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SELECTED BIBLIOGRAPHY AND ABSTRACTS OF HIGH-TEMPERATURE OPTICAL PROPERTIES AND THEIR MEASUREMENT

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ABSTRACT

This bibliography was prepared to list the sources containing emissivity and absorptivity data on materials at extremely high temperatures. Experimental work to determine data in these listings was done using both the absolute and comparative methods for obtaining values. In the absolute method the values were calculated by knowing the power input and losses and the resulting surface temperature of the sample. In the comparative method the values were obtained by a comparison of sample and blackbody radiation at the same temperature. Data available from these two methods are limited and are also inconsistent in value from one laboratory to another. Terminology in the various sources is not consistent, but definition conflicts are being resolved. One very difficult problem in comparing results in these sources is to recognize the possible error in measurements made at high temperatures, especially errors in determining temperatures of samples above 1500° K. The sample temperature and degree of specularity must be known, but present values are neither accurate nor reliable when experiments are duplicated. Accurate data for emission and absorption in the optical wavelength band of the spectrum for materials at high temperatures are necessary in heat transfer analyses and radiometric instrumentation in satellites. Emphasis in this bibliography was placed on listings giving information about the instrumentation used in the experimental work. Thus, the experimental techniques, equipment, and efforts of the

experimenters to characterize the materials used and methods to evaluate the errors are given in the sources in this bibliography.

NASA — GEORGE C. MARSHALL SPACE FLIGHT CENTER

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By

D. W. Gates

SPACE SCIENCES LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

SELECTED BIBLIOGRAPHY AND ABSTRACTS OF HIGH-TEMPERATURE OPTICAL PROPERTIES AND THEIR MEASUREMENT

INTRODUCTION

Historically, this bibliography is the result of a search for elevated temperature values of emission and absorption and the decision that experimental work was necessary. Emphasis is placed here on instrumentation, and both the absolute and comparative methods are included. The value is obtained in the absolute technique by a knowledge of the power input and losses and the resulting surface temperature of the sample, or by a comparison of sample and blackbody radiation at the same temperature in the comparative method. The experimental techniques, equipment, and efforts of the experimenters to characterize the materials used and to evaluate their errors are given.

Available data are limited and inconsistent in value from one laboratory to another. Terminology is not consistent, but definition conflicts are gradually being resolved. However, one very difficult problem is the measurement of high temperatures, especially above 1500°K. The sample temperature and degree of specularity must be known, but present values are neither accurate nor reliably reproducible.

Various investigators in the field were contacted to try to insure that the bibliography, which includes information concerning available equipment, is as complete as possible to mid-1967. Some of the articles of special interest were abstracted to facilitate entry by the user into this area of research.

BIBLIOGRAPHY

1. Taylor, A. H.: Measurement of Diffuse Reflection Factors and a New Absolute Reflectometer. Scientific Papers of Natl. Bur. of Std., vol. 16, 1920, pp. 421-436.

2. McNicholas, H. J.: Absolute Methods in Reflectometry. J. Res. Natl. Bur. Std., vol. 1, 1928, pp. 29-73.

3. Priest, I. G.; and Riley, J. O.: The Selective Reflectance of Magnesium Oxide. J. Opt. Soc. Am., vol. 20, 1930, p. 156.

4. Ornstein, L. S.: Tables of the Emissivity of Tungsten as a Function of Wavelength from 0.23 to 2.0 in the Region of Temperature 1600° - 3000°K. Physica, vol. 3, 1936, pp. 561-562.

5. Worthing, A. G.: Temperature Radiation Emissivities and Emittances. J. Appl. Phys., vol. 11, June 1940, p. 421.

6. Gouffe, A.: Temperature Corrections of Artificial Blackbodies, Taking Multiple Internal Diffusion into Consideration. NRL Trans. 429, translated from Revue d'Opt., vol. 24, 1945, pp. 1-10.

7. Hamaker, H. C.: Radiation and Heat Conduction in Light-Scattering Material. Parts I - IV, Philips Res. Rep. 2, 1947, pp. 55-67, 103-111, 112-125, 420-425.

8. McMahon, H. O.: Thermal Radiation from Partially Transparent Reflecting Bodies. J. Opt. Soc. Am., vol. 90, no. 6, June 1950, p. 376.

9. Sanders, C.; and Middleton, E. K.: The Absolute Spectral Diffuse Reflectance of Magnesium Oxide. J. Opt. Soc. Am., vol. 41, no. 6, June 1951, p. 419.

10. Hamilton, D. C.; and Morgan, W. R.: Radiant-Interchange Configuration Factors. NACA TN 2836, 1952.

11. Sully, A. H.; Brandes, E. A.; and Waterhouse, R. B.: Some Measurements of the Total Emissivity of Metals and Pure Refractory Oxides and the Variation of Emissivity with Temperature. Brit. J. Appl. Phys., vol. 3, no. 3, March 1952, pp. 97-101.

12. Sanders, C.; and Middleton, E. G.: The Absolute Spectral Diffuse Reflectance of Magnesium Oxide in the Near Infrared. J. Opt. Soc. Am., vol. 43, no. 1, January 1953, p. 58.

13. DeVos, J. C.: A New Determination of the Emissivity of Tungsten Ribbon. Physics, vol. 20, 1954, pp. 690-714.

14. Geir, S.; Dunkle, R. V.; and Bevans, J. T.: Measurement of Absolute Spectral Reflectivity from 1 to 15 Microns. J. Opt. Soc. Am., vol. 44, no. 7, July 1954, p. 558.

A device that can be used for the measurement of the absolute reflectivity or reflectance of metals, paints, etc. is described. The unit is used in conjunction with a Perkin-Elmer Model 83 monochromator equipped with an NaCl prism for the wavelength range 1.0 to 15.0 microns. Preliminary results for MgO, polished copper, molybdenum, and electrolytic gold are presented.

15. Dike, P. H.: Temperature and Its Measurement. High-Temperature Technology, I. E. Campbell, ed., John Wiley & Sons, Inc., 1956, pp. 335-357.

Methods, optical pyrometers, emissivity, reflected radiation, "total" radiation pyrometry, emissivity as affecting radiation pyrometry, flame radiation, and color temperature are among the topics discussed. This represents an attempt to present briefly some of the methods by which the laws of radiation are applied to the measurement and control of high temperatures. Strong emphasis has been placed on sources of error, particularly those resulting from uncertain and variable emissivities of radiating bodies.

16. Douglas, E. A.: Investigation Directed Toward the Development of Ceramic Coatings with High Reflectivities and Emissivities for Use in Aircraft Power Plants. WADC TR-56-110, February 1956. [Bettinger Corp., Waltham, Mass.; Contract AF 33(616)2376]

While the emphasis is on coating development, some details are given of the measuring techniques.

17. Gardon, R.: The Emissivity of Transparent Materials. J. Opt. Soc. Am., vol. 39, no. 8, August 1956, p. 278.

18. Sundheim, B. R.; and Greenberg, J.: High-Temperature Modification of Beckman DU Spectrometer. Rev. Sci. Inst., vol. 27, no. 9, September 1956, pp. 703-704.

19. Larrabee, R. D.: The Spectral Emissivity and Optical Properties of Tungsten. Res. Lab. Electronics Tech. Rep. 328, May 21, 1957. [Massachusetts Inst. of Tech.]

20. Klemm, R. E.: Emissivity and Reflectance of Selected Surface Coatings. NAA NA-57-707-6, February 5, 1958. [North American Aviation]

21. Betz, H. T.; et al.: Determination of Emissivity and Reflectivity Data on Aircraft Structural Materials. WADC TR 56-222, Part 2, October 1958.

22. Olson, O. H.; and Morris, J. C.: Determination of Emissivity and Reflectivity Data on Aircraft Structural Materials. WADC TR 56-222, Part 3, 1959.

23. Reid, C.; and McAlister, E.: Measurement of Spectral Emissivity from 2 to 15 Microns. J. Opt. Soc. Am., vol. 49, no. 1, January 1959, p. 78.

24. Wade, W. R.: Measurements of Total Hemispherical Emissivity of Several Stably Oxidized Metals and Some Refractory Oxide Coatings. NASA Memo 1-20-59L, January 1959.

Methods used to obtain oxide coatings of high emissivity suitable for application to the radiative cooling of hypersonic aircraft are presented. Values of total hemispherical emissivity were obtained for several high-temperature materials including type 347 stainless steel and Haynes alloys C, X, and 25. Tests were also conducted on tungsten and Haynes alloy B, but because of the nature of the oxide coatings produced, values of emissivity were not obtained. Measurements of the total normal emissivity of flame-sprayed coatings of alumina and zirconia are also included.

25. Richmond, J. C.; and Steward, J. E.: Spectral Emittance of Uncoated and Ceramic-Coated Inconel and Type 321 Stainless Steel. NASA Memo 4-9-59W, April 1959. [Natl. Bur. of Std.]

26. Wade, W. R.; and Casey, F. W., Jr.: Measurements of Total Hemispherical Emissivity of Several Stably Oxidized Nickel-Titanium Carbide Cemented Hard Metals from 600° to 1600° F. NASA Memo 5-13-59L, June 1959.

The measurements are presented for both as-received and polished test specimens together with a brief description of the equipment and procedures used. Results of investigations of the surface condition of these materials as obtained by x-ray diffraction methods, and metallurgical techniques are presented to indicate the type of surface on which these measurements were made.

27. Harrison, W. N.; Richmond, J. C.; Plyler, E. K.; Stair, R.; and Skramstad, H. K.: Standardization of Thermal Emittance Measurements. WADC TR 59-510, August 1959. [Natl. Bur. of Std.]

28. Butler, C. P.; and Inn, E. C. Y.: Method for Measuring Total Hemispherical Emissivity of Metals. Surface Effects on Spacecraft Materials, F. J. Clauss, ed., John Wiley & Sons, Inc., 1960, pp. 195-207. [Nucleonics Div., Naval Radiological Defense Lab., San Francisco; and Lockheed Missiles and Space Div., Sunnyvale, Calif.]

Method for measuring the temperature dependence of hemispherical emissivity of metals; presents typical results obtained. Although the method is not generally applicable to all types of metals, it may be particularly appropriate for special cases. Pt and Cu results are given.

29. Crompton, M.: High-Temperature Emissivity Measurements at the Martin Co. Surface Effects on Spacecraft Materials, F. J. Clauss, ed., John Wiley & Sons, Inc., 1960, pp. 212-219. [Martin Co., Baltimore, Md.]

Total normal emittance of various uncoated and coated ceramic materials was investigated as a function of temperature. Total radiation measurements were made, and two blackbodies used to calibrate systems. Rance is given up to 5000° F.

30. Dunkle, R. V.: Spectral Reflectance Measurements. Surface Effects on Materials, F. J. Clauss, ed., John Wiley & Sons, Inc., 1960, pp. 117-136. [Dept. of Mech. Engr., Univ. of California, Berkeley]

The term reflectance is used to denote the characteristic of a system rather than a property and includes the effects of surface roughness, oxide layers, evaporated films, and any type of surface contamination. Spectral reflectance of materials is paramount in the control and prediction of spacecraft temperatures, and the subject is covered as follows: types of reflectometers, Coblentz, integrating-sphere, and Gier-Dunkle blackbody. Each system has certain inherent errors, and different techniques are required for different spectral regions.

31. Olson, O. H.; and Katz, S.: Emissivity, Absorptivity, and High-Temperature Measurements at Armour Research Foundation. Surface Effects on Spacecraft Materials, F. J. Clauss, ed., John Wiley & Sons, Inc., 1960, pp. 164-181. [IIT Research Institute, Chicago]

Emissivity and absorptivity measurements have been made for the following conditions:

1. Total normal emittance from -300° to +3000° F
2. Normal Spectral emittance at 0.665 microns wavelength up to 3000° F
3. Solar absorptivity at ambient temperature
4. Normal spectral absorptivity in the 1 to 13 micron wavelength range from 200° to 1850° F

Equipment and techniques are described, but no results are shown.

32. Richmond, J. C.: Some Methods Used at NBS for Measuring Thermal Emittance at High Temperatures. Surface Effects on Spacecraft Materials, F. J. Clauss, ed., John Wiley & Sons, Inc., 1960, pp. 182-192.

33. Richmond, J. C.; and Harrison, W. N.: Equipment and Procedures for Evaluation of Total Hemispherical Emittance. J. Am. Ceram. Soc., vol. 39, no. 11, 1960, pp. 668-673. [Natl. Bur. of Std.]

34. Shaw, C. C.: Apparatus for the Measurement of Spectral and Total Emittance of Opaque Solids. Surface Effects on Spacecraft Materials, F. J. Clauss, ed., John Wiley & Sons, Inc., 1960, pp. 220-237. [Lockheed Missiles and Space Div., Sunnyvale, Calif.]

Three systems are described for measuring the total hemispherical, total normal and spectral normal emittance of opaque solids: Cary Spectrophotometer, Hohlraum Reflectometer, and Total Hemispherical-Emittance Measuring Apparatus. Comparison is made with results from several other sources of data and range is given as being from 0.4 to 25 microns wavelength and temperatures from -150 to beyond 1000° C.

35. Harrison, T. R.: Radiation Pyrometry and Its Underlying Principles of Radiant Heat Transfer. John Wiley & Sons, Inc., 1960.

36. Blau, H. H., Jr.; Marsh, J. B.; Martin, W. S.; Jasperse, J. R.; and Chaffee, R.: High Temperature Thermal Radiation Properties of Solid Materials. AFCRC TN 60-165, March 1960.

37. Stierwalt, D. L.; Kirk, D. D.; and Bernstein, J. B.: Spectral Emittance of Solids. NAVWEPS Rep. 5981 (NOLC 487) TM 43-14, AD 442866, April 1960.

38. Blau, H. H., Jr.; Marsh, J. B.; Martin, W. S.; Jasperse, J. R.; and Chaffee E.: Infrared Spectral Emittance Properties of Solid Materials. AFCRL-TR-60-416, Geophys. Res. Directorate, Air Force Res. Div., October 1960.

39. Wood, W. D.; Deem, H. W.; and Lucks, C. F.: Emissivity and Emittance — What Are They? DMIC Memo 72, Battelle Memorial Inst., Columbus, Ohio, November, 1960.

40. Blau, H. H., Jr.; and Fischer, H., eds.: Radiative Transfer from Solid Materials (Proceedings of conference held in Boston, Mass., December 12-13, 1960). Macmillan, New York.

Proceedings of the conference are given as in the title of the book, and the last section presents a review of radiation environments in space and a theoretical model for optimizing passive temperature control in slowly changing environments.

41. Wood, W. D.; Deem, H. W.; and Lucks, C. F.: Methods of Measuring Emittance. DMIC Memo 78, Battelle Memorial Inst., Columbus, Ohio, December 1960.

42. Abbott, G. L.; Alvares, N. J.; and Parker, W. J.: Total Normal and Total Hemispherical Emittance of Polished Metals. WADD-TR-61-94, Part I, 1961.

43. O'Sullivan, W. J., Jr.; and Wade, W. R.: Theory and Apparatus for Measurement of Emissivity for Radiative Cooling of Hypersonic Aircraft with Data for Inconel, Inconel-X, Stainless Steel 303,and Titanium Alloy RS-120. NASA TR R-90, 1961.

The importance of radiation as a means of cooling high supersonic and hypersonic speed aircraft is discussed to show the need for measurements of the total hemispherical emissivity of surfaces. The theory underlying the measurements of the total hemispherical emissivity of surfaces is presented, readily duplicable apparatus for performing the measurements is described, and measurements for stably oxidized Inconel, Inconel X, stainless steel 303, and titanium alloy RS-120 are given for the termperature range from 600°F to 2000°F.

44. Gravina, A.; and Katz, M.: Investigation of High Emittance Coatings to Extend Mach Number Range of Application of Structural Materials. WADD TR 60-102, March 1961.

45. Wood, W. D.; Deem, H. W.; and Lucks, C. F.: The Emittance of Coated Materials Suitable for Elevated-Temperature Use. DMIC Memo 103, May 4, 1961.

This is a compilation of original test data on emittance and reflectance of coated materials suitable for use at elevated temperatures. A very good coverage of the literature from 1940 through 1959.

46. Klein, J. D.: Radiation Heat Transfer to and from Ceramic Coatings on Metals. Am. Ceram. Soc. Bull., vol. 40, no. 6, June 1961, pp. 366-370.

47. Wood, W. D.; Deem, H. W.; and Lucks, C. F.: The Emittance of Iron, Nickel, and Cobalt and Their Alloys. DMIC Memo 119, Battelle Memorial Inst., Columbus, Ohio, July 1961.

48. Rouse, G. F.; Walker, R. F.; and Carrera, N. J.: Vaporization and Thermionic Emission of Refractory Materials. Second Semi-annual Status Report to NASA, Natl. Bur. of Std. Rep. 7392, November 30, 1961.

49. Bradley, D.; and Entwistle, A. G.: Determination of the Emissivity for Total Radiation of Small Diameter Platinum-10% Rhodium Wires in the Temperature Range of 600-1450°C. Brit. J. Appl. Phys., vol. 12, no. 2, December 1961, pp. 708-711.

51. McMahon, W. R.: High Temperature Spectral Emissivity of Some Ceramic Oxides. M. S. Thesis, Iowa State Univ. of Science and Technology, Ames, 1962.

51. Pears, C. D.: The Determination of the Emittance of Refractory Materials to 5000°F. Presented at the Second ASME Symposium on Thermophysical Properties, January 1962. [Southern Research Inst., Birmingham, Ala.]

The emittances of various refractory materials were determined at temperatures from 800° to 5000°F. These measurements were made by comparing the irradiance from a sample of the material to that from a blackbody cavity maintained at the same temperature. A thermopile-type detector was employed.

Small disc-shaped specimens were heated in an inert atmosphere by placing them on a disc that was inductively heated by a flat induction coil. The specimen temperature was measured by surface thermocouples and by optical pyrometer. The optical pyrometer readings were corrected to true temperature for the measured emittance by thermocouple calibration, gray body assumption, and spectral measurements.

The emittances of platinum, pyrolytic graphite, tungsten, molybdenum, carbides, oxides, nitrides, and silicides were determined to their destruction temperatures. Several coatings including the W-2, siliconized finishes, chrome oxides, and other specially treated surfaces were also evaluated. The emittances of the different materials varied considerably with temperature and demonstrated many influctions that could usually be associated with material phase changes and expansion coefficients, but quite often were unpredictable.

52. Seban, R. A.: Thermal Radiation Properties of Materials. WADD TR 60-370, Part II, January 1962.

53. Vassalo, F. A.; and Kirchner, H. P.: Thermal Radiation Within Solids. Final Report, WADD TR-60-697, Part II, Directorate of Materials and Processes, January 1962. [Cornell Aeronautical Lab., Inc.; Contract AF 33(616)-6996]

54. Abbott, G. L.; Alvares, N. J.; and Parker, W. J.: Total Normal and Total Hemispherical Emittance of Polished Metals. WADD TR-61-94, Part II, February 1962.

55. Moffitt, G.: Study of a Temperature Measuring System for the 1000° to 2500°C Range. ASD TR-61-487, Flight Control Laboratory, AD AD-274794, February 1962. [Barnes Engineering Co., Stamford, Conn.]

56. Dotson, L. E.: Emittance Coating Studies on Cb-1 Zr Alloy. General Electric Rep. R61FPD571, March 15, 1962.

57. Harrison, W. N.; Richmond, J. C.; and Skramstad, H. K.: Standardization of Thermal Emittance Measurements, Part III: Normal Spectral Emittance, 800° - 1400°K. WADC TR-59-510, Air Force Materials Lab., March 1962. [Natl. Bur. of Std.]

58. Wade, W. R.; and Slemp, W. S.: Measurements of Total Emittance of Several Refractory Oxides, Cermets, and Ceramics for Temperatures from 600° to 2000°F. NASA TN D-998, March 1962.

This paper is one of a series concerned with a program to determine values of total emittance of various materials which may possibly be used as construction materials for the radiative cooling of high supersonic and hypersonic aircraft. These materials include chemically oxidized Inconel, aluminum oxide and chromium oxide base paints, silicon carbide base ceramics, and chromium/aluminum oxide cermets.

59. Cox, R. L.: Emittance of Zirconia to 4600°F. Chance-Vought Rep. 3/14000/2R19, April 1962.

60. Grenis, A. F.; and Levitt, A. P.: Spectral Emissivity and Total Normal Emissivity of Commercial Graphites at Elevated Temperatures. WAL TR-851.2/1, Watertown Arsenal Laboratories, May 1962.

61. Schatz, E. A.; and McCandless, L. C.: Research for Low and High Emittance Coatings. ASD TR-62-443, Directorate of Materials and Processes, May 1962. [American Machine & Foundry Co., Alexandria, Va.; Contract AF 33(616)-7276]

Eight transparent protective coatings for gold were evaluated with respect to their ability to withstand temperatures of 1000°C and not to significantly increase the low total emittance of the substrate. Thin coatings, of the order of 100 mm, of vacuum evaporated SiO, Al_2O_3 and WO_3 were found to be highly satisfactory. Samples with a protective topcoat over gold which in turn was applied over a diffusion barrier coating of CeO_2, were able to maintain a total normal emittance of less than 0.1 for up to 20 hours at 1000°C in air.

A second aspect of the work was the study of the spectral normal emittance in the 1 to 5 micron wavelength range at 1000° C of sintered binary mixtures or pure compounds to correlate the spectral emittance of the pure components. No correlation was found. In most cases, the spectral emittance at any wavelength for the binary mixtures was between the values for the spectral emittance of the pure compounds. In some cases, however, the spectral emittance at a given wavelength was higher or lower than for either of the pure components.

62. Walker, G. H.; and Casey, F. W., Jr.: Measurement of Total Normal Emittance of Boron Nitride from 1200° to 1900° F with Normal Spectral Emittance Data at 1400° F. NASA TN D-1268, July 1962.

A technique for measuring the total normal emittance and the spectral emittance of nonconductors at high temperatures is presented. Total normal emittance data are presented for various thicknesses of boron nitride at temperatures from 1200° F to 1900° F. Spectral emittance data are also presented for boron nitride from 0.5 micron to 15 microns at 1400° F.

63. Wood, W. D.; Deem, H. W.; and Lucks, C. F.: Thermal Radiative Properties of Selected Materials. DMIC Rep. 177, November 15, 1962. [Contract AF 33(616)-7747]

A continuation that includes much of the previous DMIC Memo 103.

64. Abbott, G. L.: Total Normal and Total Hemispherical Emittance of Polished Metals. NASA SP-31,* 1963, pp. 293-304.

An apparatus has been designed, built, and tested that will measure the total hemispherical emittance, total normal emittance, normal and hemispherical spectral emittance, angular distribution of radiation and resistivity of metals from 1000° K to their melting points. The flat ribbon sample is resistance heated while held in a mount capable of 230° rotation in a vacuum of 10^{-6} torr. The apparatus and measuring techniques are described and examples of resulting data given.

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* J. C. Richmond, ed., Measurement of Thermal Radiation Properties of Solids. A symposium held at Dayton, Ohio, September 5-7, 1962, sponsored by USAF, NBS, and NASA. NASA SP-31, 1963.

65. Askwyth, W. H.; Curry, R.; and Lundberg, W. R.: A Simple Technique for Determining Total Hemispherical Emittance by Comparing Temperature Drops Along Coated Fins. NASA SP-31,* 1963, pp. 307-316.

Technique for determining total hemispherical emittance in vacuum is described. Method is based on the principle that if fins which are identical in every respect except emittance are heated at one end to the same temperature and in the same environment, the temperature drop along the length of the fin is a function of the emittance only. An analysis of the fin parameters needed for particular temperature ranges indicates that this method is practical for temperatures from -100° F to 1350° F or above. Emittance determinations are based on a comparative technique rather than on an analytical calculation. Good agreement, however, is obtained by comparing the correlation to analytical determinations of emittance.

66. Clayton, W. A.: A 500° to 4500° F Thermal Radiation Test Facility for Transparent Materials. NASA SP-31,* 1963, pp. 445-459. [The Boeing Co., Seattle, Wash.]

67. Peavy, B. A.; and Eubanks, A. G.: Periodic Heat Flow in a Hollow Cylinder Rotating in a Furnace with a Viewing Port. NASA SP-31,* 1963, pp. 553-564. [Natl. Bur. of Std.]

68. Comstock, D. F., Jr.: A Radiation Technique for Determining the Emittance of Refractory Oxides. NASA SP-31,* 1963, pp. 461-467. [A. D. Little, Cambridge, Mass.]

Paper describes a method by which the spectral emittance of a sample may be determined conveniently over a wide temperature range by use of an arc-imaging furnace. By measuring the radiation at a chosen wavelength incident on the sample and measuring the same radiation reflected from the sample, we may determine their ratio, and thus obtain the reflectance of the sample. From the value of reflectance so determined, we may now deduce the spectral emittance.

69. Cox, R. L.: A Technique for Measuring Thermal Radiation Properties of Translucent Materials at High Temperature. NASA SP-31,* 1963, pp. 469-480. [Vought Astronautics Div., LTV, Dallas]

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* J. C. Richmond, ed., Measurement of Thermal Radiation Properties of Solids. A symposium held at Dayton, Ohio, September 5-7, 1962, sponsored by USAF, NBS, and NASA. NASA SP-31, 1963.

A method is described for measuring total emittance of translucent materials in such a manner that any effect of subsurface temperature gradients can be observed. The axial temperature distribution of a disc-shaped specimen is controlled by relative positioning of a plasma torch heating the front face and a propane torch heating the rear face. Total radiation leaving the front face is measured with a thermopile detector, and corrections are applied to account for the reflection of plasma emission. Temperatures are measured internally on the specimen axis by utilizing small blackbody cavities drilled radially to the centerline. Results are presented to 4600° F for zirconium oxide.

70. Evans, R. J.; Clayton, W. A.; and Fries, M.: A Very Rapid 3000° F Technique for Measuring Emittance of Opaque Solid Materials. NASA SP-31,* 1963, pp. 483-488. [The Boeing Co., Seattle, Wash.]

This paper presents a rapid, total-normal-emittance-measurement technique useful for comparative tests. The heat source is a 10 kw tungsten-filament lamp whose energy is focused on the specimens with two 36-inch parabolic mirrors. The method described is useful between 1000 - 3000° F with all tests conducted in air. Accuracy depends on surface temperature measurements, with an accuracy of +5% and -10% when the thermocouples are used and an accuracy which depends on the deviation of the specimen from a gray body when an optical pyrometer is used.

71. Funai, A. I.: A Multichamber Calorimeter for High-Temperature Emittance Studies. NASA SP-31,* 1963, pp. 317-326. [Lockheed Missiles & Space Co., Palo Alto, Calif.]

An eight-chambered vacuum calorimetric apparatus for measuring and evaluating the total hemispherical emittance of high-temperature radiator coatings is describer. The method for obtaining emittance values is presented, and an error analysis identifies the important parameters. A detailed description of the sample heating and temperature-measuring systems are also given. Preliminary results confirm the suitability of the apparatus for measuring emittances with an accuracy of ±5%.

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* J. C. Richmond, ed., Measurement of Thermal Radiation Properties of Solids. A symposium held at Dayton, Ohio, September 5-7, 1962, sponsored by USAF, NBS, and NASA. NASA SP-31, 1963.

72. Grammer, J. R.; and Streed, E. R.: Measurement of Normal and Directional High-Temperature Total and Spectral Emittance. NASA SP-31,* 1963, pp. 489-498. [Lockheed Missiles and Space Co., Palo Alto, Calif.]

Apparatus to measure the total hemispherical and directional total and spectral emittance in the temperature range of 400° to 2000° C is described. The device consists of a water-cooled evacuated chamber in which a sample formed into a modified Mendenhall wedge enclosure is heated electrically by its own resistance. The sample can be rotated in azimuth while viewed externally through a double-slit collimating optical system. Total or spectral emittance is determined by comparing emitted radiation from the surface to radiation emitted from the enclosure as detected by a vacuum thermocouple used with or without a monochromator.

73. Gravina, A.; Bastian, R.; and Dyer, J.: Instrumentation for Emittance Measurements in the 400° to 1800° F Temperature Range. NASA SP-31,* 1963, pp. 329-336. [Republic Aviation Corp., Farmingdale, N.Y.]

Equipment is described which was used to measure simultaneously the spectral and total normal emittance of materials in the temperature range from 400° to 1800° F while contained in ambient and vacuum environments. Equipment design, set-up, and experimental procedures are presented. Also included is a description of present activities directed towards the assembly of equipment which will help improve experimental accuracy and also provide for angular emittance measurements in order to obtain more comprehensive data.

74. Harrison, W. N.: Pitfalls in Thermal Emission Studies. NASA SP-31,* 1963, pp. 3-10. [Natl. Bur. of Std.]

Attention is called to several pitfalls that often beset investigators who make thermal emittance studies. The pitfalls mentioned include the following:

1. Conflicting meanings of several frequently used terms as found in the literature, each meaning having authoritative sponsorship

2. Incomplete and hence potentially misleading descriptions of specimens on which reported data are based

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* J. C. Richmond, ed., Measurement of Thermal Radiation Properties of Solids. A symposium held at Dayton, Ohio, September 5-7, 1962, sponsored by USAF, NBS, and NASA. NASA SP-31, 1963.

3. Reference of emissivity or emittance as a property of a surface rather than a volume property (influenced by the surface)

4. Occasional omission of diffuse reflection from analyses of the optical properties of inhomogeneous bodies

5. Failure to observe the restrictions on conditions that are required fo validity of basic equations

6. Uncertainties as to the effective temperature peculiar to specimens having low absorption indices

7. Lack of suitable physical standards

Several suggestions are made for avoiding or minimizing the consequences of the pitfalls discussed.

75. House, R. D.; Lyons, G. J.; and Askwyth, W. H.: Measurement of Spectral Normal Emittance of Materials Under Simulated Spacecraft Power-plant Operating Conditions. NASA SP-31,* 1963, pp. 343-355. [Pratt & Whitney Aircraft Div., United Aircraft Corp., East Hartford, Conn.]

An apparatus was designed and constructed to determine spectral normal emittance of materials in an environment closely simulating the vacuum of space. The apparatus is capable of measuring spectral emittance of structural materials or coatings over a wavelength range accounting for the major portion of the blackbody energy at the temperature at which these measurements are made (0.5 to 1.2 microns claimed). Comparison is made of the radiant intensity normal from a specimen tube surface to that of a small blackbody hole drilled in the tube wall. Ratio of these intensities at a given wavelength is a very close approximation to the spectral normal emittance of the specimen surface. Evaluation of errors from several sources is included — scattered light from the NaCl window, scattered white light in the monochromator, and quality of the blackbody hole in the specimen tube.

76. Kjelby, A. S.: Emittance Measurement Capability for Temperatures up to 3000° F. NASA SP-31,* 1963, pp. 499-503. [Aeronca Mfg. Corp., Middleton, Ohio.]

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* J. C. Richmond, ed., Measurement of Thermal Radiation Properties of Solids. A symposium held at Dayton, Ohio, September 5-7, 1962, sponsored by USAF, NBS, and NASA. NASA SP-31, 1963.

Design and construction of a special apparatus capable of measuring emittances up to 3000° F is described. The method of determination of the total hemispherical emittance by comparison with a blackbody is the basis of the technique herein employed. If the temperatures and the areas of the unknown surface and the blackbody are made equal, the method becomes simply the determination of the ratio of the rates of emission.

77. Konopken, S.; and Klemm, R. A.: Evaluation of Thermal Radiation at High Temperatures. NASA SP-31,* 1963, pp. 505-513. [North American Aviation, Inc., Los Angeles, Calif.]

Because many materials change in radiation characteristics with increasing temperature, it has become increasingly important to determine emittance values directly instead of by the comparatively easier method of computing emittance values from reflectance data. This is particularly true if the material is partially transparent to radiation. A new apparatus is being built to extend the capability for evaluating emittance from the currently available 1500° to at least 4000° F. The technique being applied is to rotate specimens in a high-temperature furnace which is also utilized as a blackbody radiation source. The analytical techniques used to establish speed of rotation, field of view, and other design problems are discussed. A review of other radiation test equipment is also presented.

78. Limperis, T.; Szeles, D. M.; and Wolfe, W. L.: The Measurement of Total Normal Emittance of Three Nuclear Reactor Materials. NASA SP-31,* 1963, pp. 357-364. [Univ. of Michigan, Ann Arbor]

Determination of total normal emittance of 304 Stainless, A-7 Carbon steel and borated graphite for use in the nuclear reactor under construction at Monroe, Mich. Temperature range is 600° to 9500°K.

79. Metcalfe, A. F.; Moore, V. S.; and Stetson, A. R.: Emittance Measurements of Refractory Oxide Coatings up to 2900°K. NASA SP-31,* 1963, pp. 527-533. [Solar, San Diego, Calif.]

80. McElroy, D. L.; and Kollie, T. G.: Total Hemispherical Emittance of Platinum, Columbium - 1% Zirconium, and Polished and Oxidized Iron - 8 in the Range 100° to 1200°C. NASA SP-31,* 1963, pp. 365-379. [Oak Ridge Natl. Lab., Oak Ridge, Tenn.]

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* J. C. Richmond, ed., Measurement of Thermal Radiation Properties of Solids. A symposium held at Dayton, Ohio, September 5-7, 1962, sponsored by USAF, NBS, and NASA. NASA SP-31, 1963.

Equipment was developed for measuring the temperature dependence of the total hemispherical emittance of metal and alloy strips to 1200°C using direct heating in a constant-temperature, blackbody vacuum chamber. Precise specimen dimensions and thermocouple positioning are requisite to the method and the techniques developed to accomplish these are described. Results are presented which show the effects of specimen reaction with the measuring environment and specimen-oxide reactions. Electrical resistivity of the specimen was obtained from the data taken in a determination. Finally, a discussion and comparison of results with those made at Lockheed are given (paper by A. I. Funai).

81. Mikk, G.; and Askwyth, W. H.: Measurement of Total Hemi spherical Emittance of Structural Materials and Coatings Under Simulated Spacecraft Conditions. NASA SP-31,* 1963, pp. 381-391. [Pratt & Whitney Aircraft Div., United Aircraft Corp., East Hartford, Conn.]

Several test rigs were designed and constructed to measure total hemispherical emittance over a wide range of temperatures under conditions which simulate the vacuum of space. Method used in all is to compare the electrical power dissipated from an isothermal test section of a resistance-heated specimen to the total emissive power of a blackbody operating at the specimen temperature. Total hemispherical emittance is determined as a function of temperature from 200° to 2200°F and total hemispherical emittance as a function of time at fixed elevated temperatures. Specimens were either coated metal strips or coated thin-walled metal tubes. Data are compared with those of other investigators.

82. Moore, D. G.: Investigation of Shallow Reference Cavities for High-Temperature Emittance Measurements. NASA SP-31,* 1963, pp. 515-525. [Natl. Bur. of Std.]

Total normal emittance measurements were made on small specimens with shallow reference holes of circular cross section. The ratio of the radiant flux density from the surface to the flux density from the hole was measured and this value then converted to emittance by a theoretical expression based on hole dimensions. The expression applies only to diffusely reflecting materials. Measurements were made on oxidized nickel, oxidized Inconel, sintered alumina, and polished high-purity graphite over a temperature range up to 2150°K.

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* J. C. Richmond, ed., Measurement of Thermal Radiation Properties of Solids. A symposium held at Dayton, Ohio, September 5-7, 1962, sponsored by USAF, NBS, and NASA. NASA SP-31, 1963.

83. Null, M. R.; and Lozier, W. W.: Measurement of Reflectance and Emittance at High Temperatures with a Carbon Arc-Image Furnace. NASA SP-31,* 1963, pp. 535-539. [Res. Lab. of National Carbon Co., Parma, Ohio]

84. Pears, C. D.: Some Problems in Emittance Measurements at the Higher Temperatures and Surface Characterization. NASA SP-31,* 1963, pp. 541-551. [Southern Research Inst., Birmingham, Ala.]

85. Richmond, J. C., ed.: Measurement of Thermal Radiation Properties of Solids. A symposium held at Dayton, Ohio, September 5-7, 1962, sponsored by USAF, NBS, and NASA. NASA SP-31, 1963.

86. Richmond, J. C.: Harrison, W. N.; and Shorten, F. J.: An Approach to Thermal Emittance Standards. NASA SP-31,* 1963, pp. 403-422. [Natl. Bur. of Std.]

A double-beam ratio-recording infrared spectrometer was modified to record directly the normal spectral emittance of strip specimens that are heated by passing a current through them. A laboratory blackbody furnace and a hot specimen at the same temperature serve as sources for the respective beams. Temperature equalization is achieved by means of a differential thermocouple. Automatic data processing equipment corrects for "zero-line" and "100%-line" errors on the basis of previously recorded calibrations and also computes from the spectral data, as the measurement progresses, total emittance or absorptance for radiant energy having any known spectral distribution of flux.

87. Riethof, T. R.; and DeSantis, V. J.: Techniques of Measuring Normal Spectral Emissivity of Conductive Refractory Compounds at High Temperatures. NASA SP-31,* 1963, pp. 565-583. [General Electric Co., Philadelphia]

88. Seban, R. A.: System for the Measurement of Spectral Emittance in an Inert Atmosphere. NASA SP-31,* 1963, pp. 425-431. [Univ. of California, Berkeley]

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* J. C. Richmond, ed., Measurement of Thermal Radiation Properties of Solids. A symposium held at Dayton, Ohio, September 5-7, 1962, sponsored by USAF, NBS, and NASA. NASA SP-31, 1963.

Described is a system for the measurement of spectral emittance; certain operating difficulties are considered, and results for a metal and for a ceramic coating are presented to reveal satisfactory operation at temperatures from 1500° to 2000°F.

89. Slemp, W. S.; and Wade, W. R.: A Method for Measuring the Spectral Normal Emittance in Air of a Variety of Materials Having Stable Emittance Characteristics. NASA SP-31,* 1963, pp. 433-438. [Langley Research Center, NASA]

A method and apparatus is described for the measurement of spectral normal emittance in air of a variety of materials. The system permits measurements to be performed over a wavelength region of 1 through 15 microns and over a temperature range of 600° to 1800°F with an accuracy of ±5%. The advantages of this system are described. Results obtained by this system are compared with results reported by another observer using a different technique.

90. Bastian, R.; Dyer, J.; and Gravina, A.: Instrumentation for Emittance Measurements in the 400° to 1800°F Temperature Range. WADD TR-60-102, 1963. [Republic Aviation Corp., Farmingdale, N.Y.; Contract AF 33(616)-5925]

91. Pears, C. D.: The Thermal Properties of Twenty-six Solid Materials to 5000°F or Their Destruction Temperatures. ASD TR-62-765, January 1963.

92. Rudkin, R. L.; Parker, W. J.; and Jenkins, R. J.: Thermal Diffusivity Measurements on Metals and Ceramics at High Temperatures. ASD-TDR-62-24, January 1963. [Naval Radiological Defense Lab., San Francisco]

The adaption of the NRDL flash method to the measurement of the thermal diffusivity of metals and ceramics at high temperatures is described. A high intensity short duration light pulse from a xenon flash lamp is the source and the problems are discussed in this report.

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* J. C. Richmond, ed., Measurement of Thermal Radiation Properties of Solids. A symposium held at Dayton, Ohio, September 5-7, 1962, sponsored by USAF, NBS, and NASA. NASA SP-31, 1963.

93. Malakelis, E.: Development and Measurement of Emissivity Properties of Low Emissivity Materials — Final Report. Rep. 9352, AD295540, January 10, 1963. [McDonnell Aircraft Corp., St. Louis, Mo.; Contract AF 33(657)-7749]

94. Browning, M. E.; McCandless, L. C.; Pearson, E. G.; and Schatz, E. A.: Supplemental Information on High Temperature Coating and Material Programs at AMF. NASA CR-53234, American Machine and Foundry Co., March 1963.

95. Pears, C. D.: Equipment for Thermal Property Measurements to 5000°F Instruction Manual, U. S. Army Ordnance Missile Command, April 15, 1963. [Southern Research Inst., Birmingham, Ala.; Contract DA-01-021-ORD-6437]

This manual covers the general instructions necessary to assemble, operate, and maintain the equipment used in making thermal-expansion, thermal-conductivity, and heat-capacity measurements at temperatures from 500° to 5000°F. Ordering information for space parts and materials is given in the Appendix.

96. Alvares, N. J.: Total Hemispherical Emittance and Normal Spectral Emittance of Oxidation Protective Coatings. ASD TDR 63-269, July 1963. [Naval Radiological Defense Lab., San Francisco]

Total emittances of the silicide coatings developed for tungsten, tantalum, molybdenum, and niobium have been measured. Measuring technique is also described in some detail.

97. Gaumer, R. E.: Thermophysics Design Handbook. LMSC 8-55-63-3, July 1963, pp. 7-1— 7-5, 7-8. [Lockheed Missiles & Space Co., Sunnyvale, Calif.]

Discussion is given of calorimetric radiation characteristic determinations, and reference is made to more complete descriptions given in NASA SP-31 under authors Gaumer, Caren, McKellar, Streed, Stewart, Frame, and Funai.

98. Hoch, M.; and Narasimhamurty, H. V. L.: Relation Between Specific Heat and Emissivity of Tantalum at Elevated Temperatures. Final Report, ASD TDR-63-371, Materials Lab., Wright-Patterson AFC, July 1963. [Cincinnati Univ.; Contract AF 33(616)-7123]

99. Burks, T. L.; Goldberg, D. M.; Pearson, E. G.; and Schatz, E. A.: High Temperature, High Emittance Intermetallic Coatings. Part I: Emittance and Reflection of Intermetallic Compounds. Final Report ASD TDR-63-645, August 1963. [American Machine and Foundry Co., Alexandria, Va.; Contract AF 33(657)-8877]

100. Rolling, R. E.; and Seban, R. A.: Thermal Radiation Properties of Materials. Parts I-III, WADD TR-60-370, Project 7360, Air Force Materials Lab., August 1963. [Univ. of California]

101. Grisaffe, S. J.; and Spitzig, W. A.: Preliminary Investigation of Particle-Substrate Bonding of Plasma-Sprayed Materials. NASA TN D-1705, September 1963.

An investigation was undertaken to evaluate the effects of two plasma spray powders, tungsten and zirconia, and four substrate materials, glass, stainless steel, tungsten, and copper, on the particle-to-substrate bond. All substrates except glass were metallurgically polished; the glass had a sufficiently smooth surface so that mechanical interlocking would not contribute to the resultant bond. It was found that the thermal conductivity of the substrate greatly influences the particle-to-substrate bond, whereas, in general, the physical properties of the spray powder have only a slight influence on the bond.

102. Richmond, J. C.: Relation of Emittance to Other Optical Properties. J. Res. Natl. Bur. Std., vol. 67C, no. 3, September 1963, pp. 217-226.

An equation was derived relating the normal spectral emittance of an optically inhomogeneous, partially transmitting coating applied over an opaque substrate to the thickness and optical properties of the coating and the reflectance of the substrate at the coating-substrate interface.

103. Voskresenskii, V.: Concerning an Incorrect Method of Eliminating the True Temperature During Studies of the Emissivity of Materials. Teplofizika Vysokikh Temperatur, vol. 1, pp. 177-181. Translation in High Temperature, vol. 1, September - October 1963, pp. 156-160. [Scientific Research Institute of High Temperatures, USSR]

104. Harrison, W. N.; Joseph, H. M.; Richmond, J. C.; and Shorten, F. J.: Standardization of Thermal Emittance Measurements, Part IV: Normal Spectral Emittance, 800° - 1400°K. WADC TR-59-510, November 1963. [Natl. Bur. of Std.; Contract AF 33(616)-61-02]

105. Miller, L. W.; and Tatro, L. D.: Total Optical Emissivity and Electrical Resistivity of $U^{0.3}$ and $Zr^{0.7}$ in the Temperature Range 1400° to 2800°K. W-7405-ENG-36, LAMS-2965, November 19, 1963. [Los Alamos Scientific Lab., N. Mex.]

106. Plunkett, J. D.: NASA Contributions to the Technology of Inorganic Coatings. NASA SP-5014, 1964. [Denver Univ.]

Objectives of this book are stated to be:

1. Identification and evaluation of NASA contributions to the science and technology of inorganic coatings

2. Preparation of a report suitable for the dissemination of NASA contributions in a form which will assist the commercial economy

Chapter 6, Measurement of Optical Properties of Coatings, includes 500° to 1500°K and 1500°K and up. There is also a bibliography.

107. Schatz, E. A.; et al.: High Temperature, High Emittance Intermetallic Coatings. ASD TDR 63-657, Part I; Final Report on Contract AF 33(657)-8877, 1964. [American Machine & Foundry Co., Alexandria, Va.]

Spectral total reflectance (0.23 to 2.65 microns) spectral normal emittance (1-15 microns) curves are presented for high temperature, oxidation-resistant, intermetallic compounds. Major emphasis was given to sintered samples of aluminides, borides, beryllides,and silicides. Also studied were several pack cementation coatings.

108. Moore, D. G.; Clark, H. E.; Kelly, F. J.; Alderman, J. L.; Richmond, J. C.; and Harrison, W. N.: Equipment for Thermal Emittance Measurements Above 1400°K. Annual Summary Report, Natl. Bur. of Std. Project 1009-11-10493, NBS Rep. 8175, U. S. Dept. of Commerce, Natl. Bur. of Std., January 1964. [Marshall Space Flight Center, NASA]

This is one in a series of reports on a research program aimed at developing equipment and procedures suitable for reliable measurements of the total and spectral emittance of both metals and nonmetals in the temperature range 1400° - 2500°K. This program was started in 1961 and continued through 1965.

109. Slemp, W. S.: The Effects of Preoxidation Treatments on the Spectral Normal and Total Normal Emittance of Inconel, Inconel-X, and Type 347 Stainless Steel at Temperatures of 900°, 1200°, 1500°, and 1800° F. NASA TM S-51016, March 4, 1964. [Langley Research Center, NASA]

110. Wilson, R. G.: Determination of the Hemispherical Spectral Emittance of Carbon, Graphite, Zirconisa, and Ablation Material Chars from 0.37 to 0.72 Microns and 3000° to 6000°F. NASA TM S-51017, March 4, 1964. [Langley Research Center, NASA]

111. Burks, T. L.; Schatz, E. A.; and Counts, C. R., III: Improved Radiator Coatings. Part I, ML TDR 64-146, Air Force Materials Lab., June 1964. [American Machine & Foundry Co., Alexandria, Va.; Contract AF 33(657)-10764]

112. Parker, W. J.: Electronic Relaxation Effect in the Emissivity of Metals. USNRDL TR-755, U. S. Naval Radiological Defense Lab., June 1964.

113. Slemp, W. S.: Effects of Preoxidation Treatments on Spectral Normal and Total Normal Emittance of Inconel, Inconel-X, and Type 347 Stainless Steel. NASA TN D-2300, July 1964.

The spectral normal emittances of oxidized Inconel, Inconel-X, and type 347 stainless steel were determined at temperatures of 900°, 1200°, 1500°, and 1800°F over a wavelength range of 1 to 15 microns. Polishing, grit blasting, etching, or combinations of these preparations were used as preoxidation treatments. Large effects of variations in oxidation times and preoxidation treatments were found.

114. Hayes, R. J.; and Atkinson, W. H.: Thermal Emittance of Materials for Spacecraft Radiator Coatings. Ceramic Bulletin, vol. 49, no. 9, August 1964, pp. 616-621.

115. Rolling, R. E.; Funai, A. I.; and Grammer, J. R.: Investigation of the Effect of Surface Condition on the Radiant Properties of Metals. AFML TR-64-363, Air Force Materials Lab., November 1964. [Lockheed Missiles & Space Co., Palo Alto, Calif.]

116. Clark, H. E.; and Moore, D. G.: Method and Equipment for Measuring Thermal Emittance of Ceramic Oxides from 1200° to 1800°K. Symposium on Thermal Radiation of Solids, S. Katzoff, ed., NASA SP-55, 1965, pp. 241-257. [Natl. Bur. of Std.]

117. Emslie, A. G.: A Review of Some Problem Areas in the Theory of Thermal Radiation of Solids. Symposium on Thermal Radiation of Solids, S. Katzoff, ed., NASA SP-55, 1965, pp. 3-10.

This paper gives a discussion of three problem areas in the field of thermal radiation of solids:

1. Calculation, from first principles, of the optical constants n and k of homogeneous materials, such as metals and dielectrics.

2. Theories of the radiation characteristics of rough surfaces, of inhomogeneous materials such as powders, and of composite materials.

3. Computational complexity having to do with radiation and conduction interchange on a macroscopic scale in complex structures such as space vehicles

New approaches are urgently needed in most of these problem areas.

118. Katzoff, S., ed.: Symposium on Thermal Radiation of Solids. A symposium held at San Francisco, March 4-6, 1964, ML-TDR-64-159, NASA SP-55, 1965.

119. Klein, J. D.: Radiation Heat Transfer Through Scattering and Absorbing Nonisothermal Layers. Symposium on Thermal Radiation of Solids, S. Katzoff, ed., NASA SP-55, 1965, pp. 73-81. [Ames Research Center, NASA]

Steady-state radiation heat transfer through layers where both scattering and absorption occur within the layers is treated analytically by means of one-dimensional fluxes. The set of simultaneous equations — consisting of a heat-balance equation, an equation for the flux in the direction of heat flow, and an equation for the flux in the opposite direction — has a general solution to which boundary conditions are applied to derive expressions for desired quantities for an arbitrary layer. In this way the transfer through a layer and the emission from it, as well as its temperature distribution, are derived in terms of the absorption and scattering coefficients of the layer, the index of refraction, the lattice conductivity, and the heat applied to it. The treatment includes the effects of surface reflections. Radiation transfer through nonradiating layers is also treated in order to provide equations for obtaining the absorption and scattering coefficients from optical transmission measurements.

120. Lazlo, T. S.; Gannon, R. E.; and Sheehan, P. J.: Emittance Measurements of Solids Above 2000°C. Symposium on Thermal Radiation of Solids, S. Katzoff, ed., NASA SP-55, 1965, pp. 277-286. [AVCO Corp., Wilmington, Mass.]

121. Schmidt, R. N.; and Janssen, J. E.: Selective Coatings for Vacuum-Stable High-Temperature Solar Absorbers. Symposium on Thermal Radiation of Solids, S. Katzoff, ed., NASA SP-55, 1965, pp. 509-524. [Honeywell Research Center, Hopkins, Minn.]

One of the necessary design criteria for a solar thermal-cycle power system aboard a spacecraft is the thermal radiation properties of the surface on which the solar energy is absorbed. A coating which selectively absorbs solar energy but does not radiate infrared energy gives increased absorber efficiency over a nonselective blackbody at lower solar flux concentrations and higher temperatures. An interference coating consisting of multiple layers of alumina and molybdenum on a molybdenum substrate gave a solar absorptance of 0.83 and an emittance of 0.11 at 1000° F. A selective black surface, beryllium plus 1 percent copper alloy anodized in sodium hydroxide produced a very hard and durable coating with a solar absorptance of 0.91 at room temperature and a solar absorptance of 0.87 with an emittance of 0.30 at 1000° F.

122. Wilson, R. G.: Hemispherical Spectral Emittance of Ablation Chars, Carbon, and Zirconia (to 3700°K). Symposium on Thermal Radiation of Solids, S. Katzoff, ed., NASA SP-55, 1965, pp. 259-275. [Langley Research Center, NASA]

123. Brandenberg, W. M.; Clausen, O. W.; and McKeown, D.: A High Precision Method of Measuring Absorptances of Evaporated Metals. GDA ERR-AN-699, General Dynamics, Astronautics, January 1965.

124. Autio, G. W.; and Scala, E.: Normal Spectral Emissivity of Isotropic and Anisotropic Materials. AIAA J., vol. 3, April 1965, pp. 738-740. [Cornell Univ., Ithaca, N. Y.]

125. Kelly, F. J.; and Moore, D. G.: A Test of Analytical Expressions for the Thermal Emissivity of Shallow Cylindrical Cavities. Appl. Opt., vol. 4, 1965, p. 31.

126. Richmond, J. C.; Dunn, S. T.; DeWitt, D. P.; and Hayes, W. D., Jr.: Procedures for the Precise Determination of Thermal Radiation Properties. Air Force Materials Lab., Res. & Tech. Div., Air Force Systems Command, ML TDR 64-257, Part II, April 1965. [Natl. Bur. of Std.]

A laser-source integrating sphere reflectometer was designed and built to measure the reflectance of specimens at high temperatures. Calibrated for linearity of response of 0.632 microns wavelength by means of a shallow cylindrical cavity with a variable depth-to-radius ratio, having a lining of known reflectance. Ellipsoidal mirror reflectometer was calibrated for all known errors in the 1 to 7.5 micron wavelength range. Preliminary tests showed that the flux emitted by a hot specimen at temperatures up to 2500°K will not invalidate the reflectance measurement. Preliminary analysis indicates the errors in measurement of absolute reflectance with this equipment should not exceed 2 percent. Review of the literature on relation of thermal radiation properties to other properties of materials is presented, together with a summary of the work done in an effort to compute the spectral emittance of rhodium.

127. Hoch, M.; Iyer, A. S.; and Narasimhamurty, H. V. L.: Relation Between Specific Heat and Total Emittance in Tantalum, Niobium, Tungsten, and Molybdenum. J. Phys. Chem., vol. 69, April 1965, pp. 1420-1423. [Cincinnati Univ., Materials Science Program, Contract AF 33(616)-7123]

128. Grenis, A. F.: Thermal Radiation of Complex Ceramic Solids. AMRA TR 65-14, Materials Engineering Div., U. S. Army Materials Research Agency, July 1965.

The normal total emissivities and relative radiant intensities of several complex ceramic oxides were determined theoretically. It was found that the total emissivities for many of the complex solids seemed to follow an equation which states that the normal total emissivity of a complex solid is equal to the sum of the products of the normal total emissivity and the ratio of the mass/densities (relative volume ration or the mole ratio) of each of the compounds initially present. On a molecular basis, it was found that the vibratory modes of many of the complex ceramic compounds are nearly similar to the cumulative vibratory modes of the simple ceramic compounds.

129. Schatz, E. A.; Alvarez, G. H.; Counts, C. R., III; and Hoppke, M. A.: High Temperature, High Emittance Intermetallic Coatings. Part III, AFML TR-65-217, Air Force Materials Lab., July 1965. [American Machine & Foundry Co., Alexandria, Va.]

This report describes the preparation and thermal radiation properties of a number of intermetallic compounds and coatings.

130. Schatz, E. A.; Counts, C. R.; Alvarez, G. H.; and Hoppke, M. A.: Improved Radiator Coatings. Part II, ML-TDR-64-146, Air Force Materials Lab., August 1965. [American Machine & Foundry Co., Alexandria, Va.]

130. Heaney, J. B.: A Comparison of Two Emittance Measurement Techniques. NASA TM X-713-65-354, Goddard Space Flight Center, NASA, September 1965.

A technique used to measure total normal emittance that employs a Gier-Dunkle Portable Emissivity Inspection System is explained in detail. This is then compared with the familiar heated cavity Hohlraum-type measurement which gives a value to total normal emittance by summing spectral data. Emittance values obtained from samples measured on both systems are compared, and an analysis of some of the errors inherent in each measuring technique is given.

132. Kelly, F. J.: On Kirchhoff's Law and Its Generalized Application to Absorption and Emission by Cavities. J. Res. Natl. Bur. Std., vol. 69B, no. 3, September 1965, pp. 165-171.

Several authors have made the assumption that Kirchhoff's Law holds for the apparent local spectral emittance and apparent local spectral absorptance of any point on the interior surface of a cavity. The correctness of this assumption is demonstrated under certain general conditions, and its practical application to the total flux absorbed by a cavity or spacecraft is derived. An easy method for determining the total flux emitted from such a nonisothermal cavity is found when the distribution of the apparent local spectral emittance of the isothermal cavity is known. Total flux emitted from a nonisothermal cylindrical cavity for several arbitrary cases of temperature distribution on the interior surface of the cavity is calculated, and the integral equation for a diffuse cavity, whose wall emittance varies with position on the wall, is transformed to an equation having a symmetric kernel.

133. Dunn, S. T.: Flux Averaging Devices for the Infrared. Natl. Bur. of Std. Tech. Note 279, December 1965.

In order to eliminate the effect of spatial and angular sensitivity of infrared detectors and obtain accurate measurements in the infrared, several averaging devices are presented, which distribute the flux as uniformly as possible over the entire sensitive area of the detector. Tests to establish the averaging capability and useful wavelength range are shown.

134. Grenis, A. F.; and Levitt, A. P.: Infrared Radiation of Solids--Titanium-Boronitride. Materials Engineering Division, U. S. Army Materials Research Agency, AMRA TR 65-30, December 1965.

The infrared radiation properties and characteristics of titanium-boronitride were investigated in the wavelength region extending from 1.0 to 10.0 microns at a temperature of 1300 K. The normal spectral emissivity, integrated normal total emissivity, and infrared radiation intensity curves of this material for two different surface conditions were determined. Additional radiation studies were made using a mathematical interpretation based on the normal total emissivity and weight-to-density ratios of the individual constituents.

135. Richmond, J. C.: Effect of Surface Roughness on Emittance of Nonmetals. Vol. 18 of Progress in Astronautics and Aeronautics, Heller, ed., Academic Press, Inc. (New York), 1966.

It has been observed experimentally that the emittance of polished metals can be markedly increased by roughening the surface, by a factor of as much as 2 or 3. For nonmetals and particularly white ceramic materials, on the other hand, the emittance appears to be essentially independent of surface roughness, at least for wavelengths below 7 or 8 microns. This apparent anomaly is explained on the basis of the differences in the optical properties of the two types of materials.

136. Parmer, J. F.; Dunn, S. T.; and Richmond, J. C.: Survey of Infrared Measurement Techniques and Computational Methods in Radiant Heat Transfer. J. Spacecraft, July 1966, pp. 961-975.

This paper presents an analysis of 133 replies received from a questionnaire. Subject was measurements and computations in the field of radiant heat transfer, particularly in relation to the national space program and military applications. The results from the questionnaire are supplemented to give a

broad picture of the current status and future requirements in measurements of thermal emittance, measurements of infrared reflectance, and computational methods for radiant heat transfer. A brief review of the Russian literature in the field is included.

137. Richmond, J. C.; Kneissl, G. J.; Kelley, D. L.; and Kelley, F. J.: Procedures for the Precise Determination of Thermal Radiation Properties. AFML TR-66-302, Air Force Materials Lab., Air Force Systems Command, August 1966. [Natl. Bur. of Std.]

The objective of this continuing program is to develop equipment and procedures for measuring the important thermal radiation properties of materials at temperatures up to the melting point of the most refractory material and to develop physical standards for checking such equipment and procedures.

Specific coverage in this report includes:

1. Development of the laser-source integrating sphere reflectometer

2. An error analysis of the shallow cavity technique for measuring normal spectral emittance

3. Study of the feasibility of preparing emittance standards for use at temperatures above 1400°K (about 2000°F)

138. Richmond, J. C.: Effect of Surface Roughness on Emittance of Nonmetals. J. Opt. Soc. Am. vol. 56, 1966, pp. 253-254.

139. Noguchi, T.; and Kozuka, T.: Temperature and Emissivity Measurement at 0.65 with a Solar Furnace. Solar Energy, vol. 10, 1966, pp. 125-131.

140. Grenis, A. F.; and Levitt, A. P.: Infrared Radiation of Titanium Boronitride. J. Am. Ceram. Soc., vol. 49, no. 12, December 1966, pp. 629-631.

The infrared radiation properties and characteristics of the ternary solid titanium boronitride were investigated in the wavelength region from 1.0 to 10.0 microns wavelength at 1300°K. The normal spectral emittance, integrated normal total emittance, and infrared radiation intensity were determined for this material with both rough and polished surfaces. The normal total emissivity of the material was also calculated based on the weighted average of the normal total emissivities of the constituent compounds. The results are in good agreement with the experimental values.

141. Dunn, S. T.; Geist, J. C.; Moore, D. G.; Clark, H. E.; and Richmond, J. C.: Thermal Radiation Property Measurement Techniques. Natl. Bur. of Std. Tech. Note 415, April 1967.

Report of work completed on the following:

1. Completion of the development and calibration of a rotating cylinder procedure for measuring normal spectral emittance of nonconducting materials at temperatures in the range of 1200° to 1600°K

2. Analysis and calibration of an ellipsoidal mirror reflectometer

3. A study of the relation between surface roughness and geometric distribution of flux reflected from a surface

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By D. W. Gates

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This document has also been reviewed and approved for technical accuracy.

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