Designation: E491 – 73 (Reapproved 2020)

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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

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

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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.

2.2 *ISO Standard:*

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

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

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	Φ	=	dQ/dt	watt (joule/second)	$\mathrm{W, Js^{-1}}$
E	irradiance (receiver) flux density	E	=	$d\Phi/dA$	watt per square metre	$\mathrm{W{\cdot}m^{-2}}$
M	radiant exitance (source)	M	=	$d\Phi/dA$	watt per square metre	$\mathrm{W{\cdot}m^{-2}}$
I	radiant intensity (source)	I	=	$d\Phi/d\omega$	watt per steradian	$\mathrm{W{\cdot}sr^{-1}}$
		ω	=	solid angle through which flux from source is radiated		
L	radiance	L	=	$dI/(dA\cos\theta)$	watt per steradian = square metre	$\mathrm{W{\cdot}sr^{-1}{\cdot}m^{-2}}$
		θ	=	angle between line of sight and normal to surface dA		
τ	transmittance	τ	=	Φ, transmitted/Φ, incident	none	
$\tau(\lambda)$	spectral transmittance	$\tau(\lambda)$	=	$\Phi(\lambda)$, transmitted/$\Phi(\lambda)$, 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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[4] Withdrawn.

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

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 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·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·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:

$$\bar{E} = \int_v E(r,\theta,z)\mathrm{d}V / \int_v \mathrm{d}V \qquad (1)$$

where:

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

3.2.31 *irradiance, spectral* $[E_\lambda$ *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):

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

where:

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

The constants are:

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

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

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.

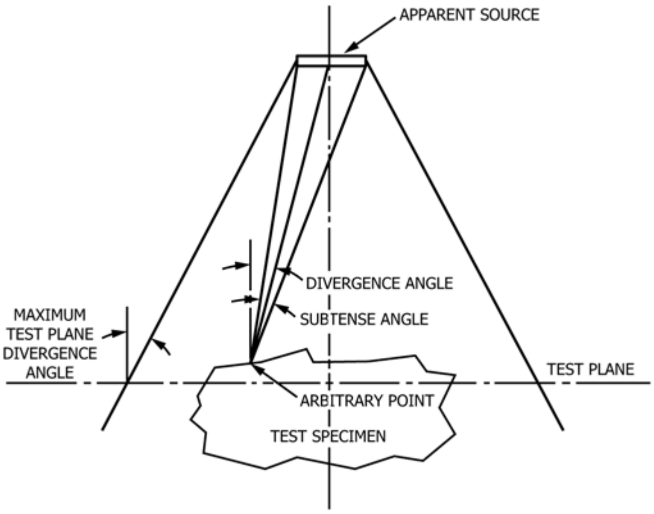

FIG. 1 Solar Subtense and Divergence Angles

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

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 $W\cdot sr^{-1}m^{-2}$.

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 $W\cdot m^{-2}$ (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 $W\cdot sr^{-1}$ (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.

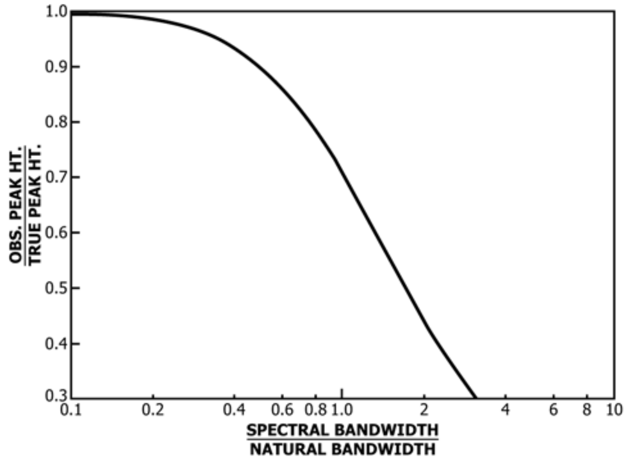

FIG. 2 Relationship of Peak Height to Spectral Bandwidth/Natural Bandwidth Ratio

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	$2.997\,925 \cdot 10^{8}$ $m \cdot s^{-1}$
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, 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

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

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 $\lambda = 0.297$ 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:

$$\alpha = \int_0^\infty \alpha(\lambda)E(\lambda)\mathrm{d}\lambda / \int_0^\infty E(\lambda)\mathrm{d}\lambda \tag{8}$$

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 100 K, $\varepsilon = 0.02$, 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