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The National Measurement System for Radiometry and Photometry

H. J. Kostkowski

Institute for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

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Final

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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THE NATIONAL MEASUREMENT SYSTEM FOR RADIOMETRY AND PHOTOMETRY

Henry J. Kostkowski

Optical Physics Division

November 1977

EXECUTIVE SUMMARY

This National Measurement System Study is on the measurement of light. More specifically it is concerned with the measurement of the energy or power in ultraviolet, visible and infrared radiation.

The study was undertaken to determine the importance of such measurements in the U.S., the accuracy and ease with which they could be made, the adequacy of this capability, and the nature of the program NBS should pursue in this measurement area.

In the last ten years, the economic and social impact of radiometric and photometric measurements has increased significantly. Such measurements are required in the manufacture of cameras, color TV and copying machines. Ultraviolet radiation is being used extensively for the polymerization of industrial coatings. An attempt is being made to use radiometry in measuring atmospheric temperatures for the purpose of forecasting weather. New solid-state lamps (LEDs) are used in a variety of visual displays. Phototherapy is used almost exclusively in the treatment of some diseases (e.g. jaundice in the newborn). Regulatory agencies are concerned with the hazardous effects of UV on the eyes and skin (skin cancer), particularly in industrial environments. Dentists are now using a commercially available "UV gun" for curing various new dental materials. Applications in the lamp industry are increasing because of our energy problems. Twenty-five percent of the U.S. electrical power is used for lighting, and thus, developing lamps that will produce the same light for less electrical power has a high priority. Improving the utilization of solar energy will require better measurements than are now available. All of these uses and applications of light require radiometry or photometry. Many of them will require a state-of-the-art accuracy of a few per cent in order to achieve their objectives.

Unfortunately, the current radiometric and photometric measurement system is inadequate for the many uses and applications described. Radiometric measurements are among the most difficult measurements to make. The radiant power varies with position, direction, wavelength, polarization and time, and the responsivity of most radiometers also varies with these and other parameters, making such measurements a difficult, multi-dimensional problem. In addition, most of the people needing radiometry have not been trained in the field. There are relatively few experts available. As a result of these two factors, measurement accuracy is poor and large differences in measurement are widespread. Much time and money is spent trying to resolve these differences, particularly when mass produced products require components from various companies and these components must meet radiometric or photometric specifications.

The cost of inadequate radiometry and photometry is very high. The electro-optical industry alone has annual sales approaching 15 billion dollars per year. A leading instrument manufacturer estimates that about $200 million is spent each year in calibrating radiometric systems or resolving discrepancies in radiometric measurements. If better radiometry can improve long-term weather forecasting as predicted, the economic impact would be tremendous. It is virtually impossible to estimate the cost of inadequate radiometry relative to medical and safety applications, but public health and safety are certainly given a high priority in this country.

Adequate radiometry today means making measurements with a few percent accuracy commonplace. This will require greater expertise in the system and more accurate, easy-to-use, and less expensive standards and techniques.

NBS has addressed itself to solving these problems. It helped organize the Council for Optical Radiation Measurement (CORM), a group largely representing industry and providing detailed information and a consensus of the needs in the system. It has worked with the Illuminating Engineering Society (IES), the Commission Internationale de L'Éclairage (CIE), and the Infrared Information Symposia (IRIS). NBS is developing more accurate, easy-to-use, less expensive standards and techniques and is beginning to monitor the capability of the system by interlaboratory comparisons. It has created specialized publications to insure that all this information is efficiently disseminated. Finally, NBS is also starting to produce a Self-Study Manual for Optical Radiation Measurements. This is expected to significantly upgrade the level of expertise in the U.S. in this area.

In summary, this study has shown that radiometry and photometry are having a significant economic and social impact in the U.S. today and this impact is expected to increase. The capability of this portion of the measurement system is inadequate for today's needs. An accuracy of a few percent is frequently needed; 10-50 percent is commonplace. The reason is that radiometric and photometric measurements are very difficult to make, and there is too little expertise to make these difficult measurements. NBS' program is designed to improve the situation by (1) making the measurements easier through simpler, inexpensive standards and techniques and (2) increasing the expertise through a Self-Study Manual on the subject.

1. INTRODUCTION

Everyone has his own built-in photometer -- the eye. The normal eye can see differences in light intensity and color of 1%. Yet the most sophisticated instruments available today do not measure the absolute intensity of light with an accuracy of better than 1%. Discrepancies of 10% are common and the 1% accuracy is only realized in a few cases and in the best standards laboratories of the world.

In spite of this situation, the accuracy and efficiency with which radiometry and photometry can be performed affects everyone in this country. Such measurements are important in

- Developing more efficient lamps (one-fourth of the electricity used in the U.S. is for lighting)
- Developing the use of solar energy
- Treating various diseases by phototherapy (e.g. jaundice in over 10,000 infants born in the U.S. each year)
- Specifying and controlling ultraviolet radiation hazards (these can cause eye damage and skin cancer)
- Pollution monitoring
- Weather forecasting
- Automating the production of many manufactured products such as lamps, cameras, film and television
- Developing and using modern defensive weapon systems.

As a result, accurate, efficient measurement of radiant power is an important factor in our energy shortage, our health, our safety, our economy and the defense of the country.

The National Measurement System Study in Radiometry and Photometry was initiated in 1971. Its primary purpose was to determine what NBS' program should be in this measurement area. A rapidly developing electro-optics industry, utilizing radiometry and photometry and the many applications of this technology to problems of public concern, provided the impetus for such a study. The first result of the study was an NBS Technical note [1] entitled "The Impact of Radiometry and Photometry and the Role of NBS". A second NBS Technical Note [2] called "The Present State of Radiometry and Photometry" followed. In the meantime, a new organization of industrial, governmental and university scientists and engineers, called the Council for Optical Radiation Measurement (CORM), was created. CORM prepared and submitted to NBS a report entitled "Pressing Problems and Projected National Needs in Optical Radiation Measurements: A Consensus of Services Desired of NBS". In March 1975 an updated version of this report was completed and submitted to NBS. During and following the preparation of these reports, a new NBS program in radiometry and photometry evolved.

In general, the approach used in conducting this National Measurement System Study was to try to answer the following four questions:

1. Why are radiometry and photometry important in the U.S. today?
2. What is the status of radiometry and photometry in the U.S.?
3. What is needed?
4. How should NBS respond?

Information was obtained primarily from personal discussions and correspondence with many concerned individuals in industry and government. Extensive interaction with industry and other government agencies is continuing. Conditions and needs change. The NBS program in radiometry and photometry must be updated to take account of these changes. The current report is a "snapshot", "taken" in March 1975, of the U.S. National Measurement System for Radiometry and Photo-metry. It is a summary of what we have learned about the System and what we are trying to do to improve it.

2. STRUCTURE OF THE MEASUREMENT SYSTEM

2.1 Conceptual System

2.1.1 Radiometry

In radiometry, the physical quantity measured is the radiant power incident on an aperature or a portion of a surface*. From this measurement and the geometry involved, various radiant power densities are calculated. These include the radiant power incident per unit area (irradiance) and the radiant power incident or exiting per unit projected area and unit solid angle (radiance). In addition, two quantities that are used to characterize sources of

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*In this Radiometry and Photometry Report, only incoherent radiant power is considered. The measurement of coherent radiant power is treated in the Study of the National Measurement System for Lasers.

radiation are often of interest. These are the intensity (of a source), which is the radiant power emitted by a source in a given direction per unit solid angle, and the total flux, which is the radiant power emitted by a source in all directions. Because accurate measurement of radiant power often requires knowledge of how the radiation is distributed relative to wavelength, λ, the spectral concentration of these quantities is also of great interest. The wavelength unit typically used in radiometry is nanometers.

The names of the major radiometric quantities, their symbols and units and their relationship to one another are listed below.

Radiant power or flux (ϕ)
WATT

Irradiance (E)
WATT $(\text{METER})^{-2}$

Radiance (L)
WATT $(\text{METER})^{-2}$ $(\text{STERADIAN})^{-1}$

Intensity (I)
WATT $(\text{STERADIAN})^{-1}$

Spectral flux (ϕ_λ)
WATT $(\text{NANOMETER})^{-1}$

Spectral irradiance (E_λ)
WATT $(\text{METER})^{-2}$ $(\text{NANOMETER})^{-1}$

Spectral radiance (L_λ)
WATT $(\text{METER})^{2}$ $(\text{STERADIAN})^{-1}$ $(\text{NANOMETER})^{-1}$

Spectral intensity (I_λ)
WATT $(\text{STERADIAN})^{-1}$ $(\text{NANOMETER})^{-1}$

$$E = \int L \cos\theta \, d\Omega = \int_\lambda E\lambda d$$

$$I = \int L \cos\theta \, dA = \int I_\lambda d\lambda$$

$$\phi = \iint L \cos\theta \, d\Omega dA = \int \phi_\lambda d\lambda$$

$$L = \int L_\lambda \, d\lambda$$

where θ is the angle between the direction of L and the surface normal. Thus all the radiant quantities are derivable from spectral radiance.

Spectral-radiance standards have been and are still principally derived from blackbodies. The spectral radiance of the radiation associated with a blackbody can be calculated from the Planck radiation equation provided that the temperature of the blackbody is known. Much of radiometry is concerned with spectral radiances corresponding to blackbody temperatures from about 1500 K to 3000 K. The uncertainty of the best thermodynamic temperature measurements in this region produces an uncertainty in spectral radiance in the visible spectral range of about 1/2%. Additional small systematic errors increase the state-of-the-art uncertainty in current spectral radiance standards to about 3/4%.

It is also possible to derive radiometric quantities from electrical measurements rather than temperature measurements. This is done by using a so-called absolute or electrically calibrated radiometer. One tries to design these instruments so that they respond in the same way to both radiant heating and electrical heating. Then, if the electrical signal is adjusted until the output of the radiometer is the same as that when the radiant power is incident, the latter is equal to the power dissipated in the radiometer by the electrical signal. Electrical-power measurements can be made much more accurately than temperature measurements. However, as of March 1975, the uncertainty of the electrical-radiant equivalence has limited the uncertainty of this method of realizing a radiometric scale to about the same as a blackbody-temperature-based scale. Nevertheless, the recent development of pyroelectric electrically calibrated radiometers make this approach much more practical than before, and it is being investigated extensively.

2.1.2 Photometry

In photometry, the physical quantities determined are similar to those in radiometry except that they are spectrally weighted by a function that approximates the spectral response of the human eye. The radiant power detected by such a "standard eye" is referred to as luminous flux. The unit of luminous flux is the lumen. It is defined in terms of the radiant power emitted by a blackbody at the temperature of melting platinum. More specifically, a lumen is the luminous flux emitted per steradian in a perpendicular direction by 1/600 000 square meters of a blackbody at the temperature of melting platinum.

The relationship between radiometric and photometric quantities is given by the equation

$$\text{Photometric Quantity} = K_m \int \begin{pmatrix} \text{SPECTRAL RADIOMETRIC} \\ \text{QUANTITY} \end{pmatrix} V(\lambda) \, d\lambda$$

where $V(\lambda)$ is the standardized spectral-response function of the eye* and K_m is the constant relating the lumen to the watt. The value for K_m may be determined by applying this equation to a platinum-point blackbody and the defined value of the lumen. Using the average of two recently reported values for the melting temperature of platinum, K_m is equal to 683 lumens per watt. The common photometric quantities, their symbols and their units are listed below.

Luminous flux (ϕ_v)
LUMEN

Illuminance (E_v)
LUMEN $(\text{METER})^{-2}$

Luminance (L_v)
LUMEN $(\text{METER})^{-2}$ $(\text{STERADIAN})^{-1}$

Luminous intensity (I_v)
LUMEN $(\text{STERADIAN})^{-1}$

The photometric quantities are related to one another in the same way as the radiometric quantities.

Since photometry initially developed because of needs in the manufacture, selling and use of lamps, the luminous intensity (of a source) has been a very important photometric quantity. Because of this and the importance of the human eye as a detector, the corresponding unit was included as one of the six Base Units of the SI system of units. Its SI definition parallels that given earlier for the lumen in terms of the platinum-point blackbody, and the name, candela, has been assigned this SI unit of luminous intensity (lumen per steradian).

The accuracy of realizing a platinum-point-blackbody standard of light has not been any better than about 1%. In addition such a realization is very tedious and has led national laboratories to maintain the candela on groups of lamps. The lamps from different national laboratories have been compared every 4 to 8 years at the International Bureau of Weights and Measures. In this way, international agreement of 1% to 2% has been maintained over a long period of time with very infrequent use of platinum-point blackbodies. The uncertainty of luminous-intensity calibrations performed at NBS has been estimated to be 1.5% relative to the candela maintained by NBS, 2.3% relative to the world mean, and 4.1% relative to the SI unit [4].

2.1.3 Reference Standards and Their Adequacy

NBS now issues a variety of tungsten-lamp reference standards calibrated in terms of the radiometric and photometric quantities described in the two previous sections. The uncertainty of these calibrations relative to absolute SI units varies from about 1% to 5% and relative to a fixed NBS base from about 1/2% to 2%. These uncertainties are adequate for many requirements in the Measurement System. However, the spectral-radiometric calibrations cost $1000 to $2000 and often require 3 to 6 months for delivery. Also there are no spectral-irradiance standards below 250 nm, no spectral-flux standards, and no detector standards above 250 nm currently available. Therefore, NBS is devoting considerable effort to making the existing standards less expensive and available in a shorter time and to developing the standards mentioned above that are not currently available. In addition NBS is proposing that the SI standards of light be redefined so that the photometric standards may be derived from their radiometric analogues using a defined value for K_m. This would reduce the uncertainty of the photometric standards to 1 to 2% and unify the radiometric and photometric systems. These additions and changes would make NBS radiometric and photometric standards adequate for most current requirements.

2.2 Basic Technical Infrastructure

2.2.1 Documentary Specification System

2.2.1.1 Standardization Institutions

There are some twenty-two organizations [2] associated with procedural standards each of which covers some aspect of radiometry or photometry. The three most active and their main area of interest are the

- Illuminating Engineering Society (IES) -- photometry
- Commission Internationale de L'Éclairage (CIE) -- photometry
- Infrared Information Symposia (IRIS) -- military infrared radiometry

*This is a roughly bell shaped curve extending from about 400 nm to 700 nm with a peak at about 555 nm.

A brief description of these organizations and the other nineteen not listed is given on page 31 of NBS Technical Note 594-6.

2.2.1.2 Survey of Documentary Standards

The major existing documentary standards for radiometry and photometry are:

IES Lighting Handbook, Fifth Edition, 1972.
Editor, John E. Kaufman
Published by the Illuminating Engineerning Society (IES),
345 East 47th Street,
New York, N.Y. 10017.

Individual reports on photometry published by the IES
Same address as above.

CIE publications on photometry
List available from
Secretary, U.S. National Committee, CIE
Room B-304, Metrology
National Bureau of Standards
Washington, D.C. 20234.

Handbook of Military Infrared Technology
Editor, William L. Wolfe
1965
Superintendent of Documents
U.S. Government Printing Office
Washington, D.C. 20402.

Various reports on military infrared radiometry
Infrared Information and Analysis Center
P.O. Box 618
Ann Arbor, Michigan 48107.

In general, these documents are useful for 5% to 10% radiometry and photometry. A special NBS Technical Note Series -- 594- on Optical Radiation Measurements -- has been established for providing detailed information useful for improving this accuracy. As of March 1975, nine of these have been published and are available from the U.S. Government Printing Office or NBS.

2.2.2 Instrumentation System

2.2.2.1 Measurement Tools and Techniques

The scientific base for radiometry has been and is still largely the Planck radiation law together with the Thermodynamic Kelvin Temperature Scale. These enable one to specify the radiation from a blackbody which is thus the basic standard.

A large number of blackbodies have been developed for use at temperatures ranging from 200 K to 3000 K. Many of these are available commercially. From about 1200 K to 3000 K, graphite tubes or cylinders heated by passing a high electric current through them have been used as blackbodies with precision and stability of better than 1% for times shorter than about one hour. From 200 K to 1200 K various metal cavities surrounded by wire heating elements (or thermoelectric coolers) have been used as blackbodies with a precision and stability of about 1% for times of about 100 hours. Though the platinum-point blackbody used in photometry has rarely been used with a precision of better than 1%, lower-melting-metal blackbodies are the most stable radiant sources available. Gold-point (1337 K) blackbodies have a precision and long-term stability of 0.01% or better. Copper-point (1357 K) blackbodies are better than 0.1% and tin (505 K) and zinc (692 K) appear to be as good as the gold-point blackbody but less data and experience are available for them than for gold. These melting point blackbodies have been designed and built by individual researchers in national laboratories. However, they are now also available commercially.

For temperatures above about 1200 K it is more convenient to use tungsten lamps as reference standards. Therefore standards laboratories usually compare the tungsten lamps to the blackbodies and issue the lamps as standards. Uncertainties of lamp standards at NBS vary from about 1% to 10% and a calibration costs from $100 to $2000. The specific standards available and their accuracy and cost are itemized in NBS Special Publication 250. The techniques used in realizing the standards and in generating additional standards are covered in the previously mentioned NBS Technical Note Series, number 594-.

In order to realize and use the above standards with 1% precision, the best commercially available lamps, power supplies, double monochromators, detectors, amplifiers, and optical components are required. The blackbodies used at NBS are generally developed in-house. Again, descriptions of much of the apparatus required are given in the 594- Technical Notes.

The development of stable silicon-diode detectors during the past 10 years has initiated a movement toward detector standards as well as source standards. Also, the recent development of electrically calibrated pyroelectric detectors and the availability of stable dye lasers is encouraging the investigation of using such black detectors instead of black emitters (blackbodies) as basic standards. These detectors are becoming available commercially.

2.2.2.2 The Instrumentation Industry

In the past 10 years, there has been a large increase in the number of commerically available radiometers and photometers. This has been motivated by the increased application of radiometry and photometry and made possible by new technological developments in electronics and in new, more stable, convenient-to-use, solid-state detectors. There are about a dozen manufacturers of such instruments.

Although these instruments generally have a precision (short term repeatability) of about 1% and are usually calibrated with lamp standards that are accurate from 1 to 2%, the accuracy of using them in practical applications is usually much worse. The reason is that for broad-wavelength-band radiometers, which most of these are, it is necessary to know the relative spectral response of the radiometer and the relative spectral distribution of the radiation being measured. Manufacturers are not currently able to supply the former information for a modest cost, and, often, the relative spectral distribution of the radiation to be measured is not known. As a result, the uncertainty of the measurement is frequently not known. It can vary from a few percent, when measurements are being made of a source whose spectral distribution is similar to the standard used in calibrating the radiometer, to 100 percent or more for greatly different spectral distributions.

2.2.3 Reference Data

The major reference data of interest in radiometry and photometry are the detailed characteristics of the various sources, detectors, monochromators, filters and other apparatus used. Most data of this type that are available come from the manufacturers of the apparatus. However, these data are rarely accurate or extensive enough for radiometry and photometry of a few percent accuracy. Often such data are developed as one is trying to achieve or use a new state-of-the-art capability. Therefore, as more and more people realize or try to achieve greater accuracy more reference data will be generated. To encourage the publication of such data, the CIE recently sent out a source questionnnaire to leaders in radiometry and photometry throughout the world. The information obtained is being consolidated into a report entitled "A Survey of Photon Sources Used for the Accurate Measurement of Visible, Near-Infrared and Near-Ultraviolet Radiation".

2.2.4 Reference Materials

There are very few reference materials used in radiometry and photometry. Mainly, they are the metals used in melting-point blackbodies, and these are available commercially with a purity of 99.999%. Such a purity appears to be adequate for 0.01% radiometry; it is not a limiting factor for the current state of the art of about 1%.

2.2.5 Science and People

The fields of science supporting this portion of the National Measurement System are primarily theoretical physics and solid-state physics. Theoretical physics provides the basis for the Planck radiation law, the effects of diffraction and coherence, and the detailed manner in which radiation is propagated. Solid-state physics provides the basis for new and improved detectors and sources of radiation -- the major tools used in radiometry and photometry.

The Optical Society of America and the Illuminating Engineering Society are the major professional societies concerned with this field of measurement, but there are a number of others also involved. Technical papers concerned with radiometry and photometry appear in a wide range of journals associated with such specialized areas as heat transfer, photobiology, astronomy, and meteorology.

The bulk of the people working in radiometry and photometry have little or no formal training in the field. This is because few colleges or universities offer any courses in radiometry or photometry, and only the Optical Science Center at the University of Arizona and the Insititue of Optics at the University of Rochester offer graduate programs in radiometry. In addition, there are very few books on the subjects. This is the situation that has led NBS to initiate the writing of the Self-Study Manual on Optical Radiation Measurements.

2.3 Realized Measurement Capabilities

The accuracy realized in radiometric and photometric calibrations at NBS varies from 1% to 5%. The May 1974 issue of Optical Radiation News, distributed quarterly by NBS and included in this report as Appendix A, gives more specific information on NBS capabilities.

Experts in well-equipped laboratories can realize accuracies in similar measurement situations almost as well as NBS, say 1½ to 6%. The slight degradation is the result of reference-standard instability and the inability outside of the NBS laboratory to recalibrate the reference standard immediately before and after the measurements of primary interest.

Most workers in the field realize 5% to 10% accuracy only with great difficuty and there is much evidence that significantly larger errors are commonplace.

Most of the optical-radiation-measuring community would like to realize a 1% accuracy as stated in the CORM Report [3] . One of NBS' major goals is to help make this a reality.

2.4 Dissemination and Enforcement Network

2.4.1 Central Standards Authorities

The central standards authority in the U.S. is the National Bureau of Standards. Following a radiometry and photometry reorganization in 1971 a coordinated long-term program was established with a goal to make 1% radiometry and photometry commonplace in the U.S. Some of the other countries that have been active in this area are Australia (NML), Canada (NRC), East Germany (DAMW), France (CNAM), Germany (PTB), Japan (ETL), Union of South Africa (NPRL), United Kingdom (NPL), USSR (IMM).

The International Bureau of Weights and Measures (BIPM) serves as a central world laboratory for conducting photometric intercomparisons and supplying calibrations to those countries of the world that have not realized their own standards. It has been trying to extend these services to radiometry as well but has not been very successful due to insufficient resources.

2.4.2 State and Local Office of Weights and Measures

State and local offices of Weights and Measures have not been active in radiometry and photometry. However, there is some evidence that this may begin to change. For example, the California Highway Patrol has asked NBS questions related to the measurement and specification of various types of automotive lamps and flashing lamps for emergency vehicles.

2.4.3 Standards and Testing Laboratories and Services

There are a number of commercial radiometric and photometric testing and calibration laboratories in the U.S. These laboratories obtain standards from NBS and produce and issue their own reference standards. In addition, they perform specialized measurements or tests for industry and other government agencies. All such laboratories that we know of are listed in Appendix B. Inclusion in the list only means that NBS is aware of the services offered by these commercial concerns. To date it has not been NBS policy to certify or endorse such laboratories or their measurement capabilities.

A few governmental agencies other than NBS (e.g. DOD and NASA) also have radiometric and/or photometric calibration laboratories. These laboratories primarily provide services for their own agencies or their contractors. Some interact strongly with NBS and, in an emergency, could provide some of the radiometric and photometric services to the public that are normally provided by NBS.

2.4.4 Regulatory Agencies

The major regulatory agencies concerned with radiometry and photometry are the Bureau of Radiological Health (BRH) and the National Institute for Occupational Safey and Health (NIOSH), both in the Department of Health, Education and Welfare, and the Occupational Safey and Health Administration (OSHA) in the Department of Labor. The legislation that created these agencies and their assigned responsibilities is outlined on pages 10 and 11 of NBS Technical Note 594-4. NBS assists these agencies in various ways ranging from general advice and consultation to detailed research projects to help insure that their standards and measurement capabilities are satisfactory.

2.5 Organizational Input-Output Transactions Matrix

2.5.1 Analysis of Suppliers and Users

The Input-Output Transactions Matrix shown on page 10 contains the following suppliers and users:

(1) The Knowledge Community -- scientific organizations, academic institutions, professional societies,

technical publishing organizations, etc.

(2) International and Foreign Metrological Organizations.

(3) Commission Internationale de L' Éclairage (CIE).

(4) Other Documentary Specification Organizations, both international (e.g., ISO, IEC, OIML) and national (ANSI, the DOD standardization agencies, GSA, IEEE standards committees, etc.).

(5) The Instrumentation Industry.

(6) NBS.

(7) DOD Standards Laboratories.

(8) Commerical Standards and Testing Laboratories.

(9) Regulatory Agencies (excluding the Offices of Weights and Measures).

(10) The Department of Defense (excluding standards laboratories and any functions already covered above).

(11) Other Federal Government Agencies, excluding any functions already covered.

(12) Industrial Trade Associations (CORM, LTEC, etc.).

(13) The Lamp Industry.

(14) The Photographic and Film Industry.

(15) Industrial, technological, commerical, or other intermediate economic users or suppliers of measurement goods and services.

(16) The General Public.

The numbers in the intersection boxes of the matrix are estimates of the direct transactions between the supplier and user defined by that box according to the following code.

A. The number in the center of each box indicates the magnitude of the transaction on a semi-quantitative "volume" basis where
  - 0 = Trivial
  - 1 = Minor
  - 2 = Moderate
  - 3 = Important
  - 4 = Major.

B. The letter or number in the lower left corner describes the rate of change of the transaction where
  - N = Declining value or needs (N for Negative)
  - D = Stable
  - 2 = Growing
  - 4 = Explosive growth.

C. The number in the upper left-hand corner indicates the importance of the transaction where
  - 1 = Purely a matter of convenience; transaction not essential, reasonable alternatives readily available.
  - 2 = Economically important; strongly desirable.
  - 3 = No satisfactory alternate source; legally required.
  - 4 = Essential; sole source; matters of life and death.

D. The number in the upper right-hand corner indicates the adequacies of the transaction goods or services where
  - 0 = No foreseeable improvements needed or desirable.
  - 1 = Under control, but could be improved.
  - 2 = Only marginally satisfactory.
  - 3 = Seriously deficient.
  - 4 = Out of control -- thoroughly unsatisfactory.

In preparing the matrix, the following guidelines were adhered to.

A. A box was left empty if the volume of transactions was negligible. If numbers were entered in one or more of the corners, then those in that box that were left blank should be read as zeros.

B. The NBS-NBS box included all the internal transactions within NBS.

C. Every user was also entered as a supplier. The transaction, from a user to a supplier, might only be information regarding measurement system needs.

2.5.2 Highlights of Transaction Matrix

The average transaction* for radiometry and photometry in the transaction matrix is represented by the following intersection box.

2.2		1.0
	1.9	
1.2		

*Obtained by adding the numbers in all the intersection boxes at each location in the box and dividing by the number of boxes.

DIRECT MEASUREMENTS TRANSACTIONS MATRIX FOR RADIOMETRY + PHOTOMETRY INPUT-OUTPUT USERS SUPPLIERS	Knowledge Community 1	International Metrological Organizations 2	Commission Internationale de L'Eclairage (CIE) 3	Other Documentary Specification Organizations 4	Instrumentation Industry 5	NBS 6	DOD Standards Laboratories 7	Commercial Standards and Testing Laboratories 8	Regulatory Agencies 9	Department of Defense (Other) 10	Other Federal Government Agencies 11	Industrial Trade Associations 12	Lamp Industry 13	Photographic and Film Industry 14	Other Industrial 15	General Public 16	17	18	19	20	21	22	23	24	25
1 Knowledge Community	3 2 3 2	3 2 3 2	3 2 3 2	2 2 3 2	3 3 2 2	3 2 3 2	3 3 2	3 3 2 2	3 3 2 2	2 3 2	2 3 1 2	2 3 1 2	3 3 2 2	3 3 2 2	2 3 1 2	1 3 1									
2 International Metrological Organizations	3 1 4 2	2 1 4 2	4 1 4 2	2 2 2 2	2 2 0	3 1 3 2							1 1	1 1											
3 Commission Internationale de L'Eclairage (CIE)	4 1 4 2	3 1 3 2	3 1 4 2	3 1 2 2	2 1 1 2	2 1 2 2						3 2 1 2	2 1 3 2	2 1 2 2	2 1 1 2										
4 Other Documentary Specification Organizations	4 3 1 2	4 2 1 2	3 3 1 2	3 2 2 3	2 3 1 2	4 2 1 2	3 2 1	2 2 1 2	2 1 1 2	2 1 2	2 3 1 2	2 2 1 2	2 3 2 2	2 3 2 2	2 3 1 2										
5 Instrumentation Industry	3 1 2 2	4 1 2 4	2 1 2 2	2 1 2 2	4 1 3 2	4 1 2 2	4 1 2	4 1 2 2	4 1 3 2	4 1 3	4 1 3 2	3 1 2 2	4 1 2 2	4 1 2 2	4 1 3 2	4 1 2									
6 NBS	3 1 4 2	3 1 3 2	2 1 2 2	2 2 2 2	3 1 3 2	4 1 4 2	4 1 4 N	4 1 4 2	4 2 2 2	2 1 2 N	3 1 3 2	2 1 4 2	3 1 4 2	3 1 4 2	3 1 2 2	3 1 2									
7 DOD Standards Laboratories	2 1 3	1 1	1 1	2 1 2	2 1 2	3 1 2	3 1 4	1 1	1 1	4 1 4	1 1 1	1 1 1	2 1 1	2 1 1	1 1 1										
8 Commerical Standards & Testing Laboratories	2 1 2 2	1 1	2 1 1 2	2 1 1 2	2 2 4 2	3 2 2	2 1 3 N	2 2 3 2	2 1 3 2	2 2 4 N	2 2 3 2	2 1 2 2	2 2 2 2	2 2 3 2	2 2 3 2										
9 Regulatory Agencies	3 1 3 2	1 1 1	2 1 2	2 1 1 2	3 1 3 2	3 1 2 2	1 1	2 1 2	3 1 4 2		2 1 2 2	2 1 2 2	3 1 2 2	1 1 1	4 2 2 2	4 3 4 2									
10 Department of Defense (Other)	2 1 2			2 1 2	2 1 2	2 1 1	4 1 4	2 1 2	1 1 1	4 1 4	1 1 1	2 1 2	2 1 1	2 1 1	2 1 2	4 1 4									
11 Other Federal Government Agencies	2 1 2 2		2 1 1	1 1	2 1 1 2	3 1 1 2	1 1 1	2 1 1 2	2 1 1 2	1 1 1	3 1 1 2	2 1 2 2	2 1 1 2	2 1 1 2	1 1 1 2	2 1 2 2									
12 Industrial Trade Associations	2 1 2 2	1 1 1	2 1 2 2	2 1 3 2	2 1 3 2	3 1 4 2	1 1 1	2 1 2 2	2 1 1 2	1 1 1	2 1 2 2	2 1 4 2	2 4 2	2 4 2	2 3 2	1 1									
13 Lamp Industry	2 2 3 2	2 1 1 2	2 4 2	2 1 3 2	4 1 3 2	4 1 3 2	4 1 3	4 1 3 2	4 1 2 2	4 1 2	4 1 3 2	3 1 4 2	4 4 2	4 3 2	4 1 3 2	4 1 4 2									
14 Photographic and Film Industry	3 2 2 2	2 1 1 2	2 3 2	2 1 2 2	2 1 2 2	4 1 2 2	4 1 2	4 1 2 2	4 1 1 2	4 1 2	4 1 2 2	3 1 4 2	4 2 2	4 4 2	4 1 3 2	4 1 4 2									
15 Other Industrial	3 3 2 2	2 1 1 2	2 2 2 2	2 1 1 2	3 1 1 2	3 1 1 2	3 1 1	2 1 1 2	2 1 1 2	4 1 1	3 1 1 2	2 1 2 2	3 1 2 2	3 1 2 2	3 1 2 2	3 1 3 2									
16 General Public						3 1 2			2 1 1 2		2 1 1 2		2 1 2	2 1 2											
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According to the code this means the average transaction is characterized by

- Moderate volume
- Growing slowly
- Economically important; strongly desirable
- Under control, but could be improved.

The main value of this average is to "calibrate" the matrix so that large deviations from the average can be easily detected. Using it in this manner, we find the following extremes relative to the suppliers.

Significantly greater volume than average:
- NBS
- Lamp Industry

Significantly less volume than average:
- General Public
- Documentary Specification Organizations
- Other Federal Government Agencies
- International Metrological Organizations

Significantly greater growth rate than average:
- Instrumentation Industry
- Lamp Industry
- Other Industries

Significantly smaller growth rate than the average:
- DOD
- DOD Standards Labs
- International Metrological Organizations
- General Public

Significantly greater importance than the average:
- Lamp Industry
- Photographic Industry
- Instrument Industry
- NBS

Significantly less importance than the average:
- International Metrological Organization
- General Public

Adequacy significantly greater than average:
- General Public
- International Metrological Organizations

Adequacy significantly less than average:
- Knowledge Community
- Documentary Specification Organizations.

At first glance, it is surprising to see how minor a role the International Metrological Organizations and the General Public appear to play in the total of all radiometry and photometry transactions. However, for this field of measurement, the International Bureau of Weights and Measures and the various national standards laboratories, though very important, interact primarily among themselves. Similarly, a number of the suppliers of these goods and services do not interact directly with the Public.

The adequacy of the transactions is obviously a question of great interest. The estimate that the Documentary Specification Organizations are supplying a very inadequate amount of information to users is a situation that requires attention. The estimate that the Knowledge Community is seriously deficient in spite of supplying a near average volume is due to the fact that even though the number of publications is not low, the number of courses and the training offered by colleges and technical schools are completely inadequate.

Trying to summarize the transaction matrix in terms of the users, in a similar manner to that of the suppliers, it is noted that there are fewer extremes. The reason for this is not clear. Such an analysis tells us only that the total transactions to DOD and the DOD Standards Laboratories have a significantly lower than average growth rate which is not surprising. It also tells us that the importance of the transactions to NBS is significantly greater than the average. This is due to the fact that a large number of transactions to NBS consist of information on measurement-system needs; and in a system that needs significant improvement, this is of great importance.

3. IMPACT, STATUS AND TRENDS OF MEASUREMENT SYSTEM

3.1 Impact of Measurements

3.1.1 Functional, Technological, and Scientific Applications

Radiometric or photometric measurements are used widely in

(1) The specification, production and quality control of many products
(2) Public health and safety
(3) Energy development and conservation
(4) Meterology
(5) Remote sensing
(6) Scientific research

Brief comments will be made on each of these areas. For more details, the reader is referred to pages 10 to 21 of NBS Technical Note 594-4.

The lamp manufacturers primarily sell light. Lamps must be specified, developed, manufactured and sold in competition with other producers, domestic and foreign. To do this efficiently and in an orderly manner requires the manufacturers to make radiometric and photometric measurements that agree, at least among themselves, to one per cent.

Photographic film and cameras must be produced so that they are compatible with one another. Colored pictures and present-day automatic cameras increase the compatibility requirements. Radiometry of a few per cent or better in each of various production and testing processes is necessary to efficiently achieve this compatibility.

Blue light is used to treat newborn children that have jaundice. However, experts are becoming concerned about the possibility of using a larger dosage of light than is necessary or desirable. Undesirable photochemical reactions can take place as well as desirable ones. Thus the amount of light used in phototherapy should be specified and controlled just as if light were a drug. Efficient and reliable radiometry is required for this purpose.

In developing more efficient lamps (same light for less electrical power) one-percent photometry is required in order to detect small improvements in efficiency. This is particularly important because most improvements in present-day lamps are expected to come in small steps of a few per cent. Similarly, radiometry will be required for determining the efficiency of solar heaters and converters in the development of solar energy.

More accurate weather forecasting, both short- and long-term, is considered possible if more accurate radiometry were available to determine temperatures throughout the earth's atmosphere. A 1% accuracy and a 0.1% long-term precision is the goal -- both beyond the present practical state of the art.

Radiometric measurements of the earth's surface from aircraft or satellites, a primary form of remote sensing, is beginning to be used and is expected to be expanded extensively in years to come. It is expected to provide a tremendous amount of information in such areas as agriculture, water and air pollution, forestry, mapping and resource management.

Much scientific research utilizes radiometry. Radiometric measurements play an important role in experiments designed to increase our knowledge of atoms, molecules, solids and liquids. It is being used increasingly in chemistry, in biology, botany, oceanography and, of course, astronomy where much of the information we obtain must be from measurements on the optical radiation that is emitted and reaches the earth.

The entire universe consists of matter and various types of radiation including optical radiation (infrared, visible, ultraviolet). Because the accurate measurement of optical radiation has always been so difficult, its use was greatly limited. As a result of new technological developments in solid state detectors, sources, optical apparatus, electronics and computers it appears as though this may be changing. In addition, the effects that optical radiation and its measurement are known to have on public safety and health, on problems associated with energy conservation and utilization, and on our economy mean that the number and reliability desired of such measurements are increasing significantly.

3.1.2 Economic Impacts -- Costs and Benefits

The cost of radiometric measurements is very high. Radiometers and spectroradiometers range in cost from about $1000 to $25,000 and standards to calibrate them from $500 to $2000. In addition radiometric measurements are among the most difficult types of measurements to make. Optical radiation varies with position in space, direction, wavelength, polarization and time. These variations must be taken into account along with the manner in which a radiometer response varies with these same parameters. When this is not done, errors of 10% are commonplace and much greater errors are also possible. Though it would be desirable to perform 1% measurements routinely, this is now the best that can be done under ideal conditions. This means also that high-level, well-trained engineers be available to make the measurements, but few such people are available. Few colleges give courses in radiometry and photometry, let along offer a complete program in this area. Additionally, there are no suitable modern textbooks on the subject. Expertise, where it exists, has been developed on the job, by "trial and error", through years of effort at high cost. Where it doesn't exist which is more frequently the case, discrepancies in measurements are large, particularly between different organizations, especially manufacturers. Resolving these discrepancies is time consuming and costly.

As an example of how expensive radiometric measurements can be, a major industrial concern has recently required spectral measurements from about 350 nm to 800 nm on a special low-level source that they wished to use as a standard for simulating stars. They made measurements themselves and had several secondary laboratories do the same. These differed by as much as 25% so NBS was requested to make the measurements also. In order for NBS to perform the measurements to within an uncertainty of about five per cent, a cost of $7500 in labor was incurred.

It has not been possible for us to determine the total costs or the economic benefits of radiometric and photometric measurements made in the Measurement System; however, there is no question that significant amounts of money are involved.

The lamp manufacturing industry has about one billion dollars of sales per year. The lamp companies tell us that if the light output of the lamps of one or a few of the companies dropped a few per cent, it would be disastrous to their sales. Similarly, not being able to determine the light output of some of the newer, more efficient lamps because of their unusual spectral distributions and large variations in intensity as a function of wavelength would seriously impair sales. On the other hand, an improved measurement capability would increase the chances of improving the efficiency of lamps [1] . When one considers that 25% of the electricity used in this country is for lighting, an improvement in efficiency of even a few per cent would have a significant impact.

Turning to the U.S. camera and film industry, the effect on their 5-billion-dollar annual sales could be significant if much poorer pictures were obtained with U.S. products than with foreign products. To avoid this, quality control in production must be maintained, and this requires reliable radiometry.

The economic benefits of improving the accuracy of radiometric measurements in meteorology should be very large. If one per cent measurements were commonplace in meteorology, experts tell us that long-term weather forecasting would be possible [1]. The economic benefit to U.S. farmers alone, if they were able to predict more accurately the best time to plant or to harvest, would be quite large.

It has been reported that the routine use of remote sensing would save the U.S. 59 billion dollars [1]. Inability to make accurate radiometric measurements is one of the limitations to more extensive use of remote sensing.

Thus, even though one cannot say how much it would cost the 15-billion-dollar-a-year electro-optics industry if the currently available radiometry and photometry in this country did not exist or how much will be saved in energy by better weather forecasting or remote sensing when 1% measurements become commonplace, there is little question that the amounts will be much greater than the approximately one million dollars per year spent at NBS to provide standards, standard techniques and "know how" to maintain and improve these measurements in the U.S.

3.1.3 Social or Human Impacts

Radiometric and photometric measurements that affect the person on the street directly are those used for health and safety. One example of this are the ten thousand newborn infants that are treated for jaundice (hyperbilirubinemia) each year by illumination with high-intensity light. The only other treatment for this disease, prevalent in many premature infants, is a blood exchange which is more dangerous and for which many small hospitals do not have the required facilities. However, even phototherapy can be dangerous if the intensity of the dosage isn't under good control. This requires an easy-to-use 10% radiometry which probably does not exist in any hospital at the present time [5] but is well within the current state of the art.

Excessive quantities of ultraviolet light are hazardous, causing skin burn, eye damage and ultimately skin cancer. At the same time, ultraviolet is being used more extensively in industry, in photochemistry, in graphic arts and in photopolymerization of plastic materials for coatings. Dentists are beginning to use ultraviolet "guns" for curing new epoxy materials used in dentistry. Regulations are now being established by BRH and NIOSH to protect the public from excessive ultraviolet light. These regulations will require reliable measurements by industry and the regulators.

Another example of the importance of radiometry to each one of us is the potential effect of supersonic transportation and other things such as aerosol products, etc., on upper-atmosphere chemistry. "Experts" debate what changes might occur which would result in a significant increase in the ultraviolet radiation incident on the earth's surface, and in turn would have a great effect on life on earth. A National Academy of Sciences panel, convened to examine the subject, observed that it was extremely important to obtain base-line data of solar ultraviolet flux and to monitor this base line accurately [1].

3.2 Status and Trends of the System

Radiometric and photometric measurements are difficult to make, expensive and generally have very poor accuracy. This is due in part to the nature of the measurements, but the situation is much worse than necessary due to the lack of adequate inexpensive standards and the lack of adequately trained people to make the measurements. One strength in the system is that new solid-state detectors, sources, miniature electronics and miniature computers are improving the instruments available for these measurements. In addition, developments are taking place at NBS which should improve the overall situation significantly within a few years. These consist of (1) attempts to train those needing to make radiometric and photometric measurements by preparing a Self-Study Manual for this purpose, (2) developing additional and less expensive standards and calibration services and (3) developing new-type electrically calibrated radiometers that will improve certain types of radiometric measurements.

4. SURVEY OF NBS SERVICES

4.1 The Past

The history of radiometry and photometry at NBS may be divided into three periods that we refer to as (1) the Early Period, starting in the 1920's and extending to about the mid 1950's, (2) the Transition Period, from about 1955 to 1965, and (3) the Modern Period, starting in the mid 1960's and extending to the present.

Radiometry in the Early Period was one primarily involved with experiments verifying the Planck radiation law. However, irradiance (watt·meter $^{-2}$) standards were developed with uncertainties of about 5%. Extensive applications for radiometry did not exist; moreover, the technology required for practical radiometry was not available.

The situation was somewhat different for photometry. The widespread use of light bulbs for illumination developed a need for light measurements, which were required in order to have an orderly marketplace for "selling light." As a result photometry was quite active, culminating in the 1930's in the development of the platinum-point blackbody for the standard of light. Following this, for about twenty years, a variety of standard lamps and calibration techniques were developed which were adequate for illumination purposes. By 1955, these photometric standards and calibration methods had a stability and a precision of a few percent. Accuracy, which was not nearly as important as consistency and agreement with others, was given little serious attention and is estimated to have been about 5%.

The Transition Period, between about 1955 and 1965, saw the first practical standards in spectroradiometry. The U.S. space program was the motivating factor. Also suitable detectors and electronics were becoming available. The accuracy of the spectral-radiant standards was between 5 and 10% and irradiance standards were improved to an accuracy of two or three per cent. The standard lamps and calibration methods in photometry that were developed earlier were now being used routinely. Photometric comparisons conducted by BIPM showed international agreement within a few per cent. There was very little interaction between radiometry and photometry.

For radiometry the Modern Period began in the mid 1960's. Photoelectric optical pyrometers made it possible to determine blackbody temperatures more accurately. Military requirements in radiometry were added to those of the space program and provided the motivation to use this increased temperature-measurement capability to develop spectral-radiance standards with an accuracy of 1%. In addition, the practical application of electrically calibrated thermopile detectors was initiated. It produced irradiance standards with an accuracy of 0.5%.

For photometry the Modern Period didn't start until about 1970. A rapidly growing electro-optical industry required better and additional photometric as well as radiometric standards and measurement techniques. Also a tighter coupling between photometry and radiometry was desired. An extensive reorganization took place at NBS in 1971, combining the radiometric and photometric activities and initiating a strong effort to improve and extend standards and calibrations in this area. By 1975, practical electrically calibrated pyroelectric detectors had been developed and with dye lasers are providing a new, exciting measurement approach with great potential.

Also, this period saw the development of a much stronger interaction between NBS and industry via a new organization called the Council for Optical Radiation Measurements. In addition, more emphasis was being placed on disseminating details of NBS technical efforts through the Optical Radiation Measurements Technical Notes and communicating more rapidly and generally through the Optical Radiation Newsletter.

The major weakness of the modern program has been that the resources have not been sufficient to produce what is needed as early as it is needed.

4.2 The Present -- Scope of NBS Services

4.2.1 Description of NBS Services and Program

The radiometric and photometric activities at NBS are primarily situated in the Optical Radiation Section and Radiometric Physics Section of the Optical Physics Division of the Institute for Basic Standards. In FY 1977, the budget associated with these activities is about 1¼ million dollars, and the staff consists of twenty-one technical people made up of thirteen senior scientists and engineers and eight junior professionals or technicians. The radiometric and photometric services are developed around the following ten-point program.

(1) Maintenance of existing standards and provision of calibrations based on these standards.

Approximately 26 calibration services are offered covering the major radiometric and photometric quantities for which significant interest exists. Uncertainties in the calibrations vary from 0.5% to 10%. NBS Special Publication 250 gives the details of these services. The dollar volume is about 90 thousand dollars per year.

(2) Reducing the cost and delivery time of calibrations.

The most expensive single, routinely offered calibration costs $2400 and has an average delivery time of about 6 months. An extensive effort is under way to significantly reduce costs and delivery times through automation.

(3) Development of new standards and calibrations.

The new standards and calibrations currently being developed or recently developed are spectral response of silicon diode detectors that are widely needed throughout the system, ultraviolet D_2 discharge irradiance standards for calibrations associated with measurements of hazardous radiation, and spectral total (geometrical) flux standards so the lamp industry can better characterize and specify their new, more efficient lamps.

(4) Dissemination of information on measurement techniques and reference data.

An NBS Technical Note series entitled OPTICAL RADIATION MEASUREMENTS has been introduced in order to publish more detailed information than is possible in the scientific and engineering journals and to publish progress reports on long-term efforts. A newsletter now published four times a year disseminates information such as notices of meetings, new calibration services and intercomparisons, and highlights of NBS research and development.

(5) Providing leadership and assistance in developing greater expertise in the System.

NBS is producing a SELF-STUDY MANUAL ON OPTICAL RADIATION MEASUREMENTS which will be directed at a bachelor's-degree-level professional with no training in radiometry or photometry. It is being published in parts as completed. Four chapters have been published, and two more are undergoing final editorial review before publication.

(6) Develop and maintain a Measurement Assurance Program to continuously assess the accuracy and precision of the System.

Thus far this effort has been limited to interlaboratory comparisons involved in transferring calibrations from NBS standards to working standards.

(7) Provide leadership and consulation in solving national problems involving radiometry and photometry.

NBS has organized a workshop on radiometry requirements in solar energy utilization, has participated on an NRC-NAS committee concerned with phototherapy of newborn infants having jaundice, is helping develop the radiometry needed for remote sensing and is assisting the Environmental Protection Agency and the Bureau of Radiological Health relative to their radiometric needs.

(8) Perform research on new techniques and instruments.

Research on a new set of modern tools and techniques such as electrically calibratable pyroelectric detectors and dye lasers is being pursued.

(9) Interact extensively with the System in order to understand its needs and priorities.

Users from industry, government and science have organized into the Council for Optical Radiation Measurement (CORM). CORM has submitted to NBS two reports on Pressing Problems and Projected National Needs in Optical Radiation Measurements: A Consensus of Services Desired of NBS.

(10) Interact with the international measurement system to insure that our national system is adequately integrated with it.

NBS is actively involved in the Advisory Committee of Photometry and Radiometry (CCPR) of the International Committee of Weights and Measures and in the Commission Internationale de L'Éclairage (CIE). For example NBS in conjunction with the Measurement Laboratory of Australia has prepared a publication pressing for the redefinition of the unit of light. This redefinition ties photometry directly to spectroradiometry and will enable photometry to better serve modern-day industrial needs.

4.2.2 Users of NBS Services

The major users of NBS services are those in the System desiring to make accurate radiometric or photometric measurements or measurements that are consistent with others being made in the U.S. or the world. Currently the major users are the

- Lamp Industry
- Photographic Industry
- Instrument Industry
- DOD Standards Laboratories
- Commercial Standards Laboratories
- Other Federal Government Agencies (BRH, EPA, GSA, NASA, NOAA)
- Other Industries (Aerospace, Electronics, Computing, Copying, etc.)

As an example of the specific companies involved, Appendix C contains a list of the last fifty customers requesting photometric calibrations from NBS.

Users of NBS calibration services generally use the calibration to establish their own set of working standards. These working standards are then used in such activities as (1) calibrating radiometers and photometers, (2) controlling the quality of production of items like lamps, film, cameras, or components of larger radiometric or photometric systems, (3) establishing intensity or dosage levels for public safety or health, or (4) performing research in product development or science.

In addition to physical standards, NBS also disseminates information via its scientific papers, its Technical Reports and its Newsletter. These are distributed to members of CORM and to others that request them. CORM members now total over 260 and are listed in CORM Report No. 2 [3].

In general, NBS calibration and information services provide a means for the entire National Measurement System to be based on the same scale and units and use measurement techniques that are similar. This significantly increases the agreement in the results of radiometric and photometric measurements made throughout the System.

4.2.3 Alternate Sources

It is conceivable that, eventually, virtually all of the calibration and testing services will be obtained from the commercial secondary standards laboratories. At present, however, the frequent discrepancies in measurements encourage many users to get calibrations directly from NBS and eliminate the additional uncertainty of a middleman. It is expected that this will change as the capability of the entire System Improves.

4.2.4 Funding Sources for NBS Services

About 75% of NBS funding for radiometry and photometry comes from direct congressional appropriations. Ten per cent of the funding comes from direct charges to customers receiving NBS calibrations and tests, and fifteen per cent comes from other government agencies that have requirements for highly specialized new standards and have contracted for NBS to perform the necessary research and to develop these new standards.

4.2.5 Mechanism for Supplying Services

The mechanisms for supplying NBS services in radiometry and photometry have been discussed throughout Section 4.2. These, and a few not previously mentioned, are listed below.

- Calibrations
- Other Agency Contracts
- Publications
  - Scientific and engineering journals
  - NBS Technical Notes
  - Self-Study Manual
  - Newsletter
- Measurement Assurance Program

Organizational Contacts and
Committees (CORM, ASTM, LTEC, IRIS, CIE)
Personal Contacts (Visits, letters, phone calls).

4.3 Impact of NBS Services

4.3.1 Economic Impact of Major User Classes

Annual sales for the three major users of NBS radiometric and photometric services are about one billion dollars for the lamp industry, five billion dollars for the photographic industry and a half-billion dollars for the instrument industry [2]. CORM estimates that the annual sales of the entire electro-optics industry, which depends heavily on radiometric and photometric measurements, is 15 billion dollars [3]. An idea of the economic impact of NBS services on these companies can be obtained from many letters received in the past few years. For example, a company in the instrumentation industry wrote

"There will certainly be an unfavorable foreign trade impact if electro-optical devices of U.S. manufacture cannot be relied upon to yield uniform NBS traceable quantities. The cost impact in this area can easily run into millions of dollars."

A company in the lamp industry wrote

"The consequences of not having standards can be summarized as follows. 1) The (lamp) industry is unnecessarily penalized millions of dollars through rejection of product offerings due to differing measurement level . . ."

The social impact of NBS services is significant relative to national security, citizen health and safety, and advances in fundamental research. Many of the anti-ballistic missle defense systems utilize radiometric guidance systems which require calibrations tracable to NBS. Concerning health and safety, a representative of a leading lamp company wrote NBS a letter stating

"All germicidal, sun lamps and ozone producing lamps come under the jurisdiction of the U.S. Department of Health, Education and Welfare, Food and Drug Administration via the Federal Hazardous Substances Act Sec. 11(b) 15 U.S.C. 1270(b) 1274 which allows their agents to inspect the product, its package labeling, its characteristics, its place of manufacture and its energy emission. In order to accurately define the latter, UV reference standards are required."

In the area of basic research, many advances are made possible by new instrumentation. A leading manufacturer of electro-optical products writes

"The design and application of new electro-optical products is in many cases being retarded by the relatively inaccurate optical standards. Voltage, current and resistance can be routinely measured to within 0.01% by almost any electronics firm, while 1% optical measurements are very difficult even for NBS or other national standard laboratories."

Additional examples of the economic impact of NBS radiometric and photometric services can be obtained on pages 12 to 21 in NBS Technical Note 594-4. The role NBS services plays relative to these impacts is to provide the basic standards and techniques so that national and international agreement exists in measurements, specifications and related activities associated with the development, production, marketing and use of electro-optical products.

4.3.2 Technological Impact of Services

A few examples of technologies supported by NBS radiometric and photometric services are the

- Development of more efficient lamps
- Solar energy conversion
- Electro-optical instrumentation
- Photopolymerization.

Since 25% of the electrical power generated in the U.S. is used for lighting, the development of lamps that can produce the same light with less electricity will have a tremendous impact. The lamp manufacturers claim that technological advances in light sources come in small increments, which if not discernible due to lack of precision and accuracy in measurement may go unnoticed and therefore discourage further development [1].

In order to develop efficiently the widespread use of solar energy for heating or for the production of electricity, better radiometry is required. Efficiencies of solar energy converters cannot now be measured routinely to better than about 20%. Standards and techniques being worked on at NBS would play a major role in improving this situation.

A leading detector manufacturer says

"state-of-the-art advancements in detector technology necessitate like advancements in determination and transfer of standards".

Another detector manufacturer adds

"It seems to me that this whole newly emerging area of electro-optics fundamentally rests on a basic calibrations and traceability capability. Without that fundamental capability, strongly supported by the National Bureau of Standards, the electro-optic industry is trying to walk on water."

Relative to photopolymerization, a lamp industry spokesman writes

"The growing application for the use of UV light sources in photochemistry, in graphic arts or for photopolymerization of plastic materials for coatings, etc., is hampered by lack of accurate measuring devices. We have had the experience of purchasing a UV meter, which when compared to laboratory standards, had an error in excess of 100%, undoubtedly due to lack of adequate reference standards."

Again, the role NBS services play in supporting these technologies is to provide the standards and the radiometric "know-how" so that adequate agreement exists in measurements made by different people, in different industries and at different times.

4.3.3 Pay-off from Changes in NBS Services

The CORM report prepared in 1973 [3] requested that NBS develop calibration techniques and provide calibrations for light emitting diodes (LEDs). The report stated that

"There is more than a 40% disagreement in specifications assigned to these devices by the various manufacturers. In order to provide a fair basis for domestic competition and improve foreign sales, these calibrations should be made available. Without these calibrations, the development of the associated technology will be retarded."

NBS was able to respond rapidly to this request. It worked with industry in developing a suitable standard and then developed a technique for calibrating these standards. In 1974 seven standard LEDs were calibrated for several radiometric and photometric quantities with an uncertainty of between two and three per cent and purchased by the major manufacturers and users of LEDs. The calibrations have provided a simple, direct means of calibrating instruments for the measurement of similar LEDs and will make possible more meaningful specifications and more uniform and predictable finished products using LEDs.

The most recent CORM report, prepared in 1975 [3], lists detector standards and calibrations as the highest priority for new standards required of NBS. A letter from a leading instrument manufacturer written in 1972 states that

"It is estimated that between 5% to 10% of the effort expended in last year's electro-optical market was spent in calibrating systems or resolving calibration and stability problems. This amounts to about $200 million. A savings of approximately one-half of this amount could be expected with the successful design of a new detector standard by NBS."

A small (1½ million dollars in annual sales) manufacturer of silicon photodiodes states, in its correspondence with NBS,

"We believe that we can continue our growth rate at 50 to 70% a year, and continue our overseas export growth rate at 150% a year only with more fundamental electro-optical calibration and standards support from the National Bureau of Standards."

Developing such detector standards has a high priority at NBS.

Finally, relative to impact, the question "Why is Federal participation by NBS appropriate?" might and should be posed. NBS Technical Note 594-4 answers the question in great detail on pages 27 to 29. Some of the reasons given for "Why NBS?" include:

(1) Diversified nature of the industry with only a few of the companies large enough to fund the complex research and development required to provide accurate standards and calibrations.
(2) Need for a centralized focus.
(3) Statutory obligation of NBS.
(4) NBS's role to strengthen and advance the nation's science and technology.
(5) Promotion of strength in the economy and equity for the buyer and seller.
(6) Provision of standards and test methods for protection of the public from specific hazards.
(7) Position of NBS on international standards committees.
(8) Industry desire for NBS participation.

A very large company which uses photometric standards extensively, a company which could afford to set up its own primary standards laboratory, asked and answered the question of "Why NBS?" in a letter they wrote us. We thought it appropriate to end this section with their reply.

"Why NBS? Theoretically, some other laboratory could maintain the standards for luminous flux, keeping this standard in line with the rest of the world, but anything other than the U.S. Government would seem something less than independent and neutral with respect to setting commerical, industrial, and consumer standards. In addition, the U.S. Government is a huge consumer itself which should justify some means of evaluating the products it purchases."

4.4 Evaluation of NBS Program

The NBS program in radiometry and photometry is strongly supported by CORM and by the NAS-NAE-NRC Evaluation Panel for the Optical Physics Division. Eight of the ten items in the NBS Ten-Point Program cover specific things requested by U.S. industry. The remaining two items concern (1) providing assistance to other government agencies working on national problems involving radiometry and photometry and (2) research on a new set of modern tools and techniques for radiometry and photometry of the future. In fact, these two items interact strongly with the other eight items specifically requested by CORM and, in the long run, will be useful in meeting all the urgent needs of the System.

Progress is being made on each of the ten points in the NBS program. Unfortunately performing state-of-the-art standards work in the definitive manner required is time consuming -- more so than is widely realized. Repeated efforts to increase the staff and budget to speed up the effort have not been successful. As a result it is estimated that another three years (1980) will be required to meet the major requests made by industry in CORM Report Nos. 1 and 2 issued in 1972 and 1975 respectively.

4.5 Future

We are at the beginning of a renaissance in radiometry and photometry. By 1980, this renaissance will be well established. NBS will have made significant progress in its program of "making a few percent accuracy in radiometry commonplace". Many new and improved standards and calibrations, a Measurement Assurance Program, and a Self-Study Manual will be available. In addition, commercial instruments will have reached a new level of sophistication and efficiency. A wide variety of solid state sources and detectors and electrically calibrated pyroelectric radiometers will be packaged with appropriate mini-electronics and computers for "shirt pocket portability". A new definition for the unit of light, more useful for modern day photometry, will have been adopted. As a result of all these factors, quantitative applications of optical radiation will begin to increase substantially. Remote sensing, solar energy applications, medical therapy, and industrial processing will begin to use routinely what is now considered state-of-the-art radiometry and photometry.

What significance will this renaissance have for NBS? First, the day-to-day demands made on NBS relative to radiometry and photometry will increase significantly. Second, as the NBS Measurement Assurance Program verifies that a few per cent measurements are being made, applications and demands requiring a few tenths of a per cent will begin to emerge. This will necessitate an extensive research effort requiring new equipment, additional space and additional staff. In summary, by 1980 optical radiation measurements could be well on the way to being recognized as one of the more important "new" measurement areas for modern technology.

5. SUMMARY AND CONCLUSIONS

This National Measurement System study has revealed an extensive and important need in this country for an improved capability in radiometry and photometry. The current capability is limited by the lack of sufficiently accurate, readily available standards and calibrations and by the lack of adequate training to use, efficiently and correctly, existing standards and calibrations. NBS is uniquely situated to improve this condition and has initiated a program to do so. Those in industry, government and the universities concerned with this measurement area have organized the Council for Optical Radiation Measurement (CORM), which provides a continuous input to NBS on specific problems, needs and priorities. Such input resulted in new budget initiatives to expand greatly NBS' effort in this measurement area. Though these failed, they provided the impetus to bolster the effort through reprogramming and the attraction of visiting scientists. The resulting NBS program emphasizes the creation of new spectral and detector standards, the development of a new photometric SI unit based on radiometry, and the establishment of a well-documented, efficient calibration service and Measurement Assurance Program (MAP). Finally, and possibly of greatest importance, plans are now being carried out to produce a Self-Study Manual to provide the training in basic concepts and laboratory techniques required in the National Measurement System.

APPENDIX A.

Optical Radiation News

This newsletter is prepared bimonthly by the staff of the Optical Radiation Section of NBS to report on items of interest in optical radiation measurements. Inquiries may be directed to A.T. Hattenburg, A223 Physics Bldg., NBS, Wash. DC 20234 (301-921-2008).

U.S. DEPARTMENT OF COMMERCE National Bureau of Standards

NO. 3 May 1974

RADIOMETRY AND PHOTOMETRY AT NBS*

Current Capability and FY 74 & 75 Efforts

The current goal in radiometry and photometry at NBS is to make 1% measurements commonplace in the United States. Our overall approach has involved:

1. Developing and providing the standards and calibrations required in our National Measurement System.

2. Disseminating the techniques and basic concepts that will be used with the above standards.

3. Assessing and verifying the capability of the System.

In addition, a small research effort has been directed towards higher accuracy measurement problems, and this effort will increase as our 1% goal is approached.

Our current distribution of effort, and that anticipated in FY 75, is shown in Table 1.

DISTRIBUTION OF EFFORT

	CURRENT	FY 75	FY 76
STANDARDS & CALIB	75%	50%	20% to ?
BASIC CONCEPTS & TECHNIQUES	10	30	30 to ?
VERIFICATION	15	15	?
RESEARCH	-	5	?

Table 1.

*This article is an expanded version of the presentation made by H. J. Kostkowski, Chief, Optical Radiation Section, at the April 22, 1974, CORM meeting at NBS

Trends are also given for FY 76. However, reader input and, in particular, the pending updating of the CORM report, "A Consensus of Services Desired of NBS", will have a significant impact on our FY 76 and longer-term efforts.

This article will summarize our present capability and FY 74 and 75 efforts, in terms of the calibration, information, and intercomparison services we provide.

Spectral radiance is usually considered the most basic radiometric measurement parameter. Figure 1 depicts the spectral radiance calibrations currently available from NBS.

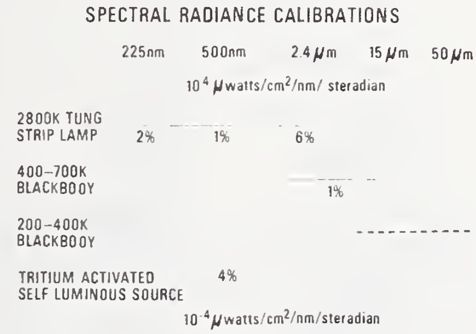

Fig. 1

The scale associated with these calibrations extends from 10^4 to 10^{-4} μW/cm^2 nm sr and the uncertainty from 0.6% to 4%. The 200-400 K blackbody calibration facility is not quite operational on a routine basis. During the coming fiscal year, our major effort in spectral radiance measurements will be directed towards making such calibrations significantly less expensive and available in a much shorter time. The present costs and delivery times vary from $1490-$1960 and from six to twelve months, respectively.

Spectral irradiance is probably the most widely used radiation parameter. Figure 2

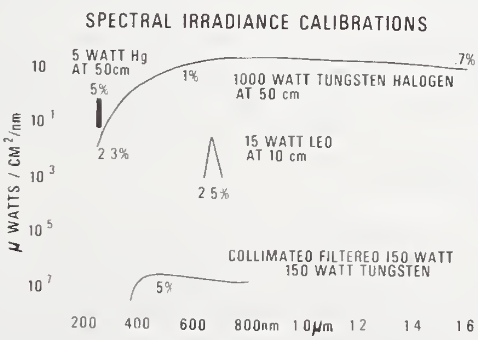

Fig. 2

shows that the available calibrations for this parameter also cover 8 orders of magnitude with an uncertainty varying from 1% at the highest level to 5% at the lowest. Our current and FY 75 efforts involving spectral irradiance include

1. Maintaining the new 1973 NBS Scale and extending it from 1.6 μm to 2.4 μm.

2. A Technical Note giving a detailed description of the apparatus and techniques used in realizing the new scale.

3. Establishing deuterium lamp standards and calibrations to 200 nm.

4. Reducing the uncertainties for color temperature standards and calibrations by a factor of approximately five.

Our current capability and available calibrations for the quantity irradiance are

600 $\mu W/cm^2$ -- 2%

3 mW/cm^2 -- 2%

30 mW/cm^2 -- 1%

130 mW/cm^2 -- 0.5%

The 30 and 130 mW/cm^2 levels are maintained with a Thermopile Electrically Calibrated Radiometer. During the past year we developed a prototype for an AC null-balance Pyroelectric Electrically Calibrated Radiometer (PECR) which, when improved, is expected to maintain the two lower levels of irradiance listed above, reduce their uncertainty and extend our available calibrations to 10 $\mu W/cm^2$. In addition, the null-balance PECR should make possible, for the first time, a radiometer which has all the following characteristics:

1. Accurately calibrated by electrical measurements

2. A flat spectral response

3. Fast

4. Sensitive

5. Easy to use.

In the irradiance area, we also plan to improve the delivery time on calibrations and provide a detailed description of our calibration procedures.

Luminous intensity calibrations at about 90, 700 and 1400 candelas with an uncertainty relative to NBS units of 1.5% and to SI units of 4% have been available for some time. In the coming year we plan to determine an NBS K_m (lumens/watt) relating the NBS luminous intensity and spectral irradiance scales. This will improve the long-term stability of the NBS luminous intensity standards, reducing the above stated 1.5% to about half this value, and will enable precise photometric calibrations to be derived from NBS spectroradiometric standards. Moreover, there is an international move under way to adopt a definition for photometric units that is based on a definition of K_m. When this occurs the SI uncertainty of 4% should be reduced to about 1%.

Luminous flux (lumens) is a photometric parameter of great interest relative to lighting and improving the efficiency of lamps. This is particularly important now because about 25% of all of the electrical energy in the United States is used for lighting. This past year our luminous flux calibrations (5 levels from 10 000 to 270 lumens) have been extended to cover miniature lamps ranging from 400 to 6 lumens with NBS uncertainties of 3% and SI uncertainties of 5%. We also published a Technical Note on the Theory of Integrating Spheres, devices frequently used in comparing lamps for luminous flux. We will soon complete the development of a gonioradiometer for a more accurate realization of luminous flux standards and for the generation of a standard for spectral flux (watts/nm). I believe we will be the first national laboratory to provide calibrations of this parameter. It is required for accurate measurements of modern high pressure and metal additive lamps.

The advent of silicon photodiode detectors a few years ago has precipitated the commercial availability of a variety of high-precision radiometers. For these devices to be used accurately, knowledge of their spectral response as a function of wavelength is required. In FY 1974 NBS initiated a program for developing such a capability. Initial calibrations from 350 to 1200 nm with an uncertainty of about 5% are expected to be available in FY 75. In the longer run, we expect that the continued development of PECR's and the use of dye lasers with these pyroelectric devices will enable us to significantly reduce this 5% uncertainty for spectral response calibrations.

Table 2 is a summary of the new calibrations provided during the past fiscal year and what we expect to make available in the coming year.

SUMMARY OF NEW CALIBRATIONS

FY 74	FY 75
LUMINOUS FLUX OF MINIATURE LAMPS (6 – 600 lumens)	SPECTRAL RADIANCE & IRRADIANCE (REDUCED COST & TIME)
IMPROVED SPECTRAL IRRADIANCE (1%)	LOW TEMP. BLACKBODIES
LED's (E_λ I_v I)	COLOR TEMP. (HIGHER ACCUR.)
SLS's (L_λ)	LUMINOUS FLUX (HIGHER ACCUR.)
LOW LEVEL COLLIMATED (E_λ)	SPECTRAL FLUX
	SPECTRAL RESPONSE
	DEUTERIUM LAMP (E_λ 200 –350 nm)

Table 2.

Relative to dissemination of techniques, two years ago we introduced NBS Technical Note 594, a continuing series of publications on optical radiation measurements. This has provided a vehicle for describing apparatus, methods, and results in considerably more detail than is possible in regular scientific and engineering journals. In FY 74 the following four such notes were issued:

594-5, "Stability and Temperature Characteristics of Some Silicon and Selenium Photodetectors" by K. Mohan, A. R. Schaefer and E. F. Zalewski.

594-6, "The Present State of Radiometry and Photometry" by Bruce Steiner.

594-7, "Approximate Theory of the Photometric Integrating Sphere" by W. B. Fussell.

594-8, "Tables of Diffraction Losses" by W. B. Fussell (Available June 1974).

Technical Notes on the following topics are being planned for the next 12 months:

NBS spectral radiance scale and calibrations

Apparatus and techniques used in realizing the NBS 1973 scale of spectral irradiance

Laboratory intercomparison for luminous intensity and infrared spectral radiance

Calibration of self-luminous sources

On realizing a scale of spectral flux

A facility for low-temperature blackbody calibrations

Radiometric calibration procedures

In FY 1975, we will initiate an extensive effort to produce the Self-Study Manual discussed in the March '74 Optical Radiation News. During FY 1975 the effort will be directed at the basic concepts and apparatus portion of this manual with sections on radiometric quantities, sources, detectors and dispersion devices. These will be issued as they become available in a separate technical note series.

The assessment and verification of the U.S. capability in radiometry and photometry is being conducted through interlaboratory comparisons. Intercomparisons involving luminous intensity and infrared spectral radiance have been completed and the associated reports are being written. An intercomparison involving the spectral radiance of tungsten strip lamps has been initiated and in FY 75 spectral irradiance and spectral response of detectors will be added. In the long run we expect this Measurement Assurance Program (MAP), as it is sometimes called, to include "audit packages" consisting of one or more sources, detectors and filters and a set of statistically designed self-checking experiments.

We welcome comments and questions on our current capabilities and present and next-year efforts. Priorities assigned to the various items in our program will be influenced by demonstrations of specific interest from the technical community, as evidenced by requests for new calibrations, suggested topics for our self-study manual, or participation in laboratory intercomparisons.

SPECTRAL IRRADIANCE SCALE CHANGE

On September 1, 1973, the Optical Radiation Section began issuing lamps on a new scale of spectral irradiance.[1] This 1973 scale superseded the previous (1963) scale.[2] From its realization until its replacement, the 1963 scale was maintained in banks of type DXW lamps. Four of the lamps that maintained the 1963 scale have been measured on the 1973 scale. The ratio of the spectral irradiance measured on the 1973 scale to the spectral irradiance assigned on the 1963 scale was: 0.90 at 250 nm, 0.95 at 350 nm, 1.00 at 450 nm, 0.98 at 600 nm, 0.94 at 800 nm, 0.93 at 1300 nm and 0.89 at 1600 nm. The four measured lamps differed among themselves over a range of 2-3% for all wavelengths.

The results of this experiment cannot be used to adjust accurately other lamps from the 1963 scale to the 1973 scale. Type DXW lamps have exhibited varying drift rates (with burning time)[3] and at present little is known of the magnitude of any possible "shelf effect".

The 1973 scale is being maintained by periodic reference to the NBS high accuracy spectral radiance standard and thus ultimately to a gold-point blackbody. It is expected that this procedure will eliminate, or at least minimize, the uncertainties associated with lamp drift in the future maintenance of this scale.

[1] Optical Radiation News, No. 1, January 1974.

[2] R. Stair, W. E. Schneider and J. K. Jackson, "A New Standard of Spectral Irradiance", Appl. Opt. 2, p. 1151 (1963).

[3] "Lamp Standards of Spectral Irradiance", available on request from the Optical Radiation News.

SPECTRAL IRRADIANCE INTERCOMPARISON

As part of the program to assess and verify measurements made in laboratories other than NBS, the calibration and dissemination group is planning an intercomparison of spectral irradiance measurements. This intercomparison will begin early in September 1974. It will cost the participants about $500 and require approximately one man week of work in the participating laboratory.

Laboratories interested in participating in this intercomparison may obtain further details from:

Donald McSparron
NBS, Optical Radiation Section
Room B-312, Metrology Building
Washington, D.C. 20234

(301) 921-2113

APPENDIX B. COMMERCIAL (PUBLIC ISSUANCE) CALIBRATION LABORATORIES*

Radiometric Calibrations

EG&G
Bedford Division
Cosby Drive
Bedford, MA 01730

Eppley Laboratories, Inc.
Newport, RI 02840

Optronic Laboratories
7676 Fenton Street
Silver Spring, MD 20910

Photometric Calibrations

Ann Arbor Testing Laboratories
P.O. Box 2078
Ann Arbor, MI 48103

Electrical Testing Laboratories
2 East End Avenue
New York, NY 10021

Gamma Scientific, Inc.
2165 Kurtz Street
San Diego, CA 92110

Hoffman Engineering Corporation
183 R. Sound Beach Avenue
Old Greenwich, CT 06870

Industrial Testing Laboratories
University of California
Room 6, McLaughlin Hall
Berkeley, CA 94720

Lighting Engineers, Inc.
1681 West Broadway
Anaheim, CA 92802

*Placement on this list indicates either or both of the following: (1) membership in CORM; (2) a previous request to NBS that their name be mentioned to people inquiring about the availability of calibration services in the U.S. Thus this list is in no sense comprehensive. Further, it should be clearly recognized by all users of the list that NBS is not certifying, recommending, or endorsing the laboratories or their measurement capability.

APPENDIX C. TYPICAL CUSTOMERS THAT REQUEST PHOTOMETRIC CALIBRATIONS FROM NBS

GSA
Arnold Research O.
WAMCO
NASA J.F. Kennedy Center
RCA

Sperry Flight Systems
Hoffman Eng.
Lighting Engineers
Eastman Kodak
Kaelite Corp.

McDonnell Douglas
Hughes Aircraft
Beoing Aerospace
Hughes Aircraft

Gamma Scientific
Kaelite Corp.
Dupree, Inc.
McDonnell Douglas
Singer Co.

ITL
Tektronix, Inc.
Gamma Scientific
Weston Instru.
Optronic Labs

TRW Systems
Gassen
Hoffman
Singer Co.
RCA

ETL
Weston
Eastman
Hughes Aircraft
Weston

Sperry Flight Systems
Gassen
Gaileo Corp.
Hoffman
GE

Sylvania
Weston Inst.
United Standards Laboratory
U. of Iowa
3M Company

Naval Avionics Fac.
Weston Instruments
Kollmorgen Corp.
Newark AFB
Sylvania

REFERENCES

[1] Steiner, Bruce, "Optical Radiation Measurements: The Impact of Radiometry and Photometry and the Role of NBS", NBS Tech Note 594-4, 1973.

[2] Steiner, Bruce, "Optical Radiation Measurements: The Present State of Radiometry and Photometry", NBS Tech Note 594-6, 1974.

[3] Council for Optical Radiation Measurements, "Optical Radiation Measurements: Pressing Problems and Projected National Needs in Optical Radiation Measurements -- A Consensus of Services Desired of NBS", #1/#2, Jan. 1975, E. Steeb Large Lamp Division, GE Co., Nela Park, Cleveland, OH 44112.

[4] Velma I. Burns and Donald A. McSparron, "Optical Radiation Measurements: Photometric Calibration Procedures", NBS Tech Note 594-3, 1972.

[5] Committee on Phototherapy in the Newborn, National Research Council, "Final Report of the Committee", National Academy of Sciences, 1974.

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