.1 *Classification of Solar Simulators:*

7.5.1.1 The classification of solar simulators can be accomplished in many ways. The approach taken here is to identify each of the parameters that characterize solar simulators generally and identify three classes for each parameter. Class A represents the state of the art for simulators, except for divergence angle where additional Classes 2A, 3A, 4A, and 5A are defined. Classes B and C are provided to accommodate those simulators of less sophistication. In most cases, the B and C classes designated on Table 2 will give adequate simulation. However, discretion on the part of the thermal design engineer must be exercised in the interpretation of results.

7.5.1.2 This approach is taken to give more flexibility of operation for solar simulation tests to allow the thermal design engineer to specify those parameters that are most important to the success of his test at the expense of others that are less important. For example, if spectrum were not an important parameter to the thermal design engineer but the irradiance level to be provided required the full-rated capacity of the system, then the simulator operator could remove any spectral filters or other means used to provide good spectrum and thereby increase the maximum irradiance capability of the simulator. Another example is that if divergence angle were extremely important but irradiance level were not, the simulator operator, for some types of systems, could provide an improved divergence angle at the expense of irradiance. Other trade-offs can also be made between the parameters listed in Table 3. It also follows that any solar simulator with performance characteristics that exceed or equal the class specifications for each of the seven items is a simulator with performance at that class.

7.5.2 *Methods To Reduce Spectral Sensitivity of Spacecraft or Test Specimen:*

7.5.2.1 *Effective Absorptances of Surface Materials*—If an analytical thermal model has been developed for the spacecraft or test specimen, the effective absorptance of each surface material as a function of the simulator spectrum can be calculated and applied to the thermal analytical model. This will yield a series of test equilibrium temperatures which will be different from those obtained in orbit unless the simulator spectrum correlates closely with the solar spectrum. However, if the thermal balance test equilibrium temperatures agree with those predicted by the thermal analytical model, a high degree of confidence in the accuracy of the model is obtained.

7.5.2.2 *Use of Different Surface Materials During Test*—7.1.1 describes the effects on simulation of surface materials of different thermal properties. The thermal designer may be able to desensitize the spacecraft to simulation errors by a proper choice of surface materials. However, the designer is generally constrained by the space environment and the mission objectives to use durable coatings with a variety of thermal responses. A possible alternative is to use one set of thermal coatings for space simulation test and another set for flight. A suggested criterion for thermal balance testing in which no analytical model is used is:

$$\left| \frac{\Delta\alpha_1}{\alpha_1}, \right| \frac{\Delta\alpha_2}{\alpha_2} \left|, \ldots, \right| \frac{\Delta\alpha_n}{\alpha_n} \left| \text{ are all} \leq 0.04 \right. \qquad (16)$$

where α is as defined as in 7.1.1 and Δα is the difference in α between space and simulated conditions ($\Delta\alpha = \alpha_s - \alpha_{ss}$ where *s* refers to the sun and *ss* to the solar simulator). Numerical subscripts refer to different surface coatings. This is generally difficult to achieve except with a spectrally accurate solar simulator. If electrical heat is applied to the test item where the absorptance in the simulated sun is too low, the positive tolerance given above can be increased.

7.5.3 *Methods of Reducing Uniformity Requirements of Tests:*

7.5.3.1 *Spacecraft Spinning During Test*—For certain space missions, spacecraft will be spun or tumbled to simplify thermal control or stabilization. These motions make the spacecraft less sensitive to solar beam nonuniformity as noted in 7.3.1. However, if the space mission requires that the spacecraft be stabilized or slowly rotating, generally it is not possible to spin it in the simulator without seriously compromising the test results. If the space mission allows the thermal designer the option of spinning or not, the choice of spinning will, of course, desensitize the spacecraft during simulation. Rapid rotation will tend to compensate for poor uniformity unless the uniformity gradients are primarily between planes perpendicular to the axis of rotation.

7.5.3.2 *High-Thermal-Conductivity Structures*—Some spacecraft designs use high-conductivity skins, heat pipes, and internal connections with high conductivity to equalize the temperatures in space. Furthermore, if the design is not weight-limited, extra conduction can be provided to desensitize the spacecraft during simulation.

7.5.3.3 *Active Thermal System*—Spacecraft designs sometimes use active thermal systems such as automatic louvers, electrical heaters, thermal switches, and so forth for variations in thermal balance during a mission. These and extra heaters may be used to improve simulation. By reducing the solar irradiance to the value that provides the correct heat input to the components that have a positive Δα, the deficiency in absorptance of the other components can be made up by electrically supplied heat.

7.5.4 *Methods of Reduced Subtense and Divergence Angle Requirements of Test*—A large subtense angle causes fuzzy shadows to be cast. This effect is generally minor for thermal balance testing except with very low conductivity or insulating skins. If an irradiated surface is approximately parallel to the solar beam axis, some of the rays strike the surface at a steeper angle. These minor effects can be ignored or easily taken into consideration during analysis of the data. A large divergence angle is a more serious matter. This will displace a point at the edge of a shadow cast by an appendage in proportion to the sine of the angle between the projection of the solar ray on the test plane and the shadow line. All surfaces that are not perpendicular to the solar axis are not properly irradiated depending on their angle to this axis and depths of the test volume.

7.5.4.1 *Shadow Panels*—The location of shadows can be improved by moving the shadow-casting component closer to the item shadowed. The component can frequently be removed from the test altogether and a dummy panel installed close to the item shadowed. This panel should be temperature-controlled so as to provide the proper emission to the test article. Although this will help reduce gross errors in shadow location, care must be taken to avoid substantial view factor changes for adjacent surfaces.

7.5.4.2 *Spinning Spacecraft*—This will reduce test requirement (see 7.3.1).

7.6 A—*Test Requirements Chart (*Table 2*):*

7.6.1 Table 2 should be used as a guide by spacecraft designers and others interested in space simulation. It is not intended as a standard or as a substitute for data analysis, analytical modeling, or any of the functions performed by the thermal designers. Wide latitude and flexibility are needed by those responsible for the spacecraft thermal performance. This table and the text of Section 7 should be used with that objective in mind.

7.6.2 To use the chart, enter from the left with each spacecraft characteristic, one at a time. Where a letter appears, that simulator class from Table 3 will be adequate for that spacecraft characteristic. If different letters are found in a column for that simulator characteristic, the higher quality (lower letter) must be used.

8. Instrumentation

8.1 This section describes the techniques used to measure the parameters involved in space simulation testing. This includes the measurement of solar-simulator total and spectral irradiance in air and in vacuum, the reference scale to be used, uniformity in plane and volume, solar beam divergence angle, and vacuum gages. It should be recognized that the methods and techniques discussed are not meant to be all-inclusive, but rather to represent the best approach to be used based on a combination of accuracy, ease of adaptation to most systems, and commercial availability.

8.2 *Total Irradiance Standard Detector*—This section covers the detector used by a laboratory as its primary working standard from which other detectors are calibrated and used to set irradiance levels.

8.2.1 *Reference Scale:*

8.2.1.1 It is recommended that the current International Pyrheliometric Scale (1956 as of this writing) be used as the reference. This scale is embodied in a group of electrical-conpensation type instruments maintained by the World Meteorological Organization (WMO) at Davos, Switzerland. Intercomparisons, against these standards, of regional and national primary working standard pyrheliometers are conducted there at approximately five-year intervals. The establishment of this scale is discussed in Refs (**11** to **12**).

8.2.1.2 Each laboratory or facility would have at least one reference pyrheliometer capable of ±0.5 % reproducibility with its calibration directly traceable to the current WMO scale. This instrument would be periodically (perhaps twice a year) intercompared with one of the primary pyrheliometers which preserve the IPS scale in the United States. (These pyrheliometers are maintained by the National Weather Service of NOAA.) The intercomparisons would take place at any high mountain site (2000 m or more altitude) with the sun as source. This reference instrument would then be used to calibrate the detectors normally used in simulator operations.

8.2.1.3 While total irradiance standards, traceable to NBS standards, are commercially available to calibrate detectors, it is felt that the IPS (1956) scale offers an easier way for every user to recalibrate his reference detector periodically against a common primary standard.

8.2.1.4 The reader is warned that the field of radiometry is undergoing strenuous development. On an international basis several countries are actively investigating the use of cone- and cavity-type radiometers as reference standards. Improved thermal detection capabilities, and precision readout instruments have spurred the rapid development of the so-called absolute radiometers. The development, intercomparison, and subsequent adoption of an absolute radiometer as an international reference probably will not occur for many years. Reference (**13**) will provide the reader with a more complete description of this type of radiometer.

8.3 *Measurement of Total Irradiance in Air*—This section covers a general method for measuring the total irradiance of a solar simulator in air before pumpdown or the mounting of any payload in the vacuum chamber. These measurements are made to characterize the solar beam only, and thus require the use of a view-limited detector.

8.3.1 *Dectector*—Detectors can be divided into two general types: thermal and photoelectric. The photoelectric types are characterized by a relatively rapid response and a high signal level. However, they suffer from narrow spectral response which varies with wavelength. Before this type of detector can be used for solar-simulation measurements, it is necessary to establish that spectral variation in the beam is negligible compared to the desired accuracy limits. Thermal-type detectors are usually characterized by relatively slow time constants and low signal levels and may be made to be stable with respect to environmental temperature over a limited range. Thermal types are uniformly sensitive over a wide spectral range. The thermal-type detector is recommended for use in simulator operation. It should possess the following characteristics:

8.3.1.1 It should be spectrally flat over the spectral range from 250 to 2500 nm (or greater).

8.3.1.2 It must be capable of withstanding flux densities of one solar constant (1353 $W \cdot m^{-2}$) or higher if tests require it.

8.3.1.3 It should be capable of resolving 0.01 solar constant (14 $W \cdot m^{-2}$) and exhibit repeatability of 0.01 solar constant or better.

8.3.1.4 It must have its field of view limited so as to prevent the measurement of spurious radiation such as from scattered, reflected, and emitted radiation. However, it cannot be limited to less than the subtense angle of the beam or false readings will result. In addition, a field of view of approximately 5° is necessary for calibration against the primary working standard.

8.3.1.5 Either the detector or the solar source must be equipped with a shutter mechanism or shield so that tare or zero readings can be made. The use of an electrical meter zero (such as a shorting plug in a voltmeter) is important but not sufficient. This simply zeros the voltmeter, not the entire measuring system. Also, a knowledge of the detector's time constant is obviously essential in determining the shutter open and close time. Some of the newer thermopiles have time constants of 1 s or less, while older types may be as slow as 30 s or longer.

8.3.1.6 The detector should be maintained within its specified temperature limits by whatever means recommended by the manufacturer.

8.3.1.7 The detector must either have a window cover (normally quartz) or suitable view limiting and baffle to minimize the effects of convective air currents.

8.3.2 *Calibration*—It is assumed that the operator has at his facility at least one reference pyrheliometer used as his primary working standard (see 8.2). All other detectors are calibrated against this reference. This is done outside on a clear day with natural sunlight as the source and the detectors set for normal incidence. Since the reference pyrheliometer has a field of view of approximately 5°, all other detectors must be equipped with diaphragms limiting them to about the same angle for this calibration.

8.3.3 *Location*—The detector must be mounted at the measurement location in the simulated solar beam. Sampling at several locations may be necessary to determine the mean irradiance. In some systems, particularly the module type, it may be advisable to sample the total beam at random positions and apply statistical analysis to determine the mean. A single-point measurement may be used if the value is correlated to uniformity of irradiance measurements made by relative irradiance detectors. The detector is mounted in a known position with regard to the uniformity scan and a correlation is then made between this position and the rest of the test volume.

8.3.4 *Readout Devices*—For accurate measurement of irradiance levels, a voltmeter capable of resolving the anticipated signal to 0.1 % with an accuracy of 0.25 % of full scale can be used.

8.3.5 *Other Considerations:*

8.3.5.1 Since most of the thermal transducers operate in the millivolt region, it is necessary to verify the calibration of the readout equipment using test voltage sources having impedance characteristics similar to those of the transducers. Evaluation of the level and effect of spurious noise upon the readout system performance should be done.

8.3.5.2 Parameters that require consideration in the application of thermal type radiometers are:

(a) Disposition of energy intercepted by detector and case. For example, verify that reflected radiation does not cause an increase of heat input to the heat sink of the detector.

(b) Verify when operating above the calibrated range that internal temperature differentials are small so that thermal conduction is large compared to convection and radiation.

(c) Spectral differences between the calibration source and the unknown require consideration, particularly if optics are used in the detector. Any neutral density attenuators used must

be truly neutral with respect to the spectrum of the standard and the unknown sources.

(d) The effect of stray electrically induced signals in the detector cables must be evaluated.

8.4 *Measurement of Spectral Irradiance in the 250- to 2500-nm Wavelength Range*—This section covers a general method of performing measurements of the spectral irradiance of radiation sources in the 250- to 2500-nm wavelength range. The method uses conventional spectrophotometric equipment (that is, monochromator, detectors, and so forth) to perform measurements, relative to a source of known spectral irradiance. A detailed, high-resolution measurement of the continuous spectrum can be obtained by this method.

8.4.1 *Summary of Method*—A spectral measurement of irradiance versus wavelength is made on the standard source to determine the measurement system transfer function X (λ). Spectral measurements of the unknown source (solar simulator beam) are then made in an identical manner as used for the standard source. The spectral irradiance of the solar simulator beam may then be determined by correction of the measurement by the transfer function of the instrument system.

$$\text{Transfer function } X(\lambda) = S_{\mathrm{std}}(\lambda)/E_{\mathrm{std}}(\lambda)(\tau_{\mathrm{std}}(\lambda)) \tag{17}$$

where:

$S_{\mathrm{std}}(\lambda)$ = measurement of standard,
$E_{\mathrm{std}}(\lambda)$ = known spectral irradiance of standard, and
$\tau_{\mathrm{std}}(\lambda$ = screen attenuator spectral transmittance in standard source beam (see 8.4.2.7).

$$= [S_{ss}(\lambda)/S_{\mathrm{std}}(\lambda)](E_{\mathrm{std}}(\lambda)[\tau_{\mathrm{std}}(\lambda)/\gamma_{ss}(\lambda)] \tag{18}$$

$$\text{Solar simulator } E_{ss}\lambda$$

$$= S_{ss}(\lambda)/X(\lambda)$$

where:

$E_{ss}(\lambda)$ = spectral irradiance of solar simulator,
$S_{ss}(\lambda)$ = measurement of solar simulator, and
$\tau_{ss}(\lambda)$ = screen attenuator spectral transmittance in solar simulator beam (see 8.4.2.7).

8.4.2 *Apparatus:*

8.4.2.1 *System*—Instrumentation required for the measurement consists of a monochromator, diffusing entrance optics, a standard source of special irradiance, detectors, an amplifier, and auxilary equipment. A complete system incorporating the necessary instrumentation is shown in Fig. 3. The monochromator is free to translate along an optical bench in such a way as to view either the unknown or reference sources, which are separated by a radiation shield. This configuration is shown primarily for purposes of illustration and any technique such as a rotating mirror which allows unobstructed alternate viewing of sources can be used.

8.4.2.2 *Monochromator*—An extremely wide variation of spectral irradiance can exist for the standard source and the test source over the spectral range from 250 to 2500 nm. In conjunction with the wide dynamic range of the monochromator/detector transfer function places a stringent requirement on minimizing the stray light from the monochromator. Use of a double prism/grating monochromator is recommended. Precise correlation between wavelength and instrument readout is necessary.

8.4.2.3 *Diffusing Optics*—Diffusing entrance optics for the monochromator are necessary because the optical properties of the reference and unknown sources vary greatly in spatial distribution. The transfer function of the spectral measurement system varies with this spatial distribution. However, both

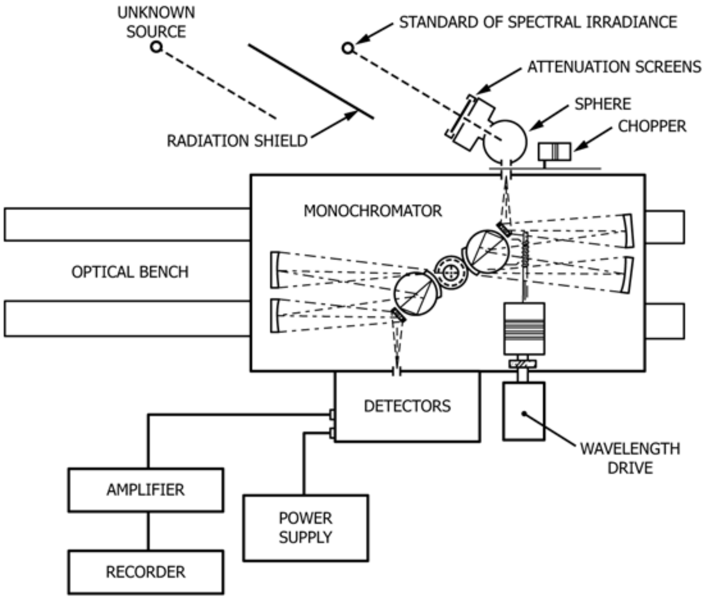


FIG. 3 Diagram of System for Measurement of Spectral Irradiance

these difficulties are minimized by using the diffusing technique. This can best be accomplished through the use of a diffusing sphere or diffusing plate which is alternately irradiated by the unknown and reference sources. For a sphere coating, MgO offers good reflectance from about 250 to 1600 nm. MgO is prepared by burning magnesium ribbon in air. Recommended Practice E259 contains additional information on the preparation of smoked MgO. At wavelengths longer than 1600 nm, the reflectance falls off fairly rapidly, but can still be useful up to 2500 nm with a sacrifice in efficiency. $MgCO_3$ in block or plate form has a high diffuse reflectance through most of the solar spectral region. The efficiency of a flatplate diffuser is about ten times that of the integrating sphere. The improved diffusing characteristics of integrating spheres may be necessary for precise measurements.

8.4.2.4 *Standard of Spectral Irradiance*—The most significant advance in spectroradiometry in recent years has been the establishment of a Standard of Spectral Irradiance by the National Bureau of Standards (**14**). This standard is a 1000-W coiled tungsten filament enclosed in a ⅜- by 3-in. quartz envelope containing a small amount of iodine.[7] The standard is issued from several commercial sources. A calibration traceable to the NBS Standard is furnished over the wavelength range from 250 to 2500 nm for each standard that is issued. The calibration is expressed in terms of power per unit area and unit bandwidth ($W/m^2 \cdot nm$) incident on a surface 50 cm distant when 8.30 A (ac or dc) is passing through the lamp. The stability of the lamp is extremely good with less than 1 % expected degradation after 50 h of careful use. However, several working standards should be calibrated by the user for routine measurements. The uncertainty in the calibration is 3 % for the visible and infrared, increasing to 8 % in the ultraviolet.

8.4.2.5 *Detectors*—To cover the full spectral range from 250 to 2500 nm, at least two photoelectric detectors are required. Phototubes and thermopiles are, in general, too insensitive to be useful. A high-sensitivity, low-noise, photomultiplier, such as the RCA 1P-28 or EMI 6256B, is used to cover the ultraviolet and visible spectral region. A PbS detector is used to cover the 600- to 2500-nm region.

8.4.2.6 *Signal Processing*—Signal levels from the detectors are typically in the microampere and microvolt region. Low noise, wide dynamic range amplifiers using synchronous or phase lock detection must be used to process these low-level signals. Although the signals may be read out on laboratory voltmeters on a point-by-point (wavelength-by-wavelength) basis, the large number of data points required for a complete scan usually leads to the use of an automatic data handling readout such as an analog strip chart or digital data recording system. Since computations are typically necessary to reduce raw data to calibrated spectral irradiance, the digital data-handling technique is preferred.

8.4.2.7 *Screen Attenuators*—In many measurements, a large difference in the irradiance between the standard source and the unknown source may exist. This irradiance ratio between the two sources can range up to several orders of magnitude and will usually vary considerably with wavelength. Unless the more intense source is attenuated by a known amount, so that the energy falling on the detector is roughly equivalent for both the standard and the unknown source, difficult linearity and dynamic range requirements will be imposed upon the detector-amplifier system. The use of neutral density screens has proven most satisfactory in attenuating radiant flux by a repeatable amount. The transmittance of these screens can be determined in conventional spectrometers whose linearity can be conveniently checked by samples with precisely known concentrations of absorbing agents. Some spectroradiometers provide such attenuation through a preprogrammed technique.

8.4.3 *Operational Considerations:*

8.4.3.1 *Monochromator Calibration*—The calibration of wavelength as a function of wavelength-drive position is accomplished by observing spectra from low-pressure arc lamps such as mercury, sodium, neon, cesium, potassium, and so forth. The wavelengths of major spectral lines are precisely known for these sources and may be found in references such as the American Institute of Physics Handbook (**15**). The calibration should be performed by scanning in the same direction (that is, long λ to short λ) as during actual measurement to minimize the problem of backlash in the wavelength drive.

8.4.3.2 *Optimization of Scan Parameters*—The optimum choice of slit width, amplification, system response time, scan rate, and so forth is dependent upon the capabilities of the system and the end use of the data. As an example, a requirement of near-perfect resolution of the spectral bands of a high-pressure arc lamp necessitates as a first consideration that the spectral bandwidth be considerably less than the natural bandwidth. This, in turn, requires increased amplification and increased system response time (increased integration interval or time constant) to achieve a reasonable signal-to-noise ratio. The scan rate must then be slow enough so that resolution is not limited by the response time of the system. A scan rate of ¹⁄₁₀ spectral bandwidth per system response time is recommended for precise work. In general, the end use of spectral irradiance measurements does not require near-perfect resolution of spectral peaks, and trade-offs can be accomplished between decreased resolution (increased slit width) and increased signal level and rate of scan. Since resolution (spectral bandwidth) is proportional to the square of slit width, a considerable increase in signal can be gained by a relatively small decrease in resolution. With decreased resolution and higher signal the system response time for the same signal-to-noise ratio can be reduced and the rate of scan can be proportionately increased. For general work a scan rate from ⅕ to 1 spectal bandwidth per system response time may be acceptable. In practice, the operator usually varies the scan parameters according to the presence or absence of band structure in the spectrum being measured. A high-resolution, slow scan is used within spectral regions containing significant band structure, while a low-resolution, rapid scan is used where band structure is absent. For measurements of solar simulator spectral irradiance to test for compliance with simulator clarification as discussed in Section 7, the slit width (spectral bandwidth) must be compatible with Table 5.

8.4.4 *Operational Procedures:*

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[7] Designation: General Electric DXW-1000.

8.4.4.1 *Preliminary Measurement*—It is desirable to obtain a preliminary indication of the relative intensity levels of the unknown and standard sources as a function of wavelength. This is accomplished by performing for each source a relatively rapid scan over the entire spectral range of interest. It is desirable for these preliminary scans that only amplification be varied to maintain adequate signal level and for slit width, scan rate and system response time to remain constant. If, however, at the extremes of the spectral range it becomes necessary to vary one or more of these parameters, the values must be the same for both the unknown and reference sources.

8.4.4.2 *Selection of Scan Parameters*—The entire spectal range is divided into subregions, each covering an order to magnitude or less change in signal level from either the unknown or standard source. A table with format similar to Table 6 should be constructed to aid in establishing the scan parameters to be used in the final measurements. A screen attenuator is selected for each of the above spectral regions to bring the signal levels of the unknown and standard sources to approximately the same value. The scan parameters are selected based upon the information obtained in the preliminary scan and the criteria discussed in 8.4.3.2. It may be necessary to repeat certain spectral regions to establish natural bandwidths and to check final selections of scan parameters in regions of band structure.

8.4.4.3 *Final Measurements*—Alternate measurements are performed on the unknown and standard sources within each of the selected wavelength regions using the scan parameters determined above. It is desirable to keep the time interval between measurement of the unknown source and measurement of the standard source as short as possible to minimize errors as a result of amplifier drift and sensitivity change. The spectral irradiance of the unknown source within each wavelength region can be determined by Eq 18 in 8.4.1 from the measured ratio of signal levels, knowledge of the transmittance of the attenuator screen, and the calibration of the standard source.

8.4.4.4 *Data Reduction and Presentation*—There are many methods of data acquisition ranging from the time-consuming, point-by-point hand recording of meter readings into a chart format to the completely automated system which provides raw data (detector output versus wavelength) into an appropriately programmed computer. Nevertheless, the basic computation techniques are embodied in Eq 17 and 18 in 8.4.1 and the subsequent discussion concerning the use of gain changes, slit width or screen attenuation. A series of sketches (Figs. 4-7) attempts to indicate in analog form the various processes which are used to transform the raw data into a normalized spectral irradiance. It must be emphasized that these are merely sketches and in no manner to be considered quantitative. The semifinished data usually can be presented in a tabular format similar to Table 7. It must be emphasized that the final normalization relates to the area under the resultant curve and that the indicated spectral irradiance value is valid only at a specific wavelength. Though by custom the plotted data are presented as a smooth curve while the true representation would be a small rectangle at each datapoint. While tabular data are most useful for subsequent computation, spectral irradiance divergences are most readily apparent when plotted. It is recommended that both formats be provided the user.

8.5 *Total Irradiance Monitoring During Testing*—This section covers the monitoring of the total irradiance during a thermal vacuum-solar simulation test. Total irradiance here

TABLE 6 Scan Parameters for Final Measurements

Wavelength Region	Attenuator Screen Transmittance		Slit Width	Amplification	Response Time	Scan Rate
	Unknown, τ_{ss} (λ)	Standard, τ_{std} (λ)				

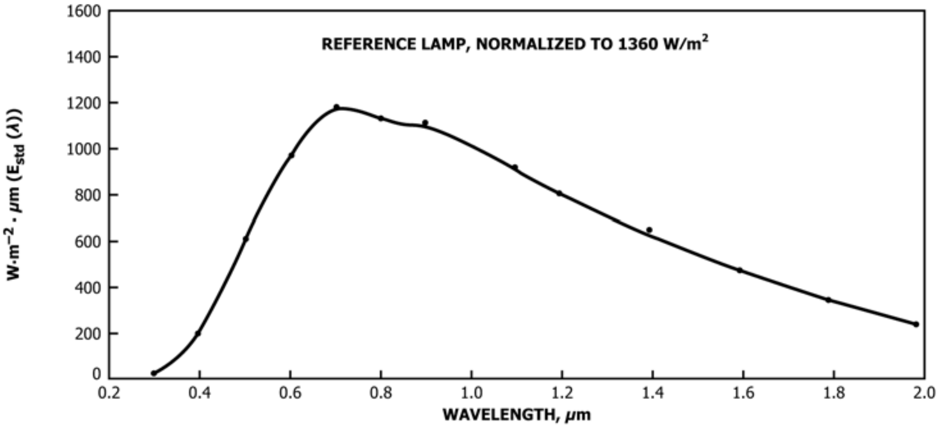

FIG. 4 Reference Spectral Irradiance

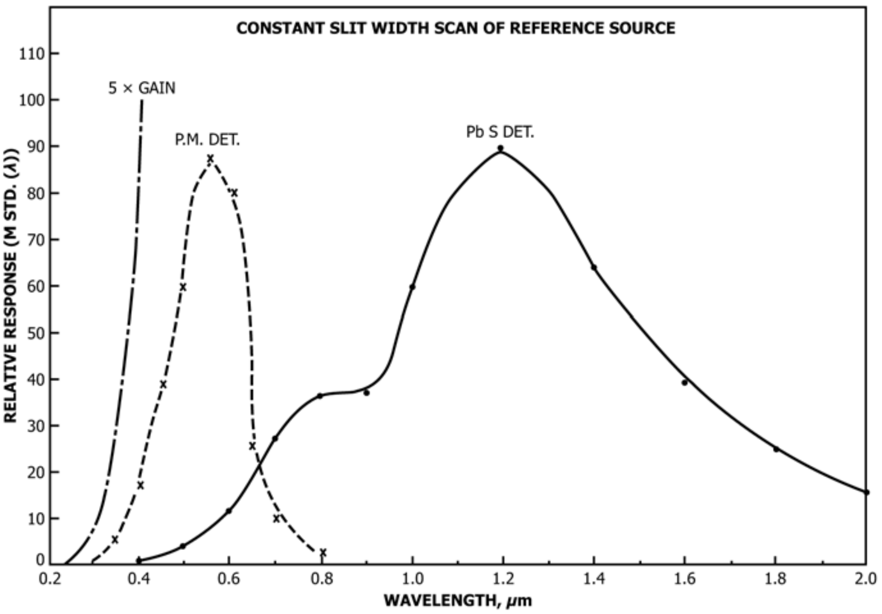

FIG. 5 Reference Source Measurements

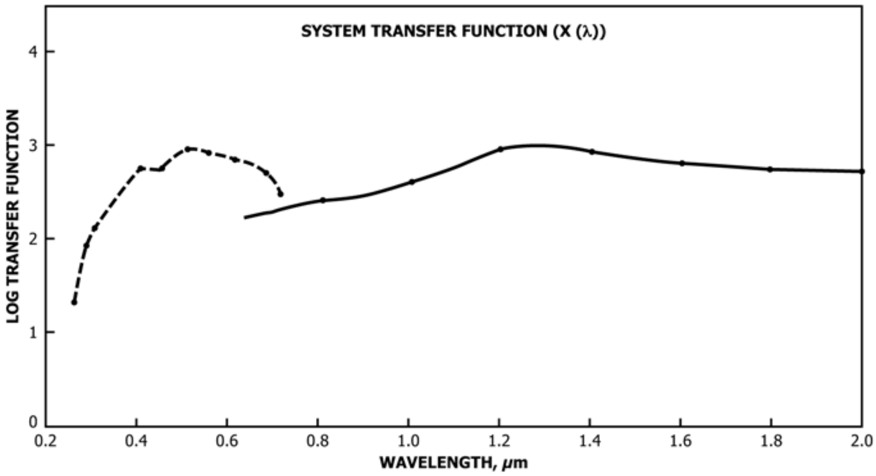

FIG. 6 System Transfer Function

refers to the total incident energy from all sources. Infrared energy from internal solar simulator optics, some vacuum gages, and the chamber view ports must be added to that from the solar beam. Also, the chamber liquid nitrogen shrouds

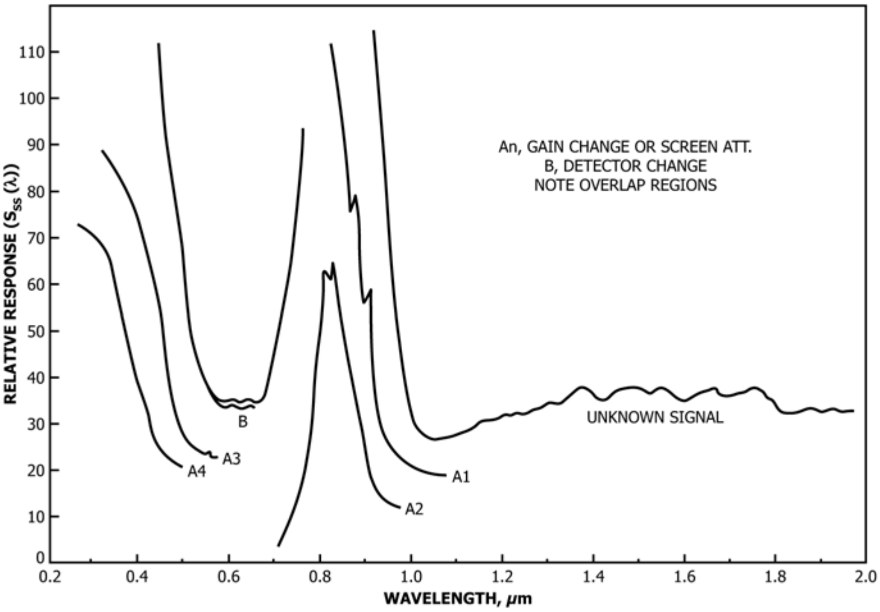

FIG. 7 Unknown Source Measurements

contribute some emitted and reflected energy. Reflections of the spacecraft can also add to the total energy balance. The total energy that arrives on the surface over the 2 π steradian view angle can be as much as 10 % greater than the solar simulation component. Additional components of radiation often create differences between predicted and measured temperatures during test.

8.5.1 *Detectors:*

8.5.1.1 Three types of detectors can be used to monitor the total irradiance during a test. The first type recommended is the same thermopile detector discussed in 8.3.1, but with certain modifications. This detector must now be capable of operating in a vacuum of 10^{-4} torr or less as well as in air. This requires that the window cover be removed during vacuum operation to prevent it from emitting infrared radiation to the detector surface. Note that the sensitivity of the radiometer under vacuum is different then in the atmosphere and in addition the removal of the window requires a change in the radiometer calibration factor. Furthermore, the detector must be maintained within its specified temperature limits. This may require the use of fluid or thermoelectric temperature control.

8.5.1.2 A second type of detector that could be used is a flat or V-grooved metal plate coated with a material of well known absorbance and emittance. Generally, the back side is insulated to eliminate uncertainties of reflected beam energy, and so forth. The plate (of arbitrary dimensions) is hung in the beam and its temperature carefully monitored with thermocouples. A calibration of temperature versus beam energy is made and thereafter used to determine the energy over the 2 π view angle. This type of detector is not as accurate as the thermopile type because the measurement depends on an accurate knowledge of the properties of the coating and also on the fourth power of temperature. Since the temperature may not be known to better than 0.5K, it is easy to see that overall accuracies of ±5 % are considered good. On the other hand, the thermopile type can be accurate to ±2 % or better. One advantage of the plate is that it does not require any means for temperature control. Thus, a facility that restricts the use of fluids under vacuum conditions would still be able to monitor beam irradiance using this type of detector.

8.5.1.3 A third type of detector may be called an electrically calibrated radiometer. In general, these radiometers contain cavities of known dimensions and optical properties. Calibration is obtained by substitution of electrical power for radiant energy.

8.5.1.4 For thermal balance testing with solar simulation sources widely differing in spectral irradiance from solar, that is, tungsten lamps, a more meaningful term than incident irradiance is the absorbed irradiance. Absorbed flux radiometers may be used as detectors rather than the total irradiance radiometer for calibration of such facilities.

8.5.2 *Recording Devices*—For beam monitoring during tests, a good strip or digital recorder should be used so that a continuous record of irradiance can be kept.

8.6 *Spectral Irradiance Monitoring*—This section covers the monitoring of the spectral content of the simulator beam. Users must be aware that the spectrum changes with time due to degradation of the optical components and variations in power supply output. The instrumentation requirements vary considerably as to the basic optical system. It has been found that the modular systems require careful checking of the spectral properties of the beam, particularly after a source or optical element has been changed. Experience has shown that the pseudo-random element replacement that occurs in an integrating system causes only a minor change in the spectral irradiance. Apparently, after a few hundred hours of operation the system has spectrally degraded to a constant level. Naturally, if the primary collimating mirror of the integrating system is recoated a spectral change should be anticipated and verified.

8.6.1 *Procedure:*

TABLE 7 Typical Computation Sheet

Wavelength	E_{std} (λ)	S_{std} (λ)	X (λ)[A]	S_{ss} (λ)	E_{ss} (λ)[B,C]	E_{ssn} (λ)[D,E]
2500						
200						
					E_{ss}	E_{ssn} = 1303 W·m^{-2}

[A] $X(\lambda) = (S_{std}(\lambda)/E_{std}(\lambda))(\tau_{std}(\lambda))$

[B] $E_{ss}(\lambda) = S_{ss}(\lambda)/X(\lambda)\tau_{ss}(\lambda)$

[C] $E_{ss} = \sum E_{ss}(\lambda)$ (Solar simulator total irradiance between 200 and 2500 nm)

[D] $E_{ssn}(\lambda) = (E_{ssn}/E_{ss})(E_{ss}(\lambda)) = (1303/E_{ss})(E_{ss}(\lambda)$ = normalized solar simulator spectral irradiance)

[E] $E_{ssn} = \sum E_{ssn}(\lambda) = 1303$ W · m^{-2} (total solar simulator irradiance normalized to solar irradiance between 200 and 2500 nm)

8.6.1.1 The spectral distribution should be measured often enough to monitor significant changes in spectral distribution. The frequency of measurement will vary with the types of lamps, power levels, spacecraft spectral sensitivity, and so forth (see Fig. 8). The spectrum of a solar simulator should be monitored periodically to keep a record of spectral change with time. A double-prism monochromator of the type described in 8.4.2.2 should be used, viewing the beam through a fused silica port. Should it be necessary to measure from inside the vacuum chamber, filter radiometer instruments are available that operate in a vacuum environment.

8.6.1.2 However, great care must be used in calibrating this type of radiometer to ensure that the air to vacuum correlation is known. A properly calibrated filter radiometer after correlation with monochromator measurements provides a rapid, economical method of verifying spectral irradiance stability.

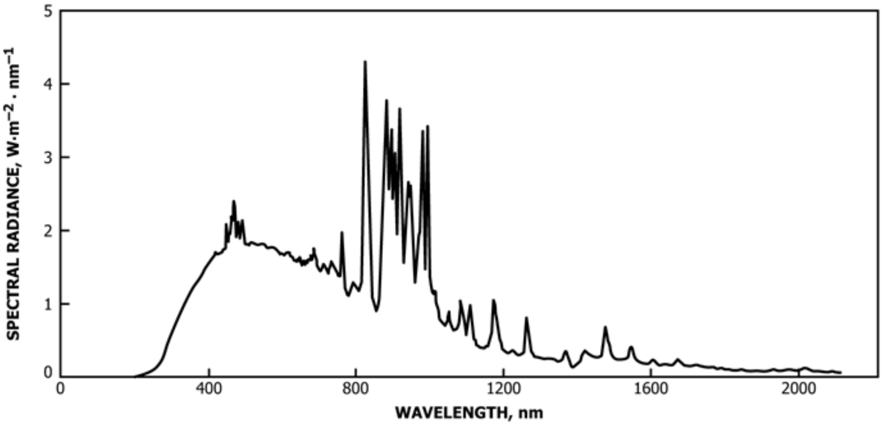

FIG. 8 Example of Spectral Irradiance Measurement—Xenon Arc Lamp

8.7 *Uniformity*—This section discusses the methods for determining the uniformity of the solar simulation system. Note that the area of the detector used for these tests must be commensurate with the size of the minimum thermally independent portion of the test article. Although it is possible to use a group of the same type of thermopile detectors as mentioned in 8.3, the slow time constant of most thermopiles places severe restrictions upon the scan rates and thus makes uniformity testing a tedious process. Where spectral nonuniformity is observed the use of the spectrally neutral thermopile-type detectors is mandatory. In describing the uniformity of a solar beam some form of statistical analysis is recommended.

8.7.1 *Plane*—In general, uniformity in a test plane should be measured with a 2- by 2-cm (or smaller) solar cell mounted on a mechanical carriage device which moves it in the area of the beam. This size solar cell is recommended because it is commercially available. Any larger sampling area would require multiple cell connections (which demand careful calibration). The cell should be loaded with a low resistance (usually 1 Ω or less) to approximate the short-circuit current (which varies linearly with irradiance). Monitoring of the cell temperature is recommended for irradiance levels above 1350 $W \cdot m^{-2}$ to ensure that it remains within the manufacturer's specified limits.

8.7.2 *Volume*—Volume uniformity is measured by making plane uniformity scans at different depth locations in the test volume. Then the variation of irradiance between planes must be determined to relate the planar data to the entire volume.

8.7.3 *Data Reduction and Presentation:*

8.7.3.1 Since any temporal change in total irradiance during the uniformity measurements will give erroneous results, it is necessary to monitor the beam at a fixed location during all uniformity scans. With the use of modern digital instruments, it is possible to ratio two signals automatically, and thus, it is possible to express uniformity deviations as a percent variation. This technique is immediately applicable to the integrating type solar simulation systems. Modular systems having individual power regulation require special consideration to prevent the uniformity data from being masked by temporal changes. For the modular systems, scanning using multiple detectors is the preferred technique.

8.7.3.2 For large area solar simulators, the uniformity scan data may be collected from multiple detectors mounted on a scanning beam or arm. In this case, the sensitivity and zero calibration of each detector must be known, and the ratioing measurement to a stationary reference detector must be accomplished. Scanning time is therefore greatly reduced; however, digital data acquisition, conversion, and computation facilities are necessary to handle the data output.

8.7.3.3 Data presentation may be either analog or digital, and chart, table, or even CRT display in format. However, some technique of displaying the variation in uniformity is preferred. Isoplots of irradiance in various planes throughout a volume are a typical display technique. Both analog and tabular data have proven to be equally useful.

8.7.4 *Spacecraft/Solar Simulator Interaction*—After uniformity scans have been completed and the test object mounted in position, spot checks should be made before pumpdown. These are performed by manually measuring the total irradiance of the simulator beam at different locations near the test object. The irradiance at these locations is frequently changed by reflections and re-reflections from spacecraft components to each other and their interactions with the chamber.

8.8 *Solar-Beam Angles*—This section covers the measurement of the divergence angle, maximum-divergence angle, subtense angle, and apparent source. (See Section 4 and Fig. 1 for definitions.) Though these angles may be computed from knowledge of the optical design, for reasons cited in 8.8.2, these characteristics should be measured by an accurate optical-angle measuring instrument such as a theodolite.

8.8.1 *Maximum-Divergence Angle*—This angle is of particular interest with direct projection systems. It can be measured with a theodolite or other optical-angle measuring instrument. However, with a direct projection system it probably is simpler to observe the pattern of illumination at the test plane. With these data, and knowing the distance from the test plane to the apparent source and the diameter of the apparent source, it is easy to calculate this angle.

8.8.2 *Divergence Angles, Subtense Angle, Apparent Source:*

8.8.2.1 The theodolite is set up at any arbitrary point in the test volume by carefully aligning its reference axis parallel to the axis of the solar beam. Then a minimum of four sightings are taken on the extreme edges of the apparent source and the angles recorded. For instance, with a vertical solar beam, the sightings might be to the north, east, south, and west edges of the apparent source. From these values the subtense and diverence angles can be computed for this point in the test volume. As an example, the subtense angle, north-south, is the difference in those angles. The east-west measurements are treated similarly. The divergence angle, north-south, is the difference between the bisector of the angles measured and the true vertical (for the example chosen).

8.8.2.2 The method given above assumes the apparent source is nearly circular, sharply defined, and of symmetrical radiant intensity about the center. If the apparent source is not circular, measurements of best and worst cases should be made. For example, with direct projection through two small windows, sightings along the long dimension of the two windows to the outside edges of each source should be made. The smaller angle across the apparent source should also be measured.

8.8.2.3 If the outline of the apparent source is not sharply defined, the minimum area from which issues 95 % or more of the total power should be used. Infrared emission from window frames, and so forth, should be included in the total energy.

8.8.2.4 If the radiant intensity is not symmetrical about the center of the apparent source, the principal measurement affected will be the divergence angle. In this event, a point must be selected in the apparent source that represents the mean value of the radiant power. The divergence angle in the test volume is the difference between the direction to this point and a line parallel to the solar axis.

8.8.2.5 After completing the angle measurements at one point in the test volume, the theodolite is moved to other points and the measurements repeated. A test volume is chosen for illustrative purposes that has a well-collimated beam and is a right circular cylinder aligned vertically. In the principal test plane the beam should be measured with the theodolite at the center, at radial distances representing ⅓, ⅔, and 3⁄3 of the beam dimension at 0, 90, 180, and 270° and at the edge of the beam at 45, 135, 225, and 315°. These test points are representative only. Different points providing equivalent coverage may be chosen for different installations. The top and bottom planes of the test volume cylinder should be tested at the beam edges at 0, 90, 180, and 270° orientations each. If these latter values are not predictable or as expected, more readings should be taken.

8.8.2.6 These measurements normally will have variations throughout the test volume. The worst cases of subtense and divergence angle should be used and quoted for the system. However, all measurements should be carefully preserved because individual test items frequently can be positioned within the nominal test volume to take advantage of the best portions of the beam.

8.9 *Vacuum Gages:*

8.9.1 Vacuum gages shall be used in accordance with Practices E296.

8.9.2 Vacuum gages shall be calibrated in accordance with Method E297.

9. Operations and Maintenance

9.1 *Applicability*—This section will discuss primarily the operation and maintenance of large space-simulation chambers with cryogenically cooled shrouds, pumping systems capable of 10^{-4} torr or less, and high-caliber solar simulators with A and B characteristics listed in Section 7. The operations described will be thermal-balance testing or systems testing integration. Many of the recommendations apply to smaller and/or less sophisticated chambers, of course. The subject matter will include chamber operation before, during, and after the test; procedures and documents; maintenance and calibration; and cleanliness and contamination.

9.2 *Related Topics*—Certain topics that are closely related to this subject matter can be found in other sections of this recommended practice:

Topic	Sections
Instrumentation Calibration	8
Safety	6
Test Requirements	7
Types of Tests and General Considerations	5

9.3 *Space Simulator Operations Organization:*

9.3.1 A great deal of flexibility exists in setting up an organization for operating a space simulator. The size and complexity of the facility and the test objectives will determine the degree of specialization and departmentalization required to operate the following systems and functions:

9.3.1.1 *Chamber Vacuum System,*

9.3.1.2 *Chamber Cryogenic System,*

9.3.1.3 *Chamber Solar Simulator,*

9.3.1.4 *Chamber Instrumentation,*

9.3.1.5 *Test Item Instrumentation Readout Equipment,*

9.3.1.6 *Building Utilities and Physical Plant Water, Electrical Systems, and Heavy Equipment, Gas Ventilation and Air Conditioning,* and

9.3.1.7 *Test Planning, Coordination, and Report Writing.*

9.3.2 The last item, test planning, deserves special consideration. There is generally a need for test planners who are able to relate the customer requirements to the facility. This group should be organizationally separate from both the customer and the chamber operating group, at least at the group engineer level, to make possible an objective outlook to the test. The test planner needs an intimate knowledge of the chamber and its performance but also familiarity with the customer's concerns such as thermal design, test item function and purpose, and so forth.

9.4 *Procedures and Documentation*—All procedures and facility performance that are routine should be documented and the documents used. The safety of the personnel, facility, and test item are dependent on proper procedures. It is generally impossible for even experienced engineers and technicians to remember all procedures in their proper order. Documents are very valuable in training new personnel, refreshing the memories of experienced personnel, and upgrading. Perhaps most important of all, the responsible engineers who prepare the procedures and the supervisors who approve them are more likely to give careful thought to the best way to carry out their responsibilities. Procedures and performance documents are also valuable to other groups such as the customer, safety department, and service departments.

9.4.1 *Facility Operations Manual:*

9.4.1.1 It is desirable to file all procedures in a single loose-leaf manual, if possible, so that a single source will be available. A typical list of topics for this manual is as follows:

INDEX OF PROCEDURES

1.0 Emergency
2.0 Operations
3.0 Maintenance
4.0 Administration
5.0 Training
6.0 Safety
7.0 Calibration
8.0 Schematic Diagrams
9.0 Special Equipment
10.0 Valves and Interlocks
11.0 Test Item Handling
12.0 Operational Instrumentation

9.4.1.2 An example of the further breakdown of each topic is that for "2.0 Operations";

2.0 OPERATING PROCEDURES

INDEX

2.1 To Close and Open Chamber Door
2.2 Chamber Pre-Evacuation
2.3 To Evacuate Chamber
2.4 To Fill the LN_2 Storage Tank
2.5 To Chill to Warm the Contamination Plates
2.6 Temperature Control of Shroud System
2.7 Mirror Temperature Control
2.8 Backfill Sequence Using GN_2, Contamination Plate
2.9 To Backfill Chamber Using Facility Filtered Air
2.10 Hourly Inspection Tour Check List
2.11 Priming and Securing LN_2 Pumps
2.12 Solar Simulator Pre-Operation Inspection Check List
2.13 Solar Hood Purge Procedure
2.14 Lamp Operating Procedure
2.15 Vacuum System Conditioning with Chamber at Atmosphere
2.16 Pre-Operation Emergency Equipment Check List
2.17 To Secure Facility

9.4.1.3 A detailed consideration of these topics is beyond the scope of this practice. Since similar documents are available at most space-simulation facilities, personal contacts should be made to obtain copies, if needed. Certain special areas of concern for solar simulation are discussed in 9.5.

9.4.2 *Facility Performance*—The performance of the various systems of the space simulator should be described in one or more documents for the use of customers and operations personnel.

9.4.2.1 *Vacuum System*—Effective pumping speed, method of trapping all pumping ports, pumpdown and chilldown time, ultimate pressure.

9.4.2.2 *Contaminant Measurement Systems*—Contaminant levels during pumpdown, test, shutdown and with the chamber open. Particulate contaminant levels in the room just outside the chamber door should be noted.

9.4.2.3 *Cryogenic System*—Reflecting and emission from the cold wall with the solar beam on and off.

9.4.2.4 *Solar Simulation System*—Solar simulation data that should be provided are:

(a) Total irradiance,
(b) Uniformity of irradiance,
(c) Spectral irradiance,
(d) Solar beam subtense angle,
(e) Divergence angle of the solar beam, and
(f) Maximum usable beam diameter and depth.

9.4.2.5 The uniformity of irradiance must relate local irradiance with position throughout the test volume, usually in the form of an isoirradiance plot (lines of constant irradiance relative to beam position in the test volume). The usable beam diameter is apparent from this plot. The isoirradiance lines may be expressed in percent of one solar constant. Measurements of irradiance should be made as described in 8.2. It is important that chamber-reference points be identified on the isoirradiance plot. The spectral-energy distribution measured should be compared to the solar spectrum, and tabulated similarly to the example contained in Table 8.

9.4.3 *Special Instruction Manuals*—Because of the great amount of detail in complex systems it is desirable to have special operating, maintenance, and instruction manuals for the solar-simulator, computer-data systems, and so forth.

9.4.4 *Daily Space Simulator Log.*

9.4.5 *Test Plan and Test Reporting*—Special documents that vary with each test include test plans and a final report (see section 9.4 describing the test planning group). Results of meetings with the customer, special test item procedures, and

TABLE 8 Spectral Energy Distribution (Class B)

NOTE 1—Eight of the bandwidths above must fall within the required ratio tolerances for Class B spectrum.

Band No.	Bandwidth, nm	AM0SI per Bandwidth, W/m^2	SSI Normalized to 1300 W/m^2 (W/m^2)	Ratio of SSI/AM0SI	Required Ratio Tolerances
1	250–300	13.8			0.35–1.65
2	300–350	44.7			0.35–1.65
3	350–400	56.9			0.35–1.65
4	400–500	188.0			0.50–1.50
5	500–600	177.0			0.50–1.50
6	600–700	151.0			0.50–1.50
7	700–850	176.0			0.35–1.65
8	850–1000	130.0			0.35–1.65
9	1000–1500	232.0			0.20–1.80
10	1500–2000	92.7			0.20–1.80
11	2000–2500	37.9			0.20–1.80
Total Irradiance 1300 W/m^2					

preliminary and final test plans should be written and distributed. The final test report should contain a copy of the final test plan.

9.5 *Calibration:*

9.5.1 *Test Equipment Calibration*—Individual items of test equipment are generally maintained in calibration by a standard lab or test equipment group in the company. If not, a routine maintenance and calibration system must be set up. Some test equipment calibrations unique to space simulation are described in Section 8.

9.5.2 *Solar Simulator Calibration:*

9.5.2.1 The solar data in 9.4.2.4 are needed by the customers and operators of the facility. Periodic calibration is necessary of the first two items, total irradiance and uniformity of total and spectral irradiance.

9.5.2.2 Calibration frequency of the solar simulator is primarily dependent on the number of operating hours accumulated on the system and the type of simulator. It is usually established by past performance of the system and covers an operating time span in which the system performance does not change. Initially, the solar simulator would normally be given an acceptance test and a thorough calibration. Then it is suggested that a calibration be performed at least twice for each test, once before the test and again after the test is completed. This is because the scanner used to calibrate the solar beam in the test volume must be removed to allow for installation of the test article. However, some facilities have retractable scanners mounted in the space chamber such that they can be deployed during the test and the uniformity of irradiance measured any number of times during the test. Two points of concern with respect to this method are: (*a*) the uniformity of irradiance is not measured exactly in the test volume at the test article position and (*b*) further inaccuracies in thermal-sink simulation occur as a result of the scanner mechanism acting as a thermal source unless it is properly shielded.

9.5.2.3 A secondary consideration is the time the simulator was in a standby condition. For example, if the simulator has been inoperative for several weeks, it is usually good test procedure to spot-check the last calibration to ensure that there has not been any significant change in the performance such as misalignment or optical degradation. However, it may be a test requirement that a specific calibration schedule be established in order to support, for example, a long-term component degradation test.

9.5.2.4 The calibration may require only a few hours or as much as one or two days to complete, depending on the size of solar simulator. However, alignment and refurbishment of the optics and lamp changes could last several weeks, depending on the type of system and lead time for procurement and/or replacement of parts.

9.5.2.5 After a number of solar calibrations have been performed, the changes in performance can be assessed as a function of operating time, calendar time, lamp operating power, and so forth. It is generally possible then to reduce the frequency of calibration. Obviously, good and complete records of the solar-simulator system, individual lamps, and other components must be kept.

9.5.2.6 The solar-simulator continuous operational time is a function of the life of the source or lamp and the reflective surface degradation rate. The lamp light output or energy output will drop off with time because of contamination deposits on the inside of the lamp. Further requirements for increased power input to the lamp result in optical degradation of the reflective surfaces. It should be pointed out that for off-axis- or mixer-type systems, spare sources may be in the system. As the original source approaches its expected life, the spare can be started. Replacement of the used sources could then be accomplished one at a time, enabling the simulator to operate continuously. The effects on the system performance would not be noticed during the replacement. For on-axis systems, the source can also be exchanged for other prealigned sources during test. The results, however, would require that the source be turned off during the exchange for a period of approximately 1 h. This is not expected to cause any significant change in the test results.

9.5.2.7 The approximate actual lamp lifetimes to be expected can be taken as the manufacturer's warranted lifetime, derated to provide the desired margin against failure. However, actual operating experience will provide the best guide since lamp life will vary considerably between different installations.

9.5.3 *Heat Sink of the Space Chamber*—Other sources of energy must be considered in the final temperature-equilibrium measurements. For example, the liquid nitrogen shroud is painted black and cooled to absorb most of the energy striking it. Solar simulation optics, test article support structure, view ports, and condition of the black paint on liquid nitrogen shrouds all contribute to the effective heat sink of the chamber. Two methods can be used to determine the chamber cold-sink properties. The first is by the use of radiometers strategically placed in the chamber at critical locations and operating irradiances measured during an actual simulated test condition. This would require the measurements to be made with the solar simulator on and off to obtain the net effective heat sink. The other method consists of determining the nature and location of all energy sources within the space environment with respect to the test article, and including this in the final thermal analysis of the test results. Total reflected and emitted radiation arriving at the test vehicle for several classes of cold sinks, exclusive of the solar simulator, is shown in Table 3.

9.6 *Operating the Facility:*

9.6.1 *Test Item Considerations*—Generally, the test item is designed, built, handled, and system-tested by others. The space-simulator operation is a service function to the spacecraft (test-item) group. However, certain aspects of the spacecraft handling, fabrication, and system test are of direct concern to and involve the simulator group. A test planner who aggressively performs this liaison function will generally ensure an on-time test completion that meets all of the objectives.

9.6.1.1 *Spacecraft Design and Fabrication*—Simulator personnel should become involved with the earliest stages of spacecraft design, especially if the designers are inexperienced. The simulator group's principal interest is in the materials of construction and component preconditioning. Self-contamination of a spacecraft and of the facility is quite common because of vacuum outgassing of improper materials.

Space-qualified material lists and components are available and should be used. A preconditioning vacuum treatment of non-qualified materials should be performed at temperatures above their expected operating temperatures. A conditioning chamber equipped with a full liquid nitrogen cold wall, heating means, and a pumping system capable of pressures below 5 × 10^{-5} torr during outgassing should be used. The minimum time and temperature required can be determined from the following equation (Ref **16**).

$$\log t_s - \log t_b = 0.0524 \ \Delta E_c \left[(1/T_s) - (1/T_b)\right] - 1 \quad (19)$$

where:

t_s = time the spacecraft component will be under vacuum in the simulator, h,
t_b = time of bakeout conditioning, h,
T_s = anticipated temperature of component in the simulator, K,
T_b = temperature of bakeout, K, and
ΔE_c = critical absorption energy, cal $(\text{J mol})^{-1} = 19.2\,(16.2 + \log t_s)\,T_s$.

9.6.1.2 *Test Fixtures, Thermal Isolation, Instrumentation*—The method of mounting the spacecraft to meet the test objectives should be worked out jointly by spacecraft and simulator personnel.

9.6.1.3 *Test Objectives*—The simulator group must keep foremost in mind the customer's test objectives. Operating procedures may have to be modified to satisfy the test.

9.6.1.4 *Spacecraft Handling*—While this is primarily the responsibility of the spacecraft crew, the entire operation must be carefully planned with simulator personnel to ensure that proper equipment is available, including building cranes, instillation equipment, simulator-preparation area, fixtures, and so forth.

9.7 *Contamination:*

9.7.1 *Particulate Contamination of the Spacecraft*—Operators of many of the newer facilities are fortunate to have cleanroom design features incorporated into the building construction. Spacecraft groups generally desire, if not demand, Class 100 000 to 10 000 cleanrooms, per Federal Standard 209-B or equivalent, or better. It is generally uneconomical to change a standard building into a cleanroom. Several alternative schemes should be considered.

9.7.2 *Air-Conditioned Space Simulator*—Frequently the space simulator can be air-conditioned with highly filtered air. Large ports or doors at the top and bottom of a chamber will permit pumping air in at the top to provide a downward flow. Excess open areas at the bottom should be sealed off to maintain a positive pressure and avoid entry of dust from the outside. Although the air velocity will seldom approach that of a laminar-flow room, surprisingly low particulate levels can be achieved. In some cases, it is possible to bring the simulator in its shipping container right into the air-conditioned space chamber. First the container is cleaned, and then the simulator is removed and mounted in the chamber for test preparation.

9.7.2.1 *Portable Cleanroom*—One or more portable laminar-flow rooms may be installed adjacent to the chamber, especially if a side-opening door is available. The chamber-door opening is sealed to the cleanroom. Test preparation, component storage, and so forth, can be carried out in the portable cleanroom.

9.7.3 *Contamination Under Vacuum:*

9.7.3.1 *Introduction:*

(a) Many sources of contamination exist in the simulated-space environment. These contaminants cause optical degradation of the solar-simulator mirrors as well as coating the space chamber and the spacecraft. Outgassing and migration of the molecules throughout the space chamber eventually reach the solar-simulator mirrors. High solar irradiance on the mirrors and the concentration of ultraviolet energy can cause major reflectance degradation of the mirrors. Then, to maintain a constant irradiance level in the test volume, an increase in input power to the system is required. Measurement of the degradation rate and correction of the irradiance in the test volume can be accomplished by continuously monitoring the solar-beam irradiance within the space environment.

(b) The most uncontrolled source of contamination that causes mirror degradation is the spacecraft. Other sources of contamination include mechanical pumps, oil diffusion pumps, residue from previous tests, and atmospheric exposure. Basic chamber contamination should be measured prior to test. Then, during the test of the spacecraft, the total contamination can be determined and a comparison of the chamber background should indicate the spacecraft contamination. These measurements may be taken by means of a mass spectrometer, witness plates, quartz crystal microbalances, or other similar devices. This information provides a history for determining the causes of mirror degradation and corrective action to prevent recurrence in the future.

9.7.3.2 *Contaminants from the Spacecraft:*

(a) Most residues obtained during the after space simulation tests show that the contaminants are outgassed materials from the spacecraft, and/or its cabling and fixtures. Selection of proper materials during the design stage and preconditioning (see 9.6.1.1) will eliminate or greatly reduce this problem.

(b) If these precautions have not been taken, it may be necessary to consider a bakeout phase in the test sequence. This could eliminate, or at least reduce, the degradation of the solar simulator. The bakeout phase should remove most of the contaminants from the spacecraft and test fixtures. Before the thermal vacuum test, the test articles are baked at a maximum allowable temperature until a pressure of no more than twice the anticipated chamber pressure during the test is reached. If this is not feasible, the bakeout may be discontinued after achieving a pressure of 1 × 10^{-5} torr or less for a period of 4 h. The test article is placed within a semi-enclosure inside the space chamber. The test-article temperature is brought up slowly and the chamber pressure monitored. The test article is

heated by infrared panels or similar devices located within the enclosure. The enclosure is kept at a low temperature to trap and condense the contaminants as they are liberated.

9.7.3.3 *Contamination from the Facility During Test:*

(a) In addition to contamination from the spacecraft, contaminants can come from a large variety of sources within the space chamber and its associated equipment. Examples are backstreaming diffusion and mechanical-pump oil, cleaning detergents, and volatiles in shroud paint, wiring, organic seals.

(b) It is probably true that most contamination comes from the test item. However, this should not be used as a shield for mediocre chamber operations. Some spacecraft are clean but have devices unusually sensitive to the chamber contaminants.

(c) Measuring low levels of high molecular weight contaminants is difficult; it is expensive in equipment and personnel. Less sophisticated measurement techniques generally show no contamination. Furthermore, if the contaminant levels were known accurately, there is very little information available on the damage a particular compound does to a particular spacecraft surface.

(d) The fact that measurements are difficult or show negative results (with gross methods) does not mean that there is no problem.

(e) The reputation of oil diffusion pumped chambers is so poor in some quarters that some customers will not use them. Large facilities have even been converted from oil diffusion to other means of pumping. Most of the poor reputation is due to faulty operating techniques.

(f) Under these conditions the responsible simulator operator will redouble efforts to avoid contamination even though there are no effective measurements and damage data.

(g) It is probably a good assumption that most space chambers have walls that contain contaminants that will outgas or evaporate and then migrate to the spacecraft. Most large space chambers have extensive cold-shroud systems to simulate the radiation field of space. These are excellent pumps for contaminants from the spacecraft, the room temperature pressure vessel, seals, diffusion and fore pumps, and so forth. Most of the test-item contamination from such chambers occurs after pumpdown before the shrouds are cooled or during warmup of the shrouds. Thus, one of the most important operating rules is to minimize the time of vacuum operation with uncooled shrouds. Also, a clean-gas purge as described below is very helpful during these periods.

(h) A test chamber that has no cold shrouds requires a much higher degree of cleanliness. A high-temperature vacuum bakeout before test is essential if the walls could have become contaminated from the previous test item, oil pumps, organic seals, etc.

(i) A valuable accessory to the chamber cold shrouds is a contamination plate, a separate liquid nitrogen cooled plate that can be rapidly chilled during pumpdown and kept cold continuously through shroud warmup at the end of the test. It should be 1 m^2 or larger for large chambers. It should be mounted so as to minimize the radiative transfer to the spacecraft, that is, edge toward the spacecraft.

9.7.3.4 *Effect of Pressure:*

(a) At atmospheric pressure the migration of contaminants is minimal. There is little danger from contaminant migration until the mean free path (distance between molecular collisions) increases to 1⁄10 the distance from the wall to the test item. This is equivalent to 5×10^{-5} torr for a 1-m distance. If the shrouds are still warm when this pressure is reached during pumpdown, relatively large quantities of gas are being outgassed, some of which will migrate and stick to the spacecraft. Thus, the cooling of the cold shrouds should be started before this pressure is reached and purge should be used as explained in 9.7.3.5.

9.7.3.5 *Chamber Purge:*

(a) During pumpdown and warmup, when the cold shrouds are not completely cooled, it is desirable to maintain a clean-gas purge in the chamber. The shrouds, if cooled to 100K or below, act as very efficient pumps for vacuum condensible material. Without a purge or adequately cooled shrouds, the large variety of contaminants in most chambers are free to outgas, and reflect off the warm walls. Depending on the contaminants, concentration, and spacecraft surface temperature, there is a certain probability that these molecules will stick to the spacecraft. An even worse situation occurs during warmup. Then the evaporation from the shroud is greater because most of the contaminants generated during the test were frozen onto the shroud. They are released in the vicinity of the spacecraft as the shrouds warm up. Thus, the purge is needed during pumpdown–cooldown and for warmup, as well.

(b) A number of factors must be considered in the design of a purge system. The technical limit on the amount of purge gas is the danger of chilling the spacecraft. Except for this, it would be desirable to start a high purge rate before the shrouds start to warm up.

(c) It is a good procedure to turn on the purge when pumpdown is started at a rate equal to the nominal mass flow rate at the bottoming-out pressure of the first stage pumps. Normally, the diffusion pump speed is 100 to 1000 times larger than the roughing pump speed. As soon as the diffusion pumps start pumping, the purge flow rate can be increased to maintain 0.5 to 1.0×10^{-3} torr. When this pressure is reached, the contamination plate should be cooled, followed by the cold shrouds.

(d) The purge gas should be injected into the chamber on the opposite side of the chamber from the pumping ports. That is, the purge gas should surround and sweep across the test item on its way to the pumping ports. Also, the injection of gas should be through a diffuser, for example, a porous metal. Otherwise, under some conditions of flow and low pressure, high velocities will result with possible damage to the test specimen or equipment. A diffused, low-velocity flow originating near the spacecraft and moving outward from the spacecraft is the ideal. As the shroud temperature drops, the purge flow should be reduced to avoid chilling the spacecraft.

9.7.3.6 *Mechanical Roughing and Forepump:*

(a) Mechanical pumps are frequently high-contaminant sources because of their relatively high oil vapor pressures at operating temperatures. Also, the tendency of some pumps to

become contaminated with water vapor accentuates the backstreaming. Even rotary-lobe blowers and turbomolecular pumps are contaminant sources (**17**).

(b) Some of the precautions that should be taken are as follows:

(1) As the chamber is roughed down, close the roughing valve when the pressure drop in 1 min declines to 20 % of the chamber pressure. For example, if pumpdown from 50 to 40 mTorr requires less than 1 min, but it requires 1 min or more to reduce the pressure from 40 to 32 mTorr, close the roughing valve at 32 mTorr. Backstreaming rapidly increases as the bottoming-out pressure approaches.

(2) Use a purge as described in 9.7.3.5.

(3) Use effective traps in the roughing line and diffusion pump forelines. These may be high-conductance sorption traps or cold traps. In either case, the design must be adequate for effective trapping from viscous flow to molecular flow conditions.

(4) Use gas ballast in the first stage mechanical pumps to avoid water contamination of the oil.

9.8 *Maintenance:*

9.8.1 Maintenance of the solar simulator is a continuous function during thermal-vacuum testing of the spacecraft and is included here to illustrate typical problems associated with the operation of the solar simulator. The two major problems are lamp life and optical degradation. The continuous operating life of the solar simulator is primarily limited by the life of the lamp. The average lamp will degrade approximately 29 % over its life span. This means that the input power to the lamp will increase by 20 % to maintain a constant output irradiance level. As the lamp envelope darkens, it absorbs more of the ultraviolet portion of the spectrum and causes additional heating of the lamp which results in a spectral shift towards the infrared in the solar simulator spectral energy distribution performance.

9.8.2 To ensure continuous reliable system performance, the replacement lamps and refurbished optical reflective surfaces require rigid procurement specification and acceptance tests. A good example of this is the Joint Industry/Government Standard Drawing-Spectrolab, No. 015978, revision B.[8] This drawing provides for a standard configuration that is compatible for most solar simulators using the 20/30-kW xenon compact arc lamp. Similar drawings and specifications can be established for any size lamp.

9.8.3 There are several causes for spectral energy distribution shifts. One cause is normal optical degradation. This is caused by the irradiance level on the mirror surface, the type of reflective surface/substrate composition, and the environment to which the mirrors are exposed. Additional degradation is caused by the high level of ultraviolet radiation from the lamps which is detrimental to optics and materials.

9.8.4 The lamps may vary in spectral output. Darkening of the envelope will shift the spectral distribution. To overcome this degradation, the power must be increased which also shifts the spectrum.

9.8.5 Section 11 of Ref (**18**) contains more suggestions for solar simulator maintenance.

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[8] Available from Spectrolab, Inc., Division of TEXTRON, 12484 Gladstone Ave., Sylmar, CA 91342.

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