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Optical Radiation Measurements:

The Present State of Radiometry and Photometry

U.S.
DEPARTMENT
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[3] Located at Boulder, Colorado 80302.

[4] Part of the Center for Building Technology.

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Preface

This is the sixth issue of a series of Technical Notes entitled OPTICAL RADIATION MEASUREMENTS. The series consists primarily of reports of progress in or details of research conducted in radiometry and photometry in the Optical Radiation Section of the Heat Division. The current issue, however, is an exception. It attempts to characterize and analyze the radiometry and photometry portions of our National Measurement System. A basic knowledge of the operation of this system is essential in applying the resources of NBS and the technical community towards improving it. This document is included in the Optical Radiation Measurements series to further the understanding of the radiometry and photometry portions of the National Measurement System.

Henry J. Kostkowski
Optical Radiation Section
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FOREWORD

The recent rapid expansion of the electro-optics industry has generated many new devices and a wide variety of new components. This industrial and scientific activity has led to the formation of new technical groups and whole new organizations.

This remarkable growth and the resulting size and scope of problems associated with it have been chronicled both by the technical journals and by popular journalism. A survey of related serious problems and their consequences has already appeared in this Technical Note series under the title "The Impact of Radiometry and Photometry and the Role of NBS" [1][1]. This review dealt with the relation between precise and accurate optical radiation measurement and areas of national concern. It identified prominent areas of impact.

By contrast, the present note identifies the origins and the extent of problems within optical radiation measurement. It focuses on the performance of the measurements themselves. The preceding Note identified the external motivation for specific levels of agreement among measurements. The present Note describes the internal state of, and interrelationships among, optical radiation measurements. It analyzes the components of the system comprising these measurements in the U.S. It identifies new trends in the flow of information within the system. And finally, it draws conclusions on the improvement of agreement among radiation measurements now causing wide concern.

Prominent issues and conclusions are reviewed in an executive summary at the end of the document.

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[1]Figures in brackets indicate the literature references at the end of this paper.

"Enormous sums are involved annually in electrical lighting contracts, lamps of certain candle-power being usually specified. Disputes between the consumer and the lighting company are an almost daily occurrence. It is not that the lighting company seeks to take advantage of suitable standards but rather that the company, which usually aims to furnish a satisfactory service, is handicapped by the lack of authoritative standards."

-- Samuel Wesley Stratton in
address advocating the estab-
lishment of a National
Standardizing Bureau, 1900.

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THE PRESENT STATE OF RADIOMETRY AND PHOTOMETRY

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The electro-optics industry and the public that depends on it are part of an informal but influential system for optical radiation measurement. The growth of this industry and of public concerns related technically to it have put severe new strains on this measurement system. The system itself must therefore be analyzed. The state of the art, on which the measurement system depends, is surveyed in terms of basic measurement parameters. The measurement system is analyzed in terms of its three basic components: the flow of physical standards, the generation of procedural standards, and the funding framework. The roles of the professional society and of the Council for Optical Radiation Measurement are reviewed. New requirements of the system are identified. Finally, the methodology of the study is reviewed in detail.

Key Words: Measurement system; photometry; professional societies; radiometry; standards.

CHAPTER I

Background

A. MOTIVATION

The Stratton quotation from 1900 on page v suggests several problems that industry and government, once more after seventy years, are again facing. Lack of agreement among light measurements is again a problem of severe commercial importance. But now the problem has public and social significance as well.

Moreover, this time not only the lamp industry is involved. The even larger photographic and television industries are concerned. Many new, small, but rapidly growing, industries involving a wide diversity of technologies are making light measurements that present difficulty and serious discrepancies. Examples are new solid state light detectors, image intensifiers, and a wide variety of information displays: light emitting diodes, films, electrophoretic devices, gas discharges, and liquid crystals [1-3].

One primary source of this resurgence of optical radiation measurement difficulty is novelty. Completely new and changed products, made possible with new rapidly advancing electro-optics technology, differ greatly from their predecessors and from one another. Moreover, the measurements involved are frequently new to those making them. Coupled with both types of novelty is the inherent complexity of the measurements. These factors interact to produce surprisingly large disagreements. "Gross errors, perhaps as high as ±30%, are now known to be occurring, and with disturbingly high frequency, in our particular field of optical sensing (photo-emissive detectors, visible and near UV/IR)" [4]. The sources of such problems are the subject of this Note.

B. THE DICHOTOMY BETWEEN PHOTOMETRY AND RADIOMETRY

A fundamental feature of the measurement of light is the existence of two separate, not-precisely-convertible, systems of quantities.

The physicist working with electromagnetic radiation typically needs to identify the *flux:*

$$\phi$$

that is the power or photon rate of flow, with which he is working. For radiation transfer problems and for the spectral-characterization of surfaces such as film or room illumination, the ratio of flux to area, or *irradiance:*

$$E = d\phi/dA$$

is a quantity of primary importance. Optical systems, because they conserve both flux and the geometrical throughput, $\cos\theta dA d\Omega$ (where θ is the angle between the normal to the surface and direction in question and Ω is the solid angle involved), conserve the ratio of flux to throughput, or *radiance:*

$$L = d^2\phi/\cos\theta \, dA d\Omega$$

This is the radiometric quantity of primary importance in imaging systems.

In principle photometric, that is luminous, quantities could be derived from the corresponding radiometric quantities by performance of an algorithm. Thus the spectral radiometric quantity of interest could be integrated with an agreed normalized eye-response curve, for example that of the CIE photopic observer, $\bar{Y}$ or $V(\lambda)$. The resulting integral could then be multiplied by the constant K_m, the ratio of the average eye sensitivity at its maximum in lumens to radiometric power in watts. For example, *luminance* L_v could in principle be calculated from spectral radiance,

$$L_\lambda = d^3\phi/(\cos\theta \, dA d\Omega \, d\lambda)$$

by means of the algorithm:

$$L_v = K_m \int V(\lambda) \, L_\lambda \, d\lambda$$

But in practice, a separate system of photometric quantities was required long before a complete radiometric foundation had been laid. As the Stratton quotation on page v suggests, the photometric system was already in wide use seventy years ago for the description of visible light sources. Initially there had been oil lamps and candles, which were not employed with fixtures or other optical systems. The primary interest was therefore in the comparison or prediction of illumination in a certain direction at various distances from a source. At distances large compared with the source dimensions, the concept of intensity, with dimensions of flux per unit solid angle,

$$I_v = \int L_v \cos\theta \, dA \approx d\phi/d\Omega$$

permitted such comparison of sources. This quantity, intensity, provided the practical utility that it could be identified with a source rather than with an arbitrary surface that must be specified in space at some distance from the source. Moreover, with the assistance of certain assumptions, the concept of intensity also facilitated the comparison of two different sources by means of the extremely important but highly non-linear and non-digital detector, the human eye. Given additional assumptions, the necessity for independent but unavailable radiometric data was avoided (or more accurately, obscured).

Initially, arbitrary candles were established as national units of luminous intensity. These units were then compared with, and defined according to, the intensity per unit area in the aperture of a platinum blackbody. This unit was incorporated into the SI system as a Base Unit. The present definition then (1) permits independent laboratory realization of the unit of luminous intensity, and (2) provides a loose coupling to radiometry via Planck's law and the melting point of platinum. Presently used values of the melting point of platinum vary from 2040.8 [5] to 2045 K [6]. These values lead to the values for the coupling constant, K_m: 690 lm/W and 673 lm/W respectively. Very recently, Blevin has shown that consideration of the index of refraction of air raises previously published measured melting points 0.3 K and lowers the corresponding K_m by 3 lm/W [7]. The 3% spread between 687 and 670 is comparable to the 2% spread in photometric measurements made in national laboratories, as described later in Appendix B. Few measurements are more certain than this. Most are substantially less certain.

Thus, although in principle photometric quantities could have been derived from radiometric quantities, in practice the corresponding unit systems have developed along independent paths. In radiometry the quantities realized are those just noted: spectral radiance, spectral irradiance, and irradiance. In photometry, the quantities realized are not the corresponding quantities, luminance and illuminance or illumination, but rather luminous intensity and luminous flux. The difference in the genesis and operation of the two unit systems reflects the contrasting nature of the measurements actually made in the two fields. These differences are of much more than academic interest with the recent growth of the electro-optics field and the consequent rapidly increasing desire for convertibility between the two systems of measurement in the characterization of a single object.

C. THE CONCEPTUAL MODEL

Measurements of optical radiation can be divided into three interrelated but distinct shells and each of these into radiometric and photometric components (Figure 1). In areas

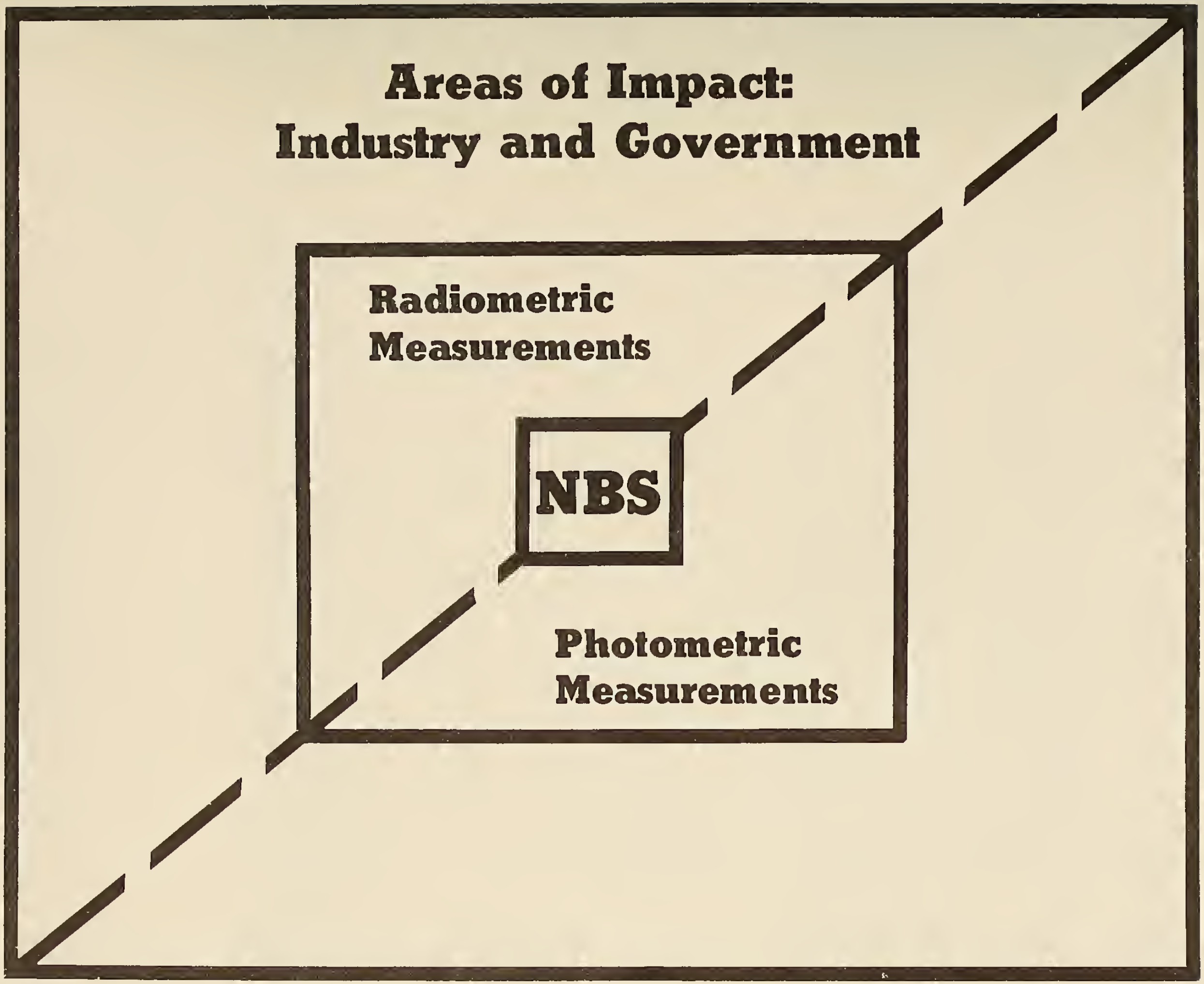

Figure 1. Relationship of areas of preceding study [1], outer box, to the area of present study, middle box, and to NBS, the inner box.

of impact the measurements made by a wide variety of industries, and increasingly by government agencies, are generally motivated by non-measurement considerations. For example, production, improvement in efficient energy utilization, and concern for public safety and health are issues of current concern. The specific rationale for improvement in optical radiation measurement, which is to be found in the outer box in Figure 1, thus comes from outside the system of measurements itself, the middle and inner boxes of Figure 1. The areas of impact comprising the outer box were reviewed in an earlier NBS Technical Note [1].

The optical radiation measurements themselves, the fields of radiometry and photometry, constitute an exceedingly informal but elaborate system. If this system performed satisfactorily for those who employ it, an analytical examination of this system would be of only academic, or metrologic, interest. But as the preceding Note indicated, the performance of the system is widely considered by those in the areas of impact to be severely inadequate to the demands made on it. If the system is in fact to be made more responsive to new and growing demands, it must be analyzed. This analysis forms the core of the present Note.

At the center of the informal system of optical radiation measurement in the U.S. is the National Bureau of Standards. The reasons that it should be involved in the analysis of the measurement system and in subsequent action to improve the system have been reviewed previously [1]. Programs designed to address the current problems are presently being developed by Dr. H. J. Kostkowski, Chief of the Optical Radiation Section, and his staff.

The looseness of the coupling between radiometry and photometry, as currently practiced, is also symbolized in Figure 1. The problems in the areas of impact that radiometry and photometry were designed to address also show a corresponding division. The influence of this historical division is still strong and must be acknowledged. But both parts must now be analyzed together as components of a larger system. This system is already being unified at NBS. Elsewhere it is rapidly becoming highly interrelated.

CHAPTER II

Present State of the Art

A. EXPLOSIVE GROWTH IN DEMAND

The feasibility of various solutions to the measurement problems will depend on their origin and extent. One source of desire for vastly improved radiometry and photometry can be found in two distinct types of growth: (1) rapid movement of the frontiers of electro-optics *technology* and (2) growing *public awareness* that technology must solve or ameliorate large scale problems that have important technical elements. In each of these cases the growth involved has two aspects. First is a rapid general expansion characteristic of the middle part of the growth curve for new fields. Second is a broad diversification in the technology, diversification involving expansion in multiple directions simultaneously.

A survey of the initial development in demand for sophisticated optical radiation measurement appeared in the preceding Note [1]. Prominent examples both of rapidly moving technology and of increasing public awareness were described there. Commercial as well as technical concern with the present status was cited in detail.

The rate of growth can perhaps most succinctly be summarized by a Table. It shows recent and projected dollar volume for several parts of American industry most directly affected by optical radiation measurement.

TABLE
(Source: Reference 8)

Millions of Dollars

	1967	1968	1969	1970	1971	1972	1975	1980
Lamp (bulbs)					943	1015	1243	1703
Lighting Fixtures					2254	2478	3301	5259
TV Tubes	823	680	580	464	500	520		
Optical Instruments	407	458	484	508	535	565	675	995
Photographic Equipment	3665	4009	4317	4403	4667	5040		

The parallel increase in diversification of the technology as well as its dramatic increase in efficiency is illustrated in Figure 2 [9-11]. By incorporating new technology the efficiency of space illumination increased more than twenty fold between 1905 and 1965. Even these recent data were rendered obsolete on 3 October 1973, while the current Note was in press, by the announcement of low pressure sodium lamps generating 183 lumens per watt [12], an increase in 74% over the highest value in Figure 2. Other specific examples of recent growth are reviewed in Appendix A.

B. NATURE OF THE MEASUREMENTS

1. Five-Fold Parameter Variation

Optical radiators and detectors typically differ from one another in five different parameters: the total power or photon flux level or sensitivity; spatial distribution of (or sensitivity to) this flux; spectral distribution (or sensitivity to) this flux; temporal distribution (or sensitivity to), this flux; and polarization.

a. Level

Differing power or photon flux levels are generally unavoidable in optical radiation measurement. With a gread deal of effort and cleverness, such differences can of course be minimized in the standards laboratories. But the field of optical radiation measurement in essence consists of the measurement of differences in level as a function of various parameters. In general, therefore, these differences are to be measured and not avoided.

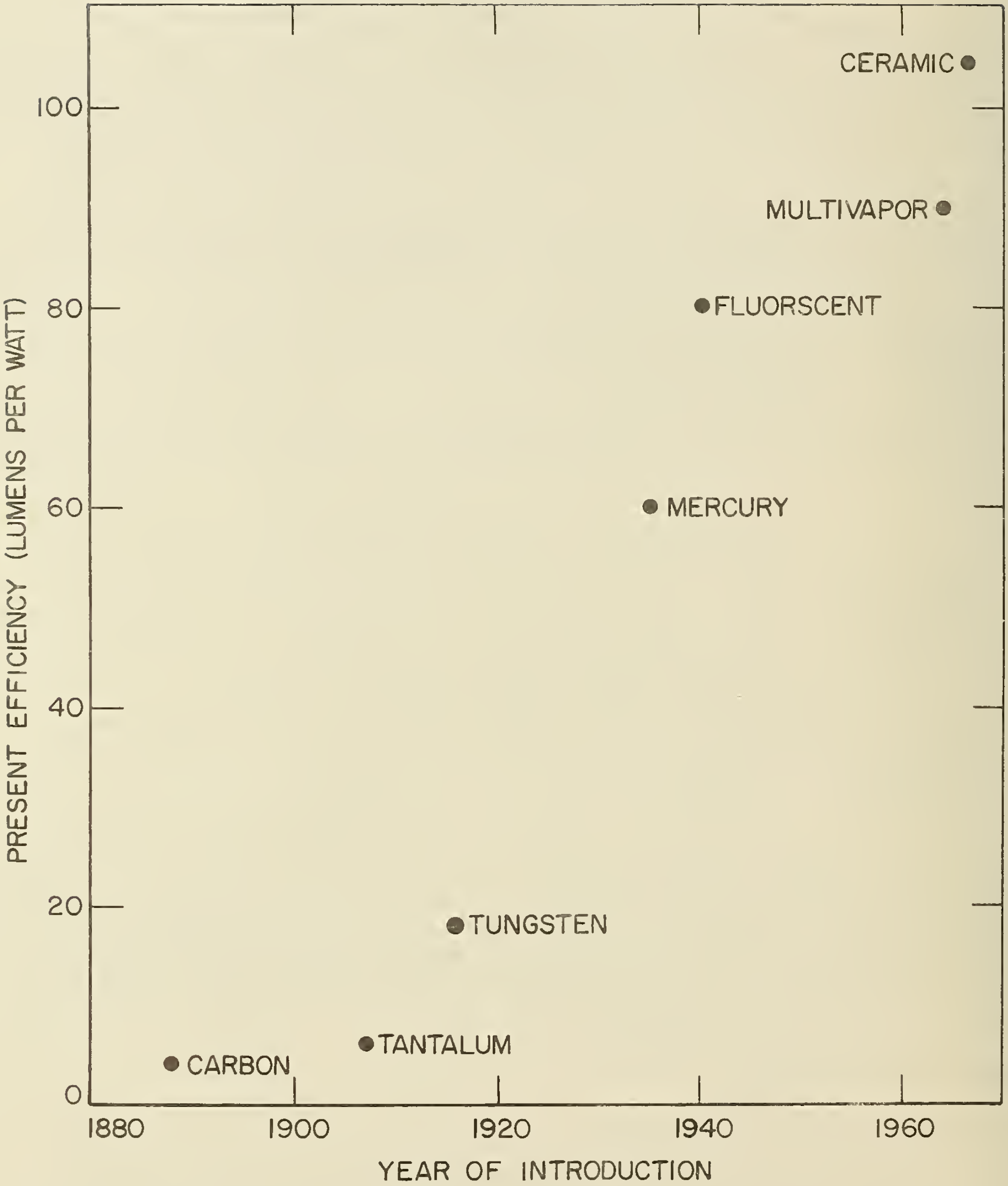

Figure 2. Growth curves of lamp efficiency for various types of lamps as a function of time of introduction (Source: References 9-11).

If detectors were generally linear, or if standards existed over the twelve decades of general measurement from one watt to 10^{-12} watts, then the measurement of different levels would not constitute a problem. But neither of these conditions obtains. Detectors are generally non-linear by unknown amounts, and standards do not exist at more than a few levels. The further one gets from the level of the standards [13], the lower the level of agreement. Many approaches to the determination of detector linearity have been used; they were reviewed recently by Sanders [14]. The various techniques provide differing combinations of accuracy, convenience, and freedom from interactions with the other parameters: directional, spectral, temporal, and polarization dependence. Thus, the choice of an optimum technique may thus be rather complex. Underestimation of this complexity is frequently associated with large disagreements among measurements.

b. Spatial distribution and sensitivity

With rare exceptions, the spatial distribution of commonly used sources and the spatial sensitivity of detectors are generally significantly non-uniform. The lack of uniformity in the flux distribution of lamps, for example, is sufficient to introduce question in the total flux produced by different types such as incandescent lamps and fluorescent lamps [15], and even among the various types of fluorescent lamps. Agreement among measurements of light emitting diodes is hindered by unpredictable variation with distance [16]. The orientation of standard lamps in the measurement of directional properties such as irradiance and intensity has contributed a major source of error [17-18].

Work with detectors frequently involves differences in image size, location, and angle of incidence. The non-uniformity of response of detectors is thus only rarely insignificant but is frequently ignored in actual measurements. New solid state detectors promise to be substantially more uniform than vacuum photodiodes and multipliers, whose response involves a complex integral of photocathode characteristics and electron optics. The solid state devices surely offer a simpler approach to some radiometric and photometric problems. But the extent of improvement in agreement among measurements remains to be determined.

c. Spectral distribution and sensitivity

The spectral distribution of the flux emitted by lamps now in common use varies widely [1]. Nevertheless, the photometric system has of past necessity been constructed on the assumption that the spectral distribution of lamps undergoing measurement either is identical or can be made so at the detector by appropriate filters. Fluorescent lamps have strained these assumptions to the point that arbitrary adjustments have had to be made in their comparison with incandescent lamps [19]. The measurement of flux emitted by high intensity discharge lamps indeed is so uncertain that few intercomparisons have been undertaken at all.

Similarly, spectral response differs greatly from one detector to another, perhaps even of the same type. To be sure, some new solid state detectors promise to be similar enough to each other to permit interchangeable handling for the first time. But such treatment is still to be performed only with great care [20].

The measurement of detector spectral response, although simple in principle is now performed commercially in the U.S. only with unacceptable levels of agreement, a factor of two. (Figure 3). Several representatives of the detector industry have turned to NBS with requests for assistance [21-22].

d. Temporal behavior

Both in radiometry and photometry the greatest emphasis has been placed on sources that are relatively stable. Although fluctuations can be observed in any source or detector, these fluctuations have frequently been of the order of percent or less over a time period of seconds or minutes. Such instability influences measurement enough that it is not to be neglected in precise measurement. But in the absence of wide fluctuation of sources, the frequency response of measurement systems has been a factor of secondary importance in their analysis.

There is however a considerable and growing number of fluctuating sources of interest. The most efficient light-producing media are arc discharges. These respond rapidly enough to 60 hertz alternating current to display considerable ripple in the emitted flux. Thus, for example, the mercury spectral lines in fluorescent lamp spectra display 60 hertz modulation, while the fluorescent continua in the same lamps do not. The spectra of high intensity discharge lamps also display this 60 hertz variation. Moreover, with increasingly accurate requirements for photography, the measurement of singly and repetitively pulsed

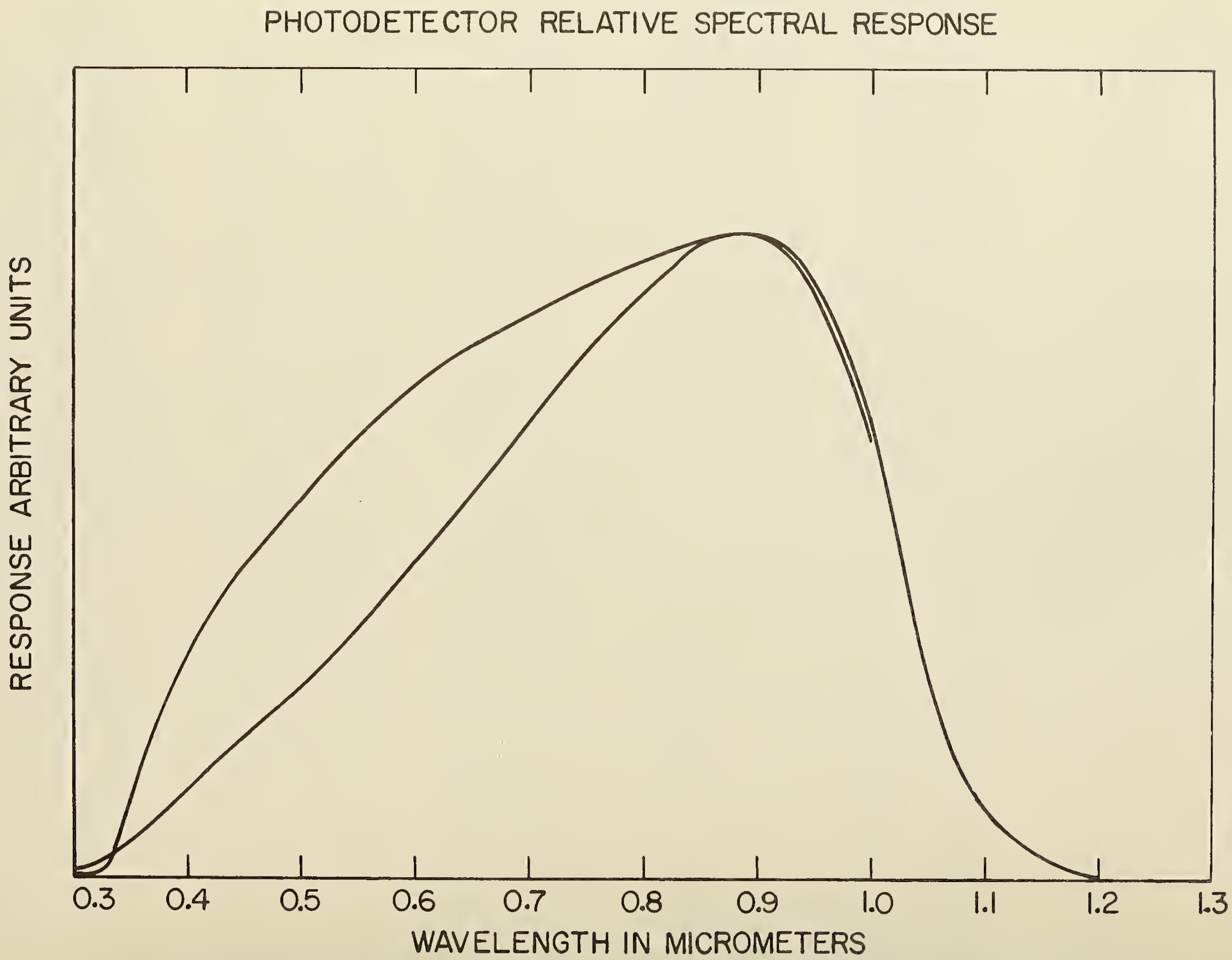

Figure 3. Commercial spectral response measurements on a silicon photodiode.

sources becomes progressively more important. These rapidly varying sources must be compared at some point with relatively unvarying sources, a comparison that requires new techniques as well as the re-evaluation of old ones.

e. Polarization

Polarization is an aspect of optical radiation measurement that is frequently ignored. In some careful work polarization either has been demonstrated to be negligible or has been reduced by the incorporation of diffusing elements into the optical system. Nevertheless, polarization is a significant problem in other areas of optical radiation measurement [23-25]. Polarization is becoming more important both because sources are increasingly remote from blackbodies in character and because optical systems, especially spectrally dispersive systems, are increasingly complex. Each reflection and dispersion can introduce a substantial amount of polarization and increase the sensitivity of the transmission of the optical system to the character of the polarization of the source.

2. Common Measurement Elements

A complete measurement will require not only an evaluation of these parameters, but also of their fundamental dependence on the environment and its fluctuation. Effects of variation in temperature, pressure, and humidity, must be determined. The temporal behavior of standards over an extended period of time must be also be learned. Earth satellite measurements in particular require an estimate of temporal stability over months or even years.

The relative importance of these various factors and their environmental dependence will depend upon the particular measurement being made and the degree of similarity of the object being measured to the measurement standards involved. In general one starts a measurement with no prior information. He must now characterize his source, detector, and optical system to the extent necessary for the particular measurement of interest. Since similar information will be desired for most standards and system components, generally available information of this type has been requested in order to save substantial duplication of effort. The detailed description of successful techniques would save similar widespread duplication in development effort by all laboratories making comparable measurements.

3. Uncertainty: A Question of a Point of View

The uncertainty of a measurement, like its beauty, is in the eye of the beholder. This is not to say, like beauty, uncertainty cannot be estimated on an objective basis. Rather the basis itself is a parameter to be assigned in context.

Several uncertainty bases are used in optical radiation measurement, for example, an uncertainty with respect to the International System (SI) will differ in general from that with respect to units maintained by NBS, or from that with respect to another group of comparable measurements. That is, uncertainty implies fidelity to a system. This system in question must be either specified or directly implied before the term "uncertainty" has meaning.

For measurements designed for severely limited reference, the point of reference must always be specified. For example, if a given measurement is intended for reference only to other measurements made in the same manner, the precision of the measurement will frequently act as a valid predictor of agreement, and might be designated the uncertainty of the measurement. If the measurement in question is destined for comparison exclusively with other measurements made in one of only a few different ways, then the precision of the result from all such measurements conceivably could be taken as a measure of uncertainty, provided that the results are sufficiently homogeneous. Figure 4 represents data similar enough to be compared in this manner. The measurement of the luminous flux produced by incandescent lamps is shown as a function of production year. In such a system incorporating only a few measurement methods, even heterogeneous data can still be reconciled by correction factors allowing for systematic differences. The application of such correction factors *de facto* defines a reference to which the uncertainty is related by the size of the factors involved.

In the most general case of assessment of uncertainty, where each potentially important comparison with other measurements cannot be anticipated, an estimate of the limits of all systematic effects must be made in order to arrive at an estimate of the overall uncertainty. Figure 2 illustrates data too dissimilar to be compared reliably without taking into account systematic effects. The spectral differences of differing lamp types are large

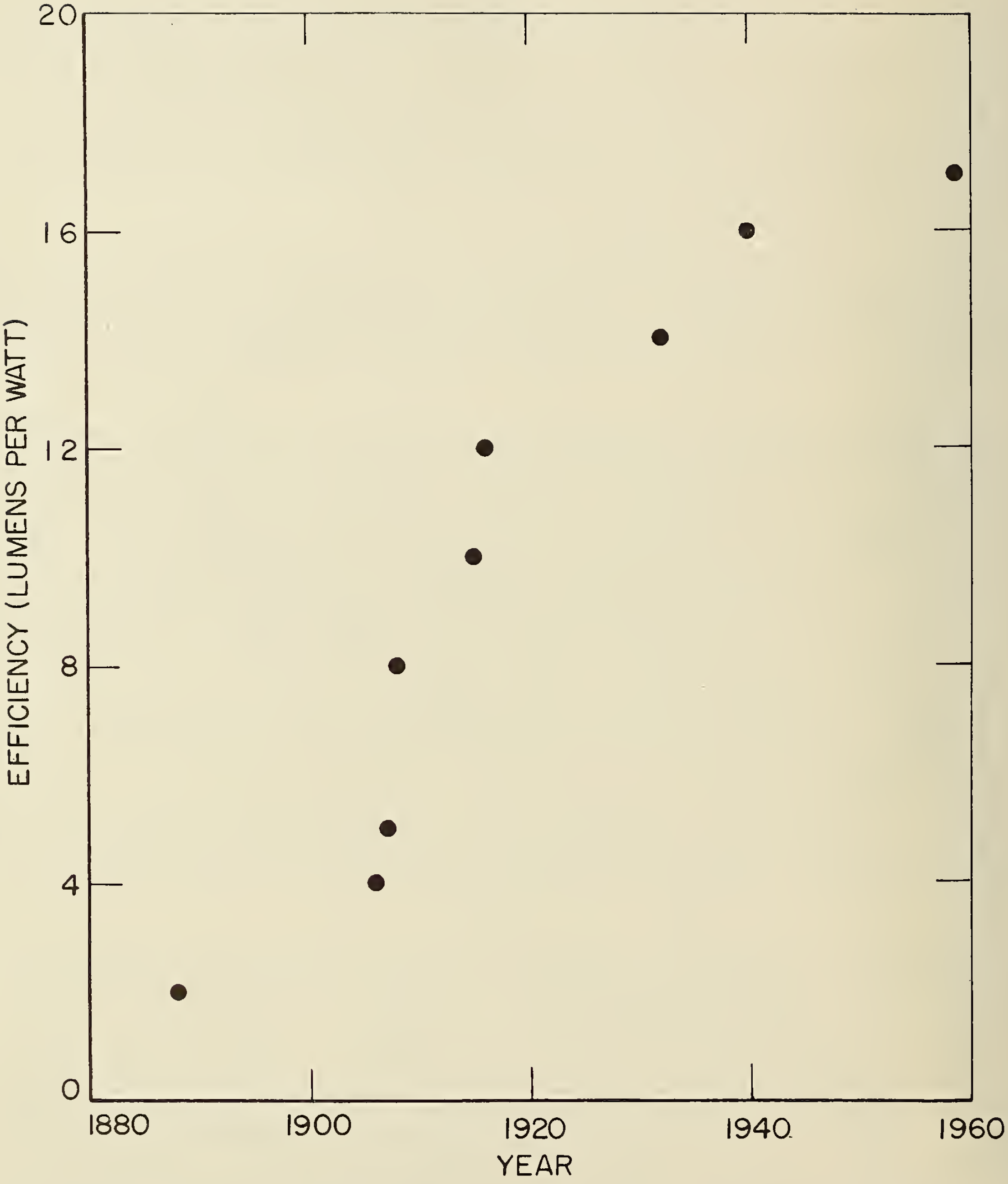

Figure 4. Increase in incandescent lamp efficiency as a function of time (Source: Reference 10).

compared with the precision of the measurements. Uncertainty here refers implicitly to international units, the SI. This is the uncertainty that conservative estimators will want to use. Because of the increasingly wide variety of measurement that are to be compared, it is the uncertainty with respect to SI that increasingly must be used to provide a reliable predictor of agreement among measurements. There is relatively little of such information presently for optical radiation measurement.

Certain consequences of the availability of systematic information can be grouped in the following manner. Progress in any field depends on two types of advance: breakthroughs provided by a new technology, and gradual but steady improvement in existing technology. For the former type of progress to take place with assurance, major systematic errors (with respect to SI) must be avoided so that the comparison of different technologies is not obscured by systematic errors comparable in size to the effects being observed. Since new technologies are particularly prone to unexamined systematic errors, critical attention must be paid to the various parts of the system. One example in classical photometry is the evaluation of the flux emitted in all directions through use of detectors with a photopic response. Since the spectral distribution of most new lamps differs so greatly from that of the incandescent lamps with which they are to be compared, the photometric detector employed in such measurements must correspond much more closely to the defined visibility curve than must a detector used simply for intercomparing different incandescent lamps of relatively similar spectral distribution.

Slow gradual progress also becomes exceedingly important in aggregate. Figure 4 shows such progress in the efficiency of incandescent lamps. The improvement of about 50% in fluorescent lamp efficiency over the last twenty years has already been cited [1]. Such gradual progress (Figure 5) will depend both on the precision of the given measurement and on the stability of a relatively arbitrary "base line". Precision is exceedingly important here because of the small size of individual increments that accumulate to an impressive size over an extended period of time.

4. Factors Associated with Automation

The automatic control of measurement presents not only new opportunities but also new requirements for optical radiation measurement. Automation offers the possibility of such voluminous data collection that much more precise information can now be obtained for a given measurement than was previously possible. To realize the advantage of this complete information, radiometric measurements must be redesigned with two factors in mind. First, smaller systematic effects will become more obvious and thus must be included in experimental investigations. The increasing visibility of measurement differences among increasingly precise numbers is leading to great commercial pressure for a better understanding of these measurements. Second, measurements must therefore be conceived with automation in mind at the planning stage.

5. Conclusion

Thus for much work in optical radiation measurement, the SI uncertainty is of growing importance. It is the required information on systematic errors that is most conspicuously lacking throughout the measurement system. Dramatically increasing precision is making this void increasingly felt.

C. TRAINING

Radiometry and photometry draw extensively from two relatively independent fields: optics and radiant heat transfer. Those with experience in one of these areas usually have little background in the other. Formal training specifically in radiometry and photometry is not widely available. Many enter from peripheral fields that employ photons as tools, such as spectroscopy or collision physics, or from the even more distant electrical engineering.

This lack of a single focus for training has important general consequences. As we shall see, the field is generally fragmented into many different schools of experience and thought. Technical papers appear in widely scattered journals. No coherent body of practice or literature has developed.

Specific technical consequences of these heterogeneous roots also can be identified. One example is the differing development and position of the concept of intensity in radiometry and photometry [18]. While the concepts of intensity and a point source have been

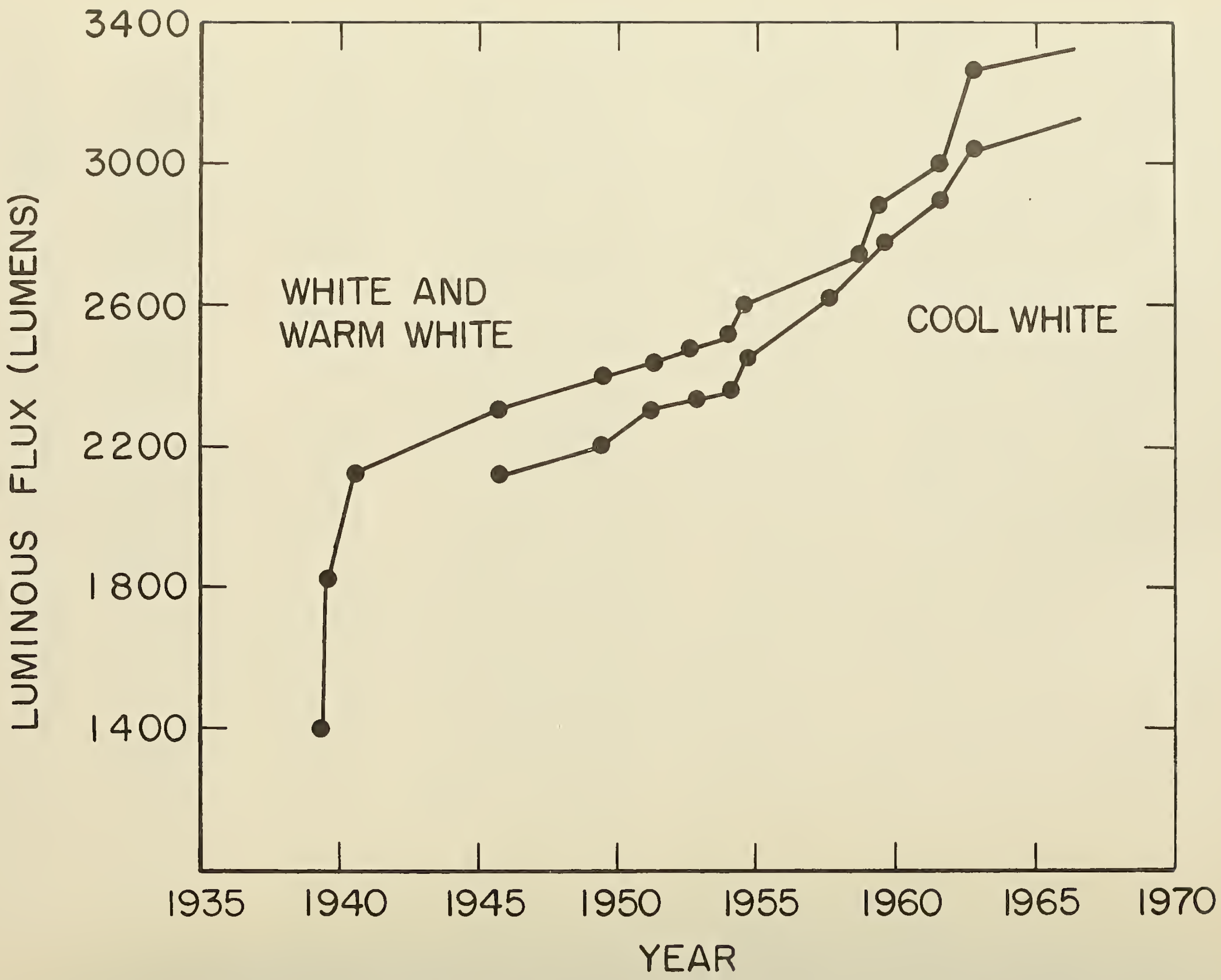

Figure 5. Increase in the luminous flux of commercial fluorescent lamps as a function of year of production.

central to the development of the photometric unit system, radiometry makes use of these concepts primarily in engineering applications. In photometry, intensity is used as the point of departure for other photometric quantities; while in radiometry, the point of departure is either radiance or flux. The distinction is not merely an academic one. Zalewski has shown that subtleties in the use of intensity can lead to practical difficulty in the realization of the unit system [18].

Another example of the fragmentation of the field of radiometry is the use of widely varying types of nomenclature for given concepts. The situation is so serious that indeed some radiometrists spend a substantial fraction of their time attempting to sort out what their colleagues are doing on an elementary level. A comprehensive radiometric dictionary is now under development by one of the most respected radiometrists, Fred Nicodemus. This dictionary should constitute a major milestone in the field. In an exactly parallel manner, experimentalists are being called upon to identify what precisely has been determined in various measurements. Only in this way can various results now be intercompared in a satisfactory manner with predictable levels of agreement.

Because it has been neglected so long, training is very badly needed. But before appropriate training is to become widely available, appropriate materials must be developed. This material requires in turn the development of a firm systematic data base so that appropriate generalizations can be drawn.

CHAPTER III

The Present Optical Radiation Measurement System

A. THE MODEL

Optical radiation measurements in the United States are not performed within a completely formalized system of measurement. The typical measurement is made by comparison to one of a variety of standards in a manner dictated by tradition, by an agreed procedure, or by reference to the laws of physics as perceived by the experimenter.

Nevertheless, the system is not completely formless. It consists of three distinct aspects: the flow of physical standards (hardware), the flow of procedural standards (software), and the flow of funding (administrative structure). The structure of each of these "subsystems" differs from the others, but all are interrelated. The rates of change of each also differ. These three system components will now be examined. Then the role of the professional society will be reviewed. Finally, the effort to identify, strengthen, and extend the structure through the formation of the Council for Optical Radiation Measurement will be described in some detail.

One general feature of the entire system was outlined in Chapter I: the dichotomy between radiometry and photometry. The division is the natural consequence of the historical development of each, which was sketched. The periods of greatest activity have taken place at different times. Separate standards and procedures have been developed. Funding has been along rather different administrative lines.

Two years ago NBS took the initiative by combining its activity in the two areas into one administrative unit. Since then, the committees on photometry both of the Comité Internationale des Poids et Mesures and the Commission Internationale de l'Eclairage have added "radiometry" to their names. The change in these committees is already more than nominal. The maintenance of two separate systems is now being actively questioned, particularly by those entering these fields for the first time. NBS has recognized that the technical effort to build bridges between the two systems, however, must be based on a firm awareness of the situation as it actually exists at present, as well as on anticipation of future modifications in the system.

B. PHYSICAL STANDARDS (HARDWARE)

The general flow of physical standards in the U.S. takes place within a framework shown in Fig. 6. A measurement occurring in any one of the areas indicated is related to other measurements by a series of operations that is referred to as a calibration chain. In general, this chain will have one link in each of the areas indicated; but such a long chain is not always involved. Another general feature of the flow of standards is a much more explicit definition near the origin of the national system, close to NBS, than at more distant points. The individual links in this chain are described in Appendix B along with data on their performance.

C. PROCEDURAL STANDARDS (SOFTWARE)

The complexity and variety of the measurements noted in the previous chapter, coupled with the existence of relatively few physical standards, has led to uncomfortably large disagreement among these measurements. The situation would nevertheless be even worse if it were not for the development of various formal procedural standards by workers in various fields. Since the systematic errors contributing to a given measurement are not in general understood quantitatively, the present levels of agreement have been achieved only through formal concurrence to perform various measurements in given ways. Because of the diversity of the fields involved, a wide variety of organizations has developed to generate and codify the required procedural accords in each field. The boundary line between the procedural-standards organizations and the professional societies is sometimes indistinct. These groups are listed and described in Appendix C.

The dominant impression left by a survey of the various organizations related to optical radiation standards is one of diversity. Various organizations have been established or utilized to deal with restricted problems. Identification of specific activity and its coordination are serious problems.

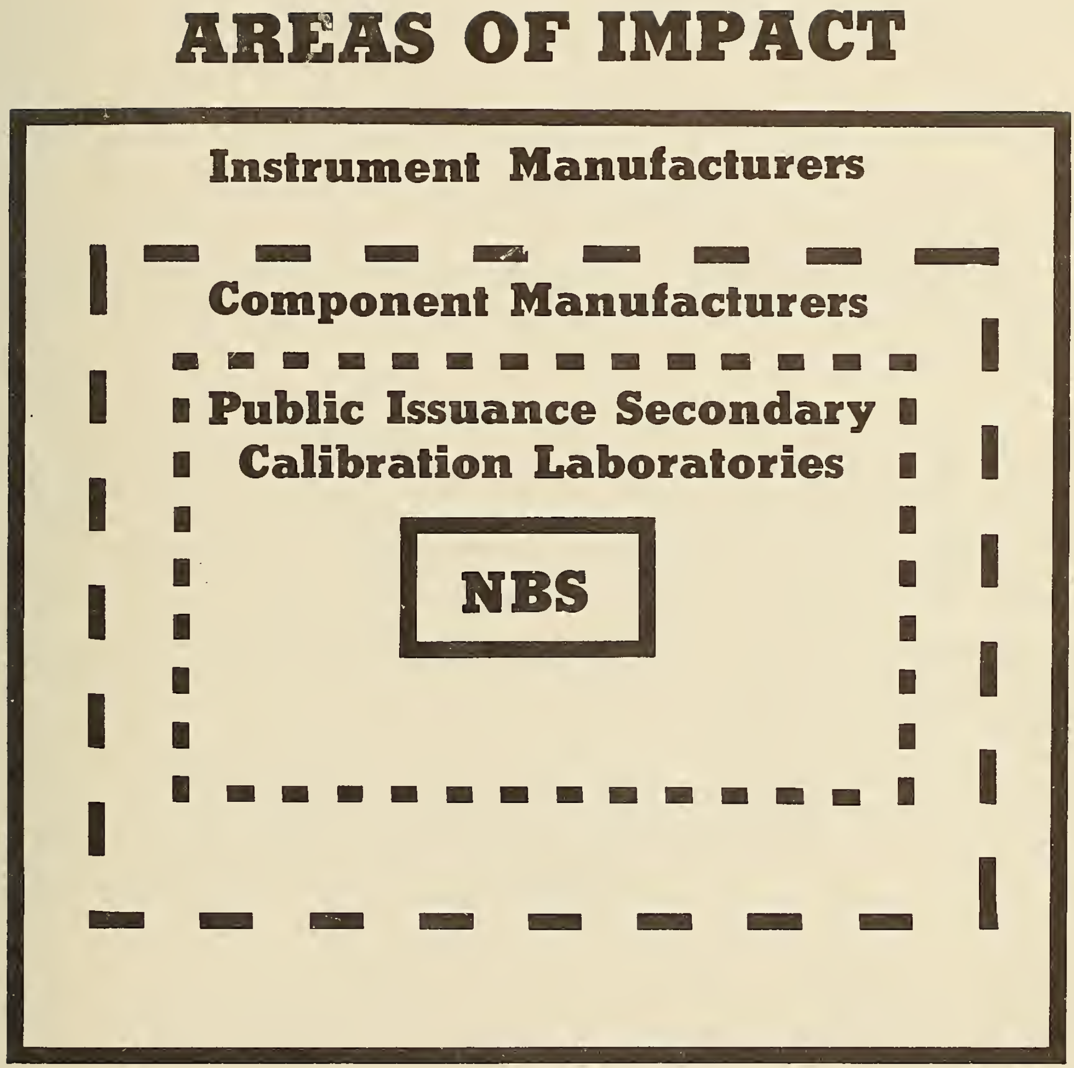

Figure 6. Physical standard measurement system.

However, an even more immediate problem has been identified by Robert D. Compton, editor of Electro-Optical Systems Design [26]. He writes "One of the beauties of the transistor and tube industry is that some semblance of order has resulted through the standardization of products through the EIA component registration process. What old timer in the electronic industry has not heard of the 2N174 transistor or the 6L6 tube? By contrast, it is a very sad commentary on the optoelectronic industry that so few devices have been registered and that, without exception, only one company makes each of those devices that have been registered. How can we expect the general usage of the phototransistors, photodiodes, LED's, and other optoelectronic devices to grow when we discourage usage of these products through the strict use of house numbers to identify products?" Mr. Compton has certainly identified a serious problem. It is even more serious than its mere statement might suggest. The radiometrist suspects that, in spite of an elaborate superstructure of standards groups, the agreements called for could not be reliably formulated at this time. If an attempt were made to do so, it would not really ameliorate the situation. Measurement agreement is not sufficiently precise, not to mention accurate, to support an identification system similar to that of the electronics industry. There is no serious question that a reliable registration procedure would be desirable. But we must advance in measurement capability to make such a system feasible. At a crucial time in the development of the new optoelectronic industry, the physical measurement system is so seriously inadequate that the procedural standards groups cannot perform important tasks.

D. FUNDING FRAMEWORK

The nature of NBS funding of work in the areas of radiometry and photometry is related strongly to the development and the status of each. Radiometry has been funded, both in the system as a whole and within NBS, substantially by other agencies of the Federal government. The primary agencies involved have been the Department of Defense and the National Aeronautics and Space Administration. This funding provided a certain slow but steady and firm development of basic measurement standards not available anywhere else in the world. Recently however, this "other agency" funding has decreased markedly, while at the same time commercial and public factors have been receiving increased attention.

Photometry, on the other hand, has until recently largely operated on a pay-as-you-go basis. Research funds have been devoted largely to the subsidization of the replication of standards and consultation among users rather than to the development of superior standards. The research base remained correspondingly weak.

The flow of funding in both areas has been far more important than the value of money involved. In radiometry, the agencies involved provided explicitly a set of priorities and implicitly a program framework for NBS. In photometry, the lower level of outside research funding has been paralleled by the absence of an external structure for the establishment of priorities. The current shift in NBS program emphasis from the relatively well-focused "other agency" interest to far more diffuse commercial needs and those of less well-established government agencies have left the field without its program formulation structure. NBS has responded to this situation by a consolidation of its effort. But how are the diffuse new needs to be correlated and priorities established apart from NBS? The sheer number of standards groups in the field seems to preclude their presenting a coherent approach to this fundamental organization problem. Two approaches present themselves. The first is coordination by the relatively small group of professional societies; the second is the establishment of a new organization for the necessary coordination. These two approaches will now be addressed in turn.

E. ROLE OF THE PROFESSIONAL SOCIETY

Many individual members of the professional societies have certainly been aware of the growing technical problems in optical radiation measurement. Nevertheless, for several good reasons the attention of the professional societies has been directed elsewhere. It will prove worthwhile to examine these reasons now before examining alternative approaches.

The primary purpose of a technical society is the advancement of the field, typically through conferences and journal publications. The professional societies tend to represent the research-oriented, most rapidly moving parts of technology. Lack of agreement among such workers is not only expected, it is really a way of life. What sets the electro-optics industry apart perhaps from others is that, even after the first wave of rapid development has passed, agreement has not followed as it has elsewhere. The man at the bench who has had to face severe measurement problems over an extended period of time is typically not active in the professional societies. He has been more active in the standards groups. The professional society member has looked at the serious measurement situation as one to which *others* should address themselves and not one involving the professional societies.

Closely correlated with these underlying factors within the professional societies has been the lack of a mechanism to provide for action. These societies are typically "presentation" societies and "debating" societies but not "action" societies. Valuable action has been undertaken on occasion. An example is the Committee on Color of the Optical Society of America. But a more typical role is represented by other activity of the Optical Society. Recent experiments are described in Appendix D.

F. THE COUNCIL FOR OPTICAL RADIATION MEASUREMENT

An outstanding characteristic of the present measurement system as defined in the preceding sections of this chapter is an absence of overall coordination of activity and a focus for cooperative effort. The reasons that NBS alone cannot fulfill this function are discussed in Appendix E. As described in that Appendix, a new cooperative venture was called for and established last year: The Council for Optical Radiation Measurement. By means of a series of meetings, the Council developed the document, "Pressing Problems in Projected National Needs in Optical Radiation Measurements: A Consensus of Services Desired of NBS" [21]. More recently, the Council has completed the formulation of a detailed "Program for Action" [27].

The Council has elected to operate as an activity of US TC 1.2 on Photometry and Radiometry of the CIE. It has done so for several reasons. In the first place, an increase in the number of independent groups in the field seems to be undesirable if avoidable. More specifically, the international impact of the technical problems dictates an approach that provides for ready expansion into international effort. And finally, the existing international CIE technical committee projects already provide a basis for an international technical effort that it would be unfortunate to duplicate in a parallel organization.

Four types of activity are called for. In the first place, dissemination of useful information and debate on suitable approaches to specific problems through professional and quasi-professional meetings seem essential. In the second place, technical activity through cooperative technical projects such as those already underway within international TC 1.2 provides an essential foundation. In the third place, communication of information on priorities throughout the field to NBS for its use in the formulation of its program is an important step to optimum expansion of the availability of physical standards. And finally, greater coordination of information about and among the procedural standards groups is a widely recognized area of concern. Separate groups have been established within the Council for the achievement of each of these four objectives.

CHAPTER IV

Challenges Facing the National Measurement System

A. SYSTEMATIC FACTORS

1. Flow of Physical Standards

In the preceding chapter the chain of calibration between two typical measurements was shown to consist of a number of links. Both the length of this chain and its weak nature are causing very serious concern among those making measurements. If the performance of the entire system is to be improved this measurement chain must be evaluated quantitatively. Since NBS is located in a calibration chain typically roughly half-way between two measurements, NBS may be in a position to exert great influence. Already by a recent change in its calibration policy in order to provide certain standards to anyone who asks, NBS has shortened some of the chains involved. In many cases a reformation of the individual links may be called for.

2. Flow of Procedural Standards

The flow of procedural standards is much less clearly defined than is the flow of physical standards. Many different organizations have addressed themselves to agreement on procedures and practices in limited measurement areas. The cooperative industry-NBS role in the formation of the Council for Optical Radiation Measurement offers some hope for additional coordination in this important area in this country. The job of coordination is an enormous one. It remains to be seen whether the CIE will rise to this challenge.

3. Flow of Information for the Establishment of Priorities

The transfer of responsibility from the Department of Defense and other relatively centralized Federal agencies to decentralized communities has left an administrative vacuum and a new and expanding need for leadership and coordination. The Council for Optical Radiation Measurement and NBS have a challenge in the fulfillment of this role.

B. TECHNICAL FACTORS

The extremely complex nature of optical radiation measurement was reviewed in Chapter II. The existence of only 25 standards [13] on which to base a wide variety of measurements is crucial. If the system were more restricted in size and if the technical nature of the problems were less complex, then perhaps it would be feasible to establish physical standards similar to every type of object that one wanted ultimately to measure. But such an approach is not feasible for so complex a system. And even if it were adequate now, it would not prove viable in the long run for a technology so rapidly advancing.

Thus, in addition to the diversity, there is the rapid growth of the field. If one were "merely" to strive to solve today's problems as completely as possible and as rapidly as possible, the resulting hasty solutions would very likely be inappropriate to the problem that actually existed upon completion of such a crash program.

Approaches must be designed to address these two technical characteristics: complexity and growth. Dr. Kostkowski, Chief of the Optical Radiation Section at NBS has noted "a standard itself does not solve your measurement problem" [28]. NBS has thus recognized the necessity for a broad approach to the solution of optical radiation measurement problems.

C. COMMERCIAL FACTORS

1. Cost

The technical constraints just described imply in addition some economic constraints. First, the complexity of the measurement means that, without substantial outside assistance, institutions making reliable measurements face very high measurement costs. Not only will highly trained people be involved, but at present a great deal of time for research will be required. The exceedingly high costs thus involved are simply not feasible for a large part of this fragmented industry. It is much cheaper to argue a case of disagreement in court, if it comes to that, rather than to set up a research laboratory to solve the problems on an individual basis.

Another cost factor involved is the size of the effort in quality control. Thousands of lamps must be measured by a large number of people in the lamp industry. Large numbers of measurements on film and cameras must be made. If the costs of sufficiently reliable measurements are to become compatible with production costs, then work must be designed to facilitate convenience, rapidity, and reproducibility. Much more effort in this direction is required.

2. Aggregation of Resources

We have seen that a great variety of technical problems must be solved in order to produce one reliable measurement of optical radiation. At the same time, similar problems must be solved for a wide variety of different measurements. It has just been noted that it is not economically feasible for most institutions involved in relatively isolated parts of the entire electro-optics field to solve individually all of the requisite problems. If the system is to be optimized only in a given plant or laboratory, the solutions will necessarily be short range solutions not generally applicable. Only by successfully addressing the entire set of technical problems can one justify a general, across-the-board approach. One basic role of the national laboratory is to analyze various specific requests received and to establish a program geared to optimizing the performance of the entire system, not of a particular segment. When the entire measurement system is brought into better agreement, intralaboratory performance will also improve dramatically and indicate to the individual company or agency that more reliable measurements have been achieved.

D. BROADENED FEDERAL CONCERN

In view of the recently increased public concern for technological answers to national questions, the Federal government is reviewing its role. Optical radiation measurement plays a part in all of the issues included in one recent outline reviewed in Appendix F.

E. CONCLUSIONS

A measurement system can be based on conclusions drawn implicitly from the various factors just described. Before defining one such system (Appendix G), it may prove useful to draw these conclusions explicitly.

1. Coordination of Activities

The complexity both of the measurement system and the administrative arrangements related to it imply the need for strong leadership. "NBS is being asked to help--to supply technical leadership and the know how in this measurement area" [29]. Nevertheless, even with a greatly expanded budget, it is clearly impossible for NBS *single handedly* either to define the problems comprehensively in detail or to bring about their solution. It was this observation that led NBS to contribute to the establishment of the Council for Optical Radiation Measurement. The question of such leadership is explored in Appendix E.

2. Source Characterization

Dr. Kostkowski has already noted that "we plan to characterize radiometric components" [28]. The necessity for such characterization is thus already recognized as part of the NBS program. Indeed until the system as a whole can perform such characterization on a broad basis, it will continue to perform unsatisfactorily. Source characterization is important not only to the lamp industry but to anyone making radiometric measurements.

3. Detector Characterization

The growing importance and stability of detectors require a parallel effort in detector characterization [22]. One can indeed anticipate that some of the burden for standards now carried by sources will be assumed in the foreseeable future by detectors [30]. Some are quite stable and easy to use. Indeed, although photometric units are defined in terms of a source, the photometric system is built *in principle* on a detector, albeit a very complex one, the human eye. Thus the use of calibrated detectors may now offer both theoretical and practical advantages over the more traditional photometric hardware.

4. Technique Building Blocks

Optical systems typically consist of more than sources and detectors. The intermediate components must be characterized not only optically but also radiometrically, that is, in their effect on the transmission of photons. In addition to the characterization of the physical components, various physical phenomena must be better understood if their influence is not to disturb serious optical radiation measurement. Examples of such effects are diffraction, polarization, and partial coherence [29].

5. System Performance Evaluation

Although some intercomparisons have been performed, as cited, there is a general paucity of precise information on operational levels of agreement. Where exactly are the problems, and the real needs? And how severe are they? The quantitative measurement of system performance by intercomparisons in a substantial variety of areas would facilitate the establishment of priorities for close attention in the measurement system [27].

6. Measurement Assurance

In the long run, the only way to guarantee that measurements in a system will agree to a desired level is to provide a program for measurement assurance. Such a program can have a variety of emphases, but it will necessarily involve periodic realistic sampling of the entire radiometric and photometric measurement system [31].

7. Types of Transfer

In addition to providing the capability to make various measurements, the system must engender communication of this capability to assure the transfer of the new technology as it is developed to the places where it is needed most. A technical paper in the literature that contains solutions to measurement problems but that goes ignored is clearly not influential. Indeed, until a system of transfer is perfected there will probably be little evidence of improvement in the measurement system as a whole.

8. Setting Priorities

That the problems described are urgent is beyond dispute. The measurement system must be coordinated in such a way that improvement is apparent to participants as early as possible. *Early attention must thus be paid to the most serious problems.* Relative urgencies must be periodically reassessed. Attention must also be paid to elements that have a *future* impact as well as an immediate one. The technical growth of the industry should be anticipated in such a way that solutions to the most severe problems are generated by the time the latter become crucial, rather than years afterward. These two priorities may appear to conflict, but in fact they need not do so. The second factor may define the elements of the program, whereas the first factor may define the weighting system attached to the various elements.

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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. Jurgen, Ronald K., "What's new in small Displays", IEEE Spectrum 9, [11], 19 (1972).

3. Gurtler, Richard W. and Maze, Craig, "Liquid Crystal Displays", IEEE Spectrum 9, [11], 25 (1972).

4. Eberhardt, Edward H., private communication.

5. Quinn, T. J., Metrologia 7, 132 (1971).

6. Comité International des Poids et Mesures, "The International Practical Temperature Scale of 1968", Metrologia 5, 35 (1969).

7. Blevin, W. R., Metrologia 8, 146 (1972).

8. U.S. Department of Commerce, Bureau of Domestic Commerce, "U.S. Industrial Outlook 1972 with Projections through 1980", (1972).

9. General Electric Company, Large Lamp Department, "High Intensity Discharge Lamps", TP109.

10. General Electric Company, Large Lamp Department, "Incandescent Lamps", TP110.

11. General Electric Company, Large Lamp Department, "Fluorescent Lamps", TP111.

12. Norelco advertisement, Wall Street Journal, p 9, 3 October 1973.

13. U.S. Department of Commerce, NBS Tech. News Bull. 56, 152, 246 (1972).

14. Sanders, C. L., J. Res. NBS, 76A, 437 (1972).

15. Martino, Joseph P., IEEE Spectrum 9, [10], 32 (1972).

16. Horwath, Joseph; private communication.

17. Zalewski, Edward F.; Schaefer, A. Russell; Mohan, Kshitij; and McSparron, Donald A.; NBS Tech Note 594-2 (1972).

18. Zalewski, Edward F.; Geist, Jon; and Schaefer, A. Russell; to be published.

19. Lamp Testing Engineers' Conference, proceedings (unpublished).

20. Budde, Wolfgang; private communication.

21. Council for Optical Radiation Measurement, "Pressing Problems and Projected National Needs in Optical Radiation Measurements: A Consensus of Services Desired of NBS", (1972).

22. Photodetector industry spokesmen; private communication.

23. Grum, Franc and Spooner, David; J. Color App. 2, 6 (1973).

24. Grum, Franc, ed., Report on Polarization, CIE TC 2.3 (1973).

25. Robinson, Barrett; private communication.

26. Compton, Robert D., "An Open Letter to the Optoelectronic Industry", Electro-Optical System Design 5, [3], 23 (1973).

27. Commission Internationale de l'Éclairage, U.S. Technical Committee 1.2, "Council for Optical Radiation Measurement: Program for Action" (1973).

28. Kostkowski, Henry, "Radiometry and Photometry, An Interview with Henry Kostkowski", Electro-Optics Systems Design 5, [1], 24 (1973).

29. Kostkowski, Henry, statement on reorganization of NBS program in Radiometry and Photometry, (1971).

30. Wendland, Paul; private communication.

31. Cameron, Joseph; private communication.

32. Bell Labs, IEEE Spectrum 8, [12], 12 (1971).

33. Elsner, David M., Wall Street Journal, 23 April (1973) p 16.

34. Ref. 1, Plate 1.

35. e.g., EG & G Light Instrumentation Application Note No. 580-34.

36. Infrared industry spokesman, private communication.

37. e.g., Honeywell Radiation Center, "Honeywell Skylab Multispectral Scanner" (1973).

38. NASA, Advance Images and Scanners Working Group Report, in press, 1973.

39. U.S. Department of Transportation personnel, private communication.

40. National Traffic and Motor Vehicle Safety Act of 1966, 15 US Code 1381.

41. Public issuance commercial calibration laboratories, private communication.

42. Douglas, C. A., private communication.

43. Underwriters Laboratories, Memo 122, 24 February 1971.

44. Johnston, Harold; Science 173, 517 (1971).

45. NAS-NRC, Summary Statement of the Ad Hoc Panel on (NO_x) and the Ozone Layer, 29 July 1971.

46. National Academy of Engineering, Task Group on Industrial Engineering, "An Assessment of Industrial Activity in the Field of Biomedical Engineering", (1971).

47. National Petroleum Council; U.S. Energy Outlook, 1971.

48. National Petroleum Council; Environmental Conservation, 1971-2.

49. Post, Richard F., Physics Today, 26, [4], 30 (1973).

50. Optical Spectra 7, [2-3], 27 (1973).

51. McLellan, Alden; Proc. Electro-Optical Systems Design Conf., New York, 244 (1972).

52. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, "Proc. of Miami Workshop on Remote Sensing", (1971).

53. Optical Spectra 7, [2], 17 (1973).

54. Finch, William A., "Earth Resources Technology Satellite-1, Symposium Proceedings September 29, 1972", Goddard Space Flight Center X-650-73-10, (1973).

55. Hanson, Kirby J., "Limitation of Radiometry to Meteorology and Oceanography" invited paper presented at the Optical Society of America Annual Meeting, San Francisco, October 1972.

56. Neer, Robert M., "Medical Significance of Light", invited paper presented at the Optical Society of America Annual Meeting, San Francisco, October 1972.

57. Oke, J. B., "Absolute Flux Measurements in Astronomy", invited paper presented at the Optical Society of America Annual Meeting, San Francisco, October 1972.

58. Betts, D. B., and Gillham, E. J., "An International Intercomparison of Radiometric Scales", Metrologia 4, 3 (1968).

59. Hyde, Edward P., "A Comparison of the Unit of Luminous Intensity of the United States with those of Germany, England, and France", Bull. NBS, 3, 65 (1907).

60. Bonhoure, J; "Rapport sur la cinquième comparaison des étalons nationaux d'intensité et de flux lumineux (1969)", Comité Consultatif de Photométrie 7^{e} Session - 1971, p. 86, (1972).

61. Jones, O. C., Statement to the Conference on Photometry and Colorimetry, Zlatni Piasatsi, Bulgaria (1973).

62. McSparron, D. A., et al., "Spectroradiometry and Conventional Photometry; An Interlaboratory Comparison", NBS Tech Note 559 (1970).

63. Commission Internationale de l'Éclairage, Committee E-1.2, "International Intercomparison of HPMV Lamps", CIE Publication 14A, 44 (1967).

64. Nündel, S., Proceedings, Conference on Photometry and Colorimetry, Zlatni Piasatsi, Bulgaria (1973).

65. U.S. Department of Commerce, NBS Tech. News Bull. 57, 148 (1973).

66. Geist, Jon; and Blevin, W. R., Appl. Opt. 12, 2532 (1973).

67. Blevin, W. R., Metrologia 6, 39 (1970).

APPENDIX A

Examples of Recent Requirements for Improved Measurement

1. ORIGINS OF DEMAND

a. New Technology

Light emitting diodes (LED's) are a visible manifestation of the new electro-optics technology. As was the case with lasers, much of the activity concerning LED's has centered around coaxing them to produce light at shorter wavelengths: first in the red, then down into the green, and ultimately into the ultraviolet. Red diodes are now common [32]; undoubtedly other colors will be appearing shortly in commercial quantities [33].

The entire history of space illumination for the past hundred years shows rapidly developing successive technologies (Figure 2) [9-11]. The most efficient lamps, both fluorescent and high intensity discharge lamps, are characterized not by a single spectral distribution but by a dozen or so that differ greatly from each other [34,9-11]. A diversity in geometrical shapes of lamps as technology progresses is another prominent feature of this development which leads to measurement difficulty. In addition, differences in the extent and type of fluctuating emission among these lamps add to the sophistication required for comparisons among different types of sources.

A parallel development has taken place in photon detector technology. Selenium solid state detectors are being replaced by silicon diodes, which have different characteristics. Relatively slow thermal infrared detectors are being replaced by a variety of quantum detectors and by a new type of thermal detector, the pyroelectric (capacitor) detector. Vacuum photodiodes and multipliers have been widely used for some time, but new photoemissive materials endow them with unfamiliar properties. Thus, the photometric measurement system, which in the U.S. and elsewhere was built largely on selenium photodiodes, is having to adjust itself to diversification not only in the types of sources measured but also in the detectors used to make the measurements. The measurement system is thus not only being improved, but technically modified in unquantified ways (with quantum detectors).

New complex instrumentation, which employs both new detectors and sophisticated low noise, solid state electronics is undergoing rapid development. New lines of equipment are either becoming available [35] or are about to be introduced shortly [36]. Established electronics firms are entering the promising new field of electro-optical measurements, e.g., Hewlett-Packard and Tektronix.

Another aspect of the growth in instrumentation derives from new applications, for example the observation of and from space. The field of remote sensing [37] is growing so rapidly that major measurement problems are just beginning to be uncovered and explored in detail [38].

b. New Public Interest

Increased public concern for safety, health, and the quality of the environment have led a number of new, surprisingly broad, Federal responsibilities. Since the review last year [1] of many of these, still others have emerged. Transportation in an area of Federal activity previously limited to state government [39-41]. In this case, a change in focus for governmental responsibility is complicated further by the introduction of new technology, entirely new types of lighting materials that render obsolete former measurement techniques [42]. In still another area of growing interest, safety, new technology in the form of very intense lights for movie production is leading Underwriters Laboratories to develop new specifications for safer handling of these lamps [43]. No standards exist at, or even close to, the irradiance levels involved.

The hazards of ultraviolet radiation are a rapidly developing field of public concern. First, the future of the protection of the earth's surface from solar ultraviolet radiation by the atmosphere is causing wide debate among scientists [44-45]. The ultraviolet output of lamps has also raised considerable concern in an area of technology where safety has not been the subject of activity in the past. Technical questions have been raised in this area by the National Academy of Engineering [46]. In addition, several pieces of legislative action embody new Federal responsibility with implications for all ultraviolet measurement: The Federal Hazardous Substances Act, the Radiation Safety and Health Act of 1968, and the Occupational Safety and Health Act of 1970 [1].

Public health issues involving optical radiation measurement arise in two clinical areas [1], phototherapy and clinical analysis. Phototherapy is being studied now by a panel of National Academy of Sciences and Engineering as a result of the widespread employment of this treatment, with little control or understanding of the dosages involved. Clinical analytical procedures operate with a similar, but not such an extreme, lack of information.

Public concern for the environment has led to activity in areas that depend on optical radiation measurement. One of these is the energy crisis, which has many other causes and implications [47-48]. There is growing public sensitivity both to power conversion and to the efficient utilization of energy. A review article summarized the situation with respect to energy conversion recently: "Whatever method is being pursued, the electro-optics community is very firmly entrenched in the search for new energy sources. The long- and short-term goals discussed in these pages seem destined to keep a great many of us diligently at work for a good many years to come" [49]. With respect to another promising type of energy conversion, "the laser reaction idea is the newest one on the fusion scene and the simplest conceptually" [50]. The efficient utilization of power is also receiving attention. Since lighting takes 25% of the electric power generated, measurement of efficiency in lighting becomes important to improving the efficiency of power utilization as a whole [1].

Pollution of the environment must be monitored if it is to be controlled in a realistic fashion. Control of pollution at some level is widely considered a desirable goal. Remote sensing approaches are being explored [51]. Problems in pollution are coupled with the energy problems through the wide availability of hydrocarbon fuels that contain relatively large amounts of sulphur, a serious pollutant. Another specific interest in monitoring attempts to control pollution is connected with substantial changes in the earth's atmosphere. Serious climatic changes may follow increased pollution as a long term effect. In the short term, as just noted, the amount of ultraviolet light, which is controlled by ozone in the upper atmosphere, may be affected. Meteorology in fact is providing some of the tightest requirements in radiometry [52].

2. CHARACTER OF THE GROWTH

a. Rapid Pace

The growth rate of dollar volume in key segments of the US electro-optics industry over the decade 1958-1967 [1] has been generally maintained since then [8]. It is now expected to continue into the forseeable future, to 1980 [8]. (See Table in main text) But cause for some U.S. concern can be found in the sudden change in the fraction of world photographic equipment and supplies represented by U.S. production. This fell from 68% in 1968 to 63% in 1970. The original U.S. market lead in electro-optics is now being followed quickly by other countries. For example, "Tokyo Electric Co. (Toshiba), Tokyo, Japan, has announced plans to open, in June, two plants to produce LED's and power transistors" [53].

The production quantities of the electro-optics industry have increasingly required the incorporation of automated measurement. This automation in turn has caused a widespread re-examination of the optical radiation measurements involved with a view toward providing both increased comparability among different measurements and greater reproducibility of a given type.

b. Wide Diversity

Some of the diversity of the growth in the electro-optics industry has been indicated in the preceding description of new technology involved in sources, detectors, and general purpose instruments.

This new technology involves a wide diversity of technical parameters. One example is a variety in the spectral range of new widely used light sources. Differences in spectral distribution and sensitivity characterize new detectors and lamps. Combined with the increasing variety of spectral characteristics are widely differing flux levels. For example, light emitting diodes are characterized both by an unconventional spectral distribution and by a substantially lower flux level than that previously involved in widely disseminated standards. At the other end of the scale is the measurement of high intensity discharge lamps, sources not only consisting for the first time primarily of spectral lines but also much more intense than those traditionally measured in the past. New flashlamps have both a different spectral distribution and higher intensity than most standards, while at the same time they furnish a very different temporal behavior from that of the standards with which they are compared.

Diversity is a characteristic also of new applications. Transportation and satellite remote sending [54] are examples of rapidly growing areas. Meteorology is a newly prominent area [55]. Photobiology and astronomy represent more historic areas of interest [56-57]. The varied authority for enforcement of new Federal regulation is increasingly important. The Departments of Health, Education and Welfare, Labor, and Commerce are involved. The Environmental Pollution Agency is responsible for an area of rapidly expanding concern.

APPENDIX B

The Flow of Physical Standards

1. NBS AND OTHER NATIONAL LABORATORIES

The central position in the U.S. of NBS radiometric standards is derived from the responsibility of the Secretary of Commerce, defined in 15 US Code 272, to undertake "the custody, maintenance, and development of the national standards of measurement, *and the provision of means and methods for making measurements consistent with those standards, including the comparison of standards used in scientific investigations, engineering, manufacturing, commerce, and educational institutions with the standards adopted or recognized by the Government*". Although photometric standards also are covered implicitly by this legislation, the responsibility of the Secretary of Commerce for photometric standards has been made even more explicit. 15 US Code 224 identifies as the specific duty of the Secretary of Commerce "to establish the values of the primary electric and photometric units in absolute measure, and the legal values for these standards shall be those represented by, or derived from, national reference standards maintained by the Department of Commerce".

NBS authority is thus far-reaching. In practice however it is not possible for NBS or indeed for the entire Department of Commerce to provide substitution standards for all types of sources and detectors used in the country. NBS has calibrated a number of incandescent lamps that are used by public issuance laboratories to calibrate radiometers and photometers. These instruments are used, in turn, to measure sources and other detectors of direct interest to industry, other agencies, and universities. However, these latter groups also receive standards directly from NBS rather than from the public issuance laboratories.

Before beginning to trace the U.S. calibration chain away from NBS, the observer should note that other countries have systems similar in principle to the one described here for the U.S. The various national systems in the past have been quite independent. But as the need for new standards grows, foreign standards will probably impinge increasingly upon the U.S. measurement system. The seldom employed chain of American standards to foreign standards typically has as an essential link intercomparisons between NBS and foreign national laboratories. In radiometry, few of these intercomparisons have in fact taken place. Indeed the only one within memory involved lamps that were so unstable as to make the results essentially useless [58]. By striking contrast, international photometric intercomparisons have taken place over many years at remarkable frequency. One of the earliest on record, in 1907, displayed a spread of approximately 2% in the measurement of luminous intensity [59]. The most recent international intercomparison, one that took place in 1969, showed a similar spread of 2% in the measurement of luminous intensity at two different color temperatures and of luminous flux at a third color temperature [60]. In the intervening years the national laboratories have repeatedly demonstrated the ability to perform photometric measurements on certain incandescent lamps with an agreement to roughly 2%. Radiometric measurements can probably be performed to a similar level of precision. Therefore, unless very special circumstances are predicated, agreement among new measurements in various countries cannot be expected routinely to agree better than about 2%. If several steps are involved in international measurements, the spread will undoubtedly be somewhat greater than this [61].

2. PUBLIC ISSUANCE SECONDARY CALIBRATION LABORATORIES

The American photometrist or radiometrist will get his reference standard typically not from NBS but from a secondary calibration laboratory. A civilian will approach one of a number of commercial calibration laboratories, which typically furnish either radiometric or photometric standards, but usually not both. Defense Department radiometrists or photometrists will generally obtain standards from a designated service laboratory. There have been few formal intercomparisons performed among any of these publis issuance secondary calibration laboratories. Customers who have obtained standards from more than one laboratory have reported differences almost routinely of the order of 10% among standards from various public issuance laboratories.

3. COMPONENT MANUFACTURERS

Until recently most photon detectors were usually found to be less stable than the most stable lamps. Those that were sufficiently stable were too insensitive to permit the filtering required for photometers. For this reason, because sources were frequently of ultimate interest, and because primary reference has been made to blackbody sources, optical radiation measurement has been largely "source-oriented" in this country. Standard sources have been furnished, but not standard detectors. In other countries, particularly England, Netherlands, Japan, Germany, and Australia, important radiometric measurements have been based on electrically calibrated radiometers, that is those for which electrical heating can be substituted for radiant heating. But even abroad, reference to electrically calibrated radiometers has been restricted largely to the national laboratories.

One exception to these generalizations, the large photographic meter industry, has operated relatively independently of the rest of the systems. Complaints about the level of agreement of such instruments have not been widespread. This is perhaps an example of a sub-system that has operated fairly readily as a gauge system decoupled from other measurements. Film does not typically have a standard CIE sensitivity. When one finds that his light meter readings are consistently too high or too low, he can allow for this bias in setting his camera. These meters are typically not recalibrated by NBS after sale.

In contrast to the detector industry, the lamp industry has always depended heavily on the availability of the standards both from NBS and from the secondary calibration laboratories. Because of the central position of these measurements to the industry, informal intercomparisons of luminous flux and closely related quantities have been arranged through an industry organization, the Lamp Testing Engineers Conference (LTEC). The results of only one of these intercomparisons have been published [62]. Through such intercomparisons, because of the availability of incandescent standards, and because of the similarity of the lamps measured, agreement among incandescent lamp measurements is not presently a serious problem. This agreement is generally comparable to that of the national laboratories in their intercomparisons: a spread of 2%.

The single most widely selling type of lamp however is the 40 watt "cool white" fluorescent lamp. This lamp differs sufficiently from other lamps [34,9-11] that an unsatisfactory spread occurs in their measurement: 2.0% when comparing with a similar fluorescent standard; 3.6% when comparing with a fluorescent standard with a different spectral distribution; 5.1% when comparing with an incandescent standard utilizing the same photometric detector used in the comparison with fluorescent lamps, and 22.6% when comparing with an incandescent standard by spectroradiometric techniques [62].

High intensity discharge lamps were compared internationally ten years ago with a spread of 7% [63]. There is the feeling in the industry that different companies may be using standards differing at least by 6% in establishing advertised values for such discharge lamps. This situation is considered to be a serious problem.

Light emitting diode manufacturers have found spreads of the order of 40% among measurements [16]. Such differences are clearly visible and intolerable commercially.

4. INSTRUMENT MANUFACTURERS

With the development of relatively stable and sensitive silicon photodiodes over the last few years, the development of convenient radiometers and photometers has blossomed. These instruments are calibrated against standards either from one of the component manufacturers, as suggested by Figure 6, or directly from one of the public issuance secondary calibration laboratories or NBS as suggested above in Section 1. Instrument manufacturers have not yet formally intercompared their instruments inasmuch as this is a new and very rapidly developing field. But those who use these instruments for measurements find substantial disagreements. The level of agreement is very likely correlated with the fact that, while the instruments may be calibrated with one type of standard source, the chain between measurements by users of two different instruments is typically coupled through NBS by way of a number of links [c.f. 61,64]. Large disagreements among commercial photometers and radiometers have led the electro-optics industry to express formal concern [1,21].

In the past it has not been unusual for different parts of a large company to be getting separate sets of optical radiation standards from NBS. This practice has now fortunately been reduced by the designation of centralized responsibility within such companies. For some time the indirect results of these previous unnecessarily long chains of calibration may continue to be felt however.

5. AREAS OF IMPACT

The ultimate user falls generally within one of four major categories: industry, government, the academic community, and the general public. The photographic industry and related enterprises are the single largest component of industrial users: 5 billion dollars. The lamp industry is comparable in size: 1 billion dollars. The aerospace and transportation industries are other substantial users. The television, theater, and movie industries use of lighting is obvious. Increasingly the computer industry and office equipment manufacturers are using new types of light source displays that are leading to new requirements.

The Federal government is rapidly increasing its concern with optical radiation measurement. Some of the federal agencies involved are:

Department of Transportation
Department of Health, Education and Welfare
Department of Labor
Department of Commerce
Department of Defense
Environmental Pollution Agency
National Aeronautics and Space Administration
General Services Administration

Academic, as well as Federal, science involves measurements of optical radiation in a wide variety of technical areas: plasma physics, atomic physics, solid state physics, and astronomy, and the science of optics itself.

Because the user community is so diverse, formal intercomparisons of optical radiation measurements have not been carried out. The existence of substantial disagreement, however, is shown by the founding and growth of the Council for Optical Radiation Measurement [21,27]. All segments of the user community are represented. Indeed, one of its most active projects is the inauguration of a series of intercomparisons [27].

APPENDIX C

Organizations Associated with Procedural Standards

In order to ascertain the role and status of these organizations as seen by participants, a questionnaire was sent to participants in the Council for Optical Radiation Measurement. Most respondents feel that the standards groups fulfill an essential function, although sometimes with less than desirable efficiency and alacrity.

A cursory review of the various organizations involved directly and indirectly in the generation of procedural standards follows. This description is based primarily on the response to the Council questionnaire: approximately 40 questionnaires were returned from the original mailing of about 200 in January, 1973. In some cases the following accounts have been modified by official spokesman. But in all cases the brevity permits only a severely limited perspective of the activities of these organizations. The serious reader will want to get a fuller picture directly from the organizations themselves.

1. AMERICAN INSTITUTE FOR AERONAUTICS AND ASTRONAUTICS (AIAA)

This professional society has concerned itself with heat balance radiometric requirements in air and space science and engineering. Its Thermophysics Committee, ASTM E-21 Committee, and IES jointly sponsor annual space simulation conferences.

2. AMERICAN METEOROLOGICAL SOCIETY (AMS)

This professional society has concerned itself largely with professional seminars. Its relationship to the generation of procedural standards has been indirect.

3. AMERICAN NATIONAL STANDARDS INSTITUTE (ANSI)

ANSI coordinates the development of national consensus standards by other voluntary standards organizations. It is perhaps better known for its procedure for formal recognition of these standards once they have been developed by these other organizations. Committee Z-36 deals with laser safety.

4. AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

ASTM has two primary functions: the development of voluntary standards and the sponsorship of symposia for the exchange of information. Committee F-1.2 deals with lasers. Committee E-12 deals with the appearance of materials. Committee E-21 deals with space simulation. The AIAA Thermophysics Committee and IES cooperate and have overlapping membership with ASTM Committee E-21 (c.f. AIAA).

5. COMMISSION INTERNATIONALE DE L'ÉCLAIRAGE (CIE)

This is one of the most prominent international organizations dealing with light measurement. Its Action Committee, whose chairman is currently Sylvester Guth of GE Nela Park, guides the technical committees. Technical Committee 1.2 on Photometry and Radiometry prepares both technical studies and procedural recommendations for the measurement of illumination in its broadest sense. These are sometimes based on intercomparisons organized by the committee. Technical Committee 1.4 on Photopic, Mesopic, and Scotopic Vision coordinates the study of, and measurement practice in, these fields. Technical Committee 2.3 on the Photometric Characteristics of Materials is now completing a comprehensive report on these characteristics and their measurement. Other recent reports deal with polarization and fluorescence.

In this country CIE consists of a U.S. National Committee made up of the U.S. representatives to the international technical committees, who are also chairmen of the US technical committees, and a number of others. Its Executive Committee appoints the U.S. technical committee chairman and the membership of the technical committee with the advice of the respective chairman. US TC 1.2 in the last 2 years has broadened the scope of traditional activity by its organization of the Council for Optical Radiation Measurement (q.v.).

6. COMITÉ CONSULTATIF DE PHOTOMÉTRIE ET RADIOMÉTRIE (CCPR)

This committee is advisory to the Comité Internationale des Poids et Mesures (CIPM; International Committee on Weights and Measures), the technical body responsible for the provisions of the Treaty of the Meter, which established the basis for the International System of Units. Recommendations of the CCPR, after review by the CIPM, are considered by the Conférence Générale des Poids et Mesures (CGPM; General Conference on Weights and Measures), which has ultimate responsibility for carrying out the provisions of the Treaty.

The CCPR consists of representatives of the national laboratories and a few designated experts. It provides a forum for discussion of, and ultimately for international agreement with respect to, the photometric unit system. To provide a quantitative background for its decisions, it arranges international comparisons of the various national standards among the national laboratories. Its most recent international intercomparison, in 1968, involved national standards of the candela, both those at the platinum point and those at CIE illuminant A (approximately 2856 K on the International Practical Temperature Scale of 1968) and of the lumen at approximately 2788 K on IPTS 1968. Thus the CCPR provides both general coordination and evidence of measurement agreement among a few international photometric standards. The application of these standards to a wider variety of photometric and radiometric measurements is left to the CIE.

7. COUNCIL FOR OPTICAL RADIATION MEASUREMENT (CORM)

The Council is an activity of US TC 1.2 of CIE. It has been formed to "fill in the cracks" between the activities of other standards groups and professional societies. It is described below in Chapter III and in detail in Appendix E.

8. ELECTRONIC INDUSTRIES ASSOCIATION (EIA)

This group represents manufacturers of electronic products. Among many other activities it provides for registration and standardization of specifications for new products, including those connected with optical radiation.

9. ILLUMINATING ENGINEERING SOCIETY (IES)

IES (not to be confused with 12 below) has been a primary vehicle for the establishment of agreement on measurement practices and procedures in the lamp and affiliated industries. Formal IES recommendations are also used as a basis for illumination practice in fields such as architecture and transportation. Meetings, written reports, and its journal deal with applications of illumination and technical background, as well as testing and measurement.

10. INFRARED INFORMATION SYMPOSIA (IRIS)

These annual symposia engage government and industrial representatives in a continuing information exchange on infrared technology largely for defense applications. Associated with these symposia are IRIS Specialty Groups. The Infrared Standards Group has provided a forum for technical review of measurement problems and, in particular, has been a useful focus for interaction with NBS on physical standards in the infrared.

11. INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (IEEE)

The Institute acts both as a professional society and as a standards-writing group. For example, IEEE has become a particularly important professional society for laser technology. It is also involved in formulating agreement both on nomenclature and on procedural standards for light emitting diodes.

12. INSTITUTE OF ENVIRONMENTAL SCIENCES (IES)

This IES (not to be confused with 9 above), along with the AIAA Thermophysics Committee and ASTM Committee E-21, (c.f. AIAA and ASTM) has taken the lead in trying to arrive at agreements on the best value to be used for the solar radiation constant.

13. INTERSOCIETY COLOR COUNCIL (ISCC)

This is a council consisting of delegates from 29 national societies, plus individual members, with a common interest in color. Its major technical activities include symposia at annual meetings and special conferences, and the activity of 14 (currently) problems subcommittees. The ISCC does not issue standards, but occasionally a problems subcommittee may publish a recommended practice with the endorsement of the Council.

14. JOINT ELECTRON DEVICES ENGINEERING COUNCIL (JEDEC)

This council has provided agreement on standard measurement conditions for characterizing photodetectors. Committee JC-23 on solid state opto-electronics devices is now beginning to establish procedures for measuring light emitting diodes.

15. LAMP TESTING ENGINEERS CONFERENCE (LTEC)

This conference meets twice a year primarily to exchange lamp measurement information among various companies in the lamp industry. The conference has carried out several intercomparisons, most notably one in cooperation with NBS published as NBS Tech. Note 559 [62]. Within the framework of this Conference, upon occasion the lamp companies have agreed to base certain measurements on particular standards in order to provide as consistent a set of nominal luminous flux values as possible throughout the industry.

16. MANUFACTURERS COUNCIL ON COLOR AND APPEARANCE (MCCA)

This is a trade association composed primarily of manufacturers of color and appearance instrumentation. One of its major objectives is to arrive at agreements on standards and techniques in order to provide greater uniformity in the measurements made with these instruments. A Collaborative Reference Program for color and gloss is being carried out on a continuing basis under the co-sponsorship of the Institute of Applied Technology of NBS.

17. OPTICAL SOCIETY OF AMERICA (OSA)

This professional society, both as a whole and in its Technical Group on Radiometry and Photometry, has been predominantly occupied with the exchange of technical information. It has published the monograph, "The Science of Color". Its Committee on Colorimetry is addressing the problem of defining scales of uniform color difference. The Society is represented in many standards organizations. (See Appendix D)

18. SOCIETY OF AUTOMOTIVE ENGINEERS (SAE)

The Society has been the primary organ for the formation of industry agreement on aircraft and spacecraft lighting as well as automobile lighting. The resulting documents formed the basis for American practice until the recent increase in Federal responsibility for highway safety standards. The SAE work was not designed for rigid enforcement, but rather as more flexible, "designed to conform to", specifications. These specifications therefore require review before Federal adoption as strictly enforced standards.

19. THE SOCIETY OF MOTION PICTURE AND TELEVISION ENGINEERS (SMPTE)

This group provides for the coordination of practice in the motion picture and television industries.

20. SOCIETY OF PHOTO-OPTICAL INSTRUMENTATION ENGINEERS (SPIE)

This professional society roughly complements in function the Optical Society of America. As the name implies, it emphasizes instrumentation and engineering. Its meetings are primarily professional in nature, frequently topical seminars.

21. WORLD METEOROLOGICAL ORGANIZATION (WMO)

This organization's Committee on Instruments and Methods of Observation (CIMO) concerns itself with the design of physical standards and measurement techniqeus for the determination of parameters characterizing solar radiation in the vicinity of the earth. The Committee has held a number of international intercomparisons of pyrheliometers, instruments for measuring the direct solar irradiance at the surface of the earth. Until very recently these measurements were not directly coupled to national radiometric standards. A general renaissance in interest in detector radiometry stated in this field before its more general appearance in this country as a solution to broader radiometric problems.

22. UNDERWRITERS LABORATORIES (UL)

These private laboratories have not been widely known for dealing with optical radiation standards. However, recently they have displayed interest in establishing limits for irradiance in close proximity to high intensity movie lights. Provision of contemplated standards would require measurements at a much higher level than that for which standards currently exist.

APPENDIX D

Expansion of the Role of Professional Societies

The professional societies are undergoing a self re-examination of their role. Experimentation is a part of this process. For example, at a recent Optical Society meeting, the Technical Group on Radiometry and Photometry held two panel discussions. The first of these discussions was entitled "New Stringent Meteorological Demands on Radiometry". Experts in the field of meteorology were invited to summarize the meteorological needs for superior radiometry. A quantitative review of some of the most sophisticated radiometric measurements on satellites was also presented as a measure of present capability. A substantial gap between needs and performance was identified but described in too cursory a fashion to be clear to everyone participating in the discussion. Nevertheless, this discussion will lead to a more ambitious symposium at a future Optical Society meeting.

At this same meeting a second panel discussion was held on a developing fundamental problem with practical consequences, the looseness in the coupling between radiometry and photometry. This discussion was entitled "Re-examination of the Photometric Unit System". A number of weaknesses in the present system were described and proposals for redefinition examined [65]. This meeting was designed to lead to a formal proposal by a US technical committee of the CIE to a meeting of the international Technical Committee this past summer. It is significant that direct action, if it is to occur, will take place outside of the framework of the Optical Society but perhaps within the framework of the CIE.

APPENDIX E

Methodology of Study

Because of the novelty of technology assessment in general and in particular of the analyses carried out in this Technical Note and in the preceding one on the impact of radiometry and photometry [1], a review both of the critical factors that have been perceived and of the responses to these factors that have been developed and tools that have evolved may find application in other areas. But *caveat emptor:* any transfer of this "technology" to other areas should follow a preliminary investigation to ascertain whether the contemplated application is indeed suitable or not.

1. GENERAL FACTORS

a. Size and Complexity

The size of the analytical job involved is far more than one person, working full time, can carry out by himself. The time factor will be explored in detail in the next section. There is the sheer volume of the potential data that must be collected, correlated, and evaluated. In addition to the enormous quantity and complexity of data, the necessity for a critical approach is crucial. And this critical approach requires technical expertise in a wide variety of technical fields. Evaluation of a broad measurement area must rely on many experts in relatively narrow technical fields.

b. Desirability of Interaction Apart from NBS

A more fundamental reason, also, exists for the desirability for the involvement of non-NBS people in key roles of the interaction. The structuring of the data collected involves critical thought and is part of a useful *educational* process. The organizational complexity of radiometry and photometry is shown by the number of different organizations involved. Key members of the community are desirous of achieving a less parochial approach to these problems, and this requires an interaction apart from NBS. The synthesis performed on the variety of needs throughout the field will be far more practicable if those who must live with the results are involved in the synthesis itself. This is not to say that NBS should not exercise strong leadership; indeed it has been asked to do so. But others must be involved in key roles as well and must share this leadership with NBS.

c. Necessity for Interaction Between NBS and Other Elements of the System

Just as it is desirable for the analysis of a system to involve participants in that system, it is also extremely important to have strong interaction between NBS and the rest of the system. At times NBS leadership may be required, as just noted. At other times, pressure by the rest of the system on NBS may be involved. But still more generally, a partnership must be established if optimum solutions are to be achieved. Before drawing conclusions from these background factors, it is useful to review critical requirements for continuity.

2. SPECIFIC CHALLENGES REQUIRING CONTINUITY

a. Novelty

The serious analysis of the national measurement system is new, although the concept of the system itself is not. A methodology must be evolved, and this takes time. The present Appendix is one contribution toward evolution of such a methodology. Technology assessment is indeed nowhere an exact science yet. Until this methodology becomes fully developed, time will be required for trial and error, re-analysis, and further trial.

b. Second-Order Interaction

It was noted in the Chapter III that the chain between NBS and the ultimate user typically has a number of links. Thus NBS has not been highly coupled to the ultimate user. Channels of direct communication must be established. This process requires time and continuity.

c. Commercial Factors

The preceding impact study [1] noted that individual companies were not strongly motivated to solve basic optical radiation measurement problems on their own. This is partly because consistency with other measurements is a far more important commercial consideration than is the strength of the tie to absolute truth in itself. Indeed, if a choice must be made, business constraints require a common measurement basis with others, rather than fidelity to physical truth. To be sure, the only way that wide agreement in a *complex* physical field can be achieved is by resort to fundamental physics. Nevertheless, a complex cooperative effort is required. This cooperation involves time, participation in a multi-faceted effort, and continuity. Agreements, either tacit or explicit, must ultimately be reached among those most directly involved; and these agreements require time and coordination.

d. Personal Confidence

Because of the commercial impact of information in this area, the flow of information requires the establishment of personal confidence. The development of personal confidence requires both time and substantial continuity.

e. Location of Right People

Because of the diversity in the field of optical radiation measurement and the variety of industries involved, substantial time is required to locate the right person in each institution. Two factors define the right person, his experience and his inquisitiveness. Those at the top of a corporate structure cannot always be expected to have at their finger tips, ready for immediate judgement, an analysis of technical factors limiting the performance of their institution. On the other hand the man at the bench in one part of a company may not have the breadth of experience to speak authoritatively even for his own company, much less for the industry as a whole. At an early stage of the coordination of analysis, basis technical factors must be identified and placed within a coherent structure. Institutional representatives must thus display not only experience but inquisitive minds and must also be prepared to do some hard work. Imaginative analysis is required of those involved at the pioneering stage.

f. Identification of Crucial Questions

When the proper person is located in an institution, or indeed even before he is located, crucial questions must be identified. The nature of these questions of course varies with the individual field. Questions on foreign trade may be important in one area and irrelevant in another. The training of staff involved in the laboratory may be a vital question in one area and relatively unimportant in another. On the one hand, critical factors in the structure of the field must be identified and their relationship to measurement problems established; on the other hand, tractable specific questions must be formulated. The crucial interaction is one of "development" and not "location" of the right questions.

g. Phrasing the Right Question

Because of the diversity of this field, phraseology itself becomes an important factor. The propensity of radiometrists and photometrists for developing nomenclature is well known. But in a deeper sense, the establishment of a suitable background may be required before questions can be properly interpreted. Without continuity this background must be continually re-established.

h. "Induction Period"

Even with the right question phrased in the proper manner, the answer may nevertheless not be immediately forthcoming. Because of the novelty of this analysis both to NBS staff and those with whom they otherwise never deal, answers, although they may already exist, may not be specifically identified in the minds of the people initially involved. Weeks or months after a question has been raised the answer may well come in an unexpected context to the novice who has been asked. More indirectly, our postulated novice may recognize, long after the original posing of a question, another person who knows the answer to the question. This analog of the "induction period" to a chemical reaction is applicable even to those experienced in such analysis. One finds relevant data in unexpected places, fertilizing the "prepared mind". These data that will not come from a crash search at the time a question is posed later may provide extremely important leads.

i. "Other Guy" Symdrome

Since the problem in the measurement system is basically one of agreement, and since scientists and technicians in general are not aware of all systematic effects on measurements being made, estimates of uncertainties will frequently not provide a reliable prediction of the level of agreement actually achieved. Because systematic errors are inadvertently ignored, the tendency is to assume that it is the other person who is in error by more than his stated uncertainty. Because the other fellow is the one presumably in error, the person making this evaluation will not be strongly motivated to search for the source of the error. It is only after considerable interaction with one's colleagues, a result of substantial continuity, that one builds up sufficient confidence in one's colleagues to motivate a serious re-examination of one's own measurement problems.

j. "Emily Post" Syndrome

Another problem, more psychological then technical in nature, but nevertheless severe, is a general reluctance to discuss measurement errors. Even in a completely objective, scientific atmosphere, it is the *possibilities* that receive primary attention, not the *difficulties*. Until a sufficiently firm relationship is established, many will not discuss in detail their measurement difficulties. "It just isn't done".

k. "State-of-the-Art" Syndrome

Even though levels of agreement are typically worse than anticipated because of the neglect of unknown systematic errors, rough levels of agreement ultimately become established in a crude fashion and recognized among experienced workers. This "effective-state-of-the-art" becomes an excuse that is used to justify the absence of better performance. If one *doesn't* do any better, then many will assume that one *can't* do any better. In established fields with long traditions such as those of radiometry and photometry, this complacency has become a barrier recently to rapid movement of the state-of-the-art. With the introduction of new people and new technical constraints such barriers to improvement can be readily removed. A "new continuity" is required to replace the old.

l. Efficiency

And finally, the determination of an efficient response to serious measurement disagreement here, as in basic research, may await a new synthesis of previously unrelated factors. Efficiency demands the identification of new techniques for current problems. This efficiency requires continuity and time for analysis.

3. PERMANENT STRUCTURES

a. Professional Societies

All of the preceding characteristics indicate the desirability of a permanent organizational structure within which appropriate individuals can be identified and their effort to improve the national measurement system coordinated. Information coordination has occurred traditionally through the various technical groups in professional societies. The question is sometimes asked, "Why not strengthen these technical groups to provide the requisite continuity and coordination?" Such an approach cannot be excluded. Indeed it offers some attractive opportunities that have not been exploited. We shall see later that these societies very likely do not offer the total answer.

(1) Technical discussion

The strongest feature of the professional societies has been the provision of a forum for technical discussions and technical papers. These are a *sine qua non* for progress in the measurement system. Without a firm technical foundation, agreement can not be achieved on a widespread scale. Nevertheless, this is only the first step; it must be followed by analysis, coordination of information, and response to specific proposals. The technical groups of these societies can indeed be used to provide for keen interaction among people in addressing specific questions. One example is the recent use of the Standards Specialty Group of the Infrared Information Symposia, which operate primarily as a technical society, to provide tentative answers to specific questions posed by NBS in its re-evaluation of needs for infrared standards and services. Other examples are given in Appendix D.

(2) Difficulties with systematic action

In spite of their great strengths, professional societies face two problems in serving as the *primary* progenitors of solutions to measurement system problems. In the first place, they offer no formal structure for systematic synthesis and the resolution of difficulties. These are societies for thought, not typically societies for action, although they may be changing in this respect. Second, participation in the professional societies typically is not fully international in scope. But the technical problems know no national boundaries and must be solved on an international scale if international problems such as trade are to be ameliorated. Cooperation, then, with an international organization is essential as a long-term solution to the measurement system analysis problem.

b. Council for Optical Radiation Measurement

(1) Origin

Early in an intensive effort by NBS to determine the status of, and needs for, the measurement of optical radiation, a parallel restlessness became evident within industry. Robert Watson, whose professional activity in industry led him to face severe measurement problems in an area where few answers were available, suggested that a group of industrial and NBS scientists in this area get together to discuss a coordinated approach to these measurement problems. Those who were known to share this mutual restlessness with the situation were invited to a meeting at NBS that took place on 28 October 1971 under the title "Conference on the Definition of Pressing Problems and Projected National Needs in Radiometry and Photometry". Representatives from twelve industrial companies, one military agency, and NBS both in Boulder and Gaithersburg took part. Two themes developed during the meeting. The first was industrial desire for more vigorous NBS action in this area and recognition that such an increase in activity would require justification from industry. The second theme was the recognition that a permanent organization ought to be formed in order to provide industrial and other-agency information for NBS and to coordinate future activity. Participants agreed as a first step to submit statements of need to NBS and then, as a second step, to gather to consider these statements together.

(2) Requirements

On 10 February 1972 a second conference was held as a follow-up to the first. It agreed to establish itself on a permanent basis as the Council for Optical Radiation Measurement and to operate as an activity of the Commission Internationale de l'Eclairage (CIE). Action was directed to the following ends:

(a) Leverage on NBS

Uppermost in the minds of participants was the desire for NBS to increase its service in the field of optical radiation measurement. The bulk of the first Council meeting was dedicated to establishment of working groups to provide a consensus on the detailed requirements and a justification for these requests. This concern with NBS activity has remained a primary focus of the Council. It resulted in the lengthy formal report to NBS described below [21].

(b) Coordination of other activities

As noted earlier in this Appendix, three types of activity were to be coordinated. In the first place, an exchange of information throughout the electro-optics industry and government agencies working in the field is vital in order to optimize progress. In the second place, the coordination of technical activities with those of the CIE is called for. And finally, the coordination of activity of the many procedural standards groups described in Appendix C is a problem that must be addressed.

(3) Operation

Because of the magnitude of the work involved and the relatively limited resources of the new organization, it was clear that effort ought to be employed with maximum efficiency. It was this consideration that led to incorporation of the activity within the program of the CIE. This act provided: (1) the coordination with existing technical projects and (2) the international interface that would be a primary requirement of long term work in the field.

The Council thus has become a full-fledged, indeed the primary, effort of Technical Committee 1.2 on Photometry and Radiometry of the US National Committee of the CIE. The most actively interested participants in the Council meetings were invited to join this US CIE Technical Committee, which then proceeded to function as the executive committee of the Council. The following statement of purpose was adopted at a September 1972 meeting of TC 1.2, and with it, a statement of operation:

> The Council for Optical Radiation Measurement (CORM) is a body of American industrial, governmental, and university scientists and engineers organized to facilitate the development of reliable standards and procedures for the measurement of optical radiation.

The Council is an activity of Technical Committee 1.2 on Photometry and Radiometry of the United States National Committee of the CIE (Commission Internationale de l'Éclairage).

(4) Initial goal

The first formal Council meeting, in February 1972, and the following meeting, in May 1972, were devoted to the preparation of a formal report to NBS "Pressing Problems and Projected National Needs in Optical Radiation Measurements: A Consensus of Services Desired of NBS" [21]. Authors for various sections were designated, and the reports of various working groups were condensed into a common format. Common elements in the requests were identified and brought together so that a unified series of proposals for new standards and techniques was developed. Key ideas were extracted for the introduction. The entire Technical Committee 1.2 met in June 1972 to review the document in detail. The resulting document was then sent to all CORM participants for comment, which would then be incorporated by a meeting of the authors into a final document presented to NBS in the fall of 1972.

(5) Permanent goals

With the report published and well received, the US Technical Committee 1.2 met in September to adopt the preceding statements of operations and purpose and a set of objectives. These were grouped into four sets of goals, as noted, grouped around four distinct sets of participants.

I. COUNCIL MEETINGS

To establish and maintain a dialogue throughout the American electro-optics industry on problems of optical radiation measurement; to use this dialogue to establish priorities and to investigate alternative solutions.

II. COUNCIL-INTERNATIONAL TC 1.2 TECHNICAL PROJECTS

To coordinate study of specific optical radiation problems and recommend solutions to them in cooperation with the international effort organized through the CIE.

III. COUNCIL-NBS INTERFACE

To establish and maintain a dialogue with NBS; to use this dialogue to inform NBS on industrial priorities; and to suggest feasible approaches to these problems.

IV. COUNCIL-STANDARDS GROUPS INTERFACE

To coordinate the dissemination of commercial standards and procedures developed by American and international standards organizations.

Communication throughout the field was to be maintained by a series of general meetings. Technical activity was to take place via ten specific projects, the first six of which were already activities of the international Technical Committee 1.2. Information for NBS was to be coordinated through establishment of a group for this purpose. And finally, the coordination of information on the various standards groups was to be coordinated by a fourth activity. Detailed programs in each of these areas have just been issued [27].

(6) Prospects for the future

Comparison of the Council program with the factors necessary for a coordinated attack on measurement problems identified in the preceding section indicates that a mechanism for continuity has now been established to carry out the various functions analyzed. Since the industry and its organizational structure are very much in a state of flux, the future is hard to predict. The degree of cooperation throughout the field achieved already leads one to be optimistic about future achievement. CORM leaders were invited to an international conference on Photometry and Colorimetry this summer in eastern Europe to describe this activity. The problems that the Council is addressing are apparently not localized, and interest is high. Whether or not the challenges are successfully met remains to be seen.

APPENDIX F

Relation of Improved Optical Radiation Measurement to Broadened Federal Concern

1. PROMOTING ACCURATE, MEANINGFUL, AND COMPATIBLE SCIENTIFIC AND TECHNICAL MEASUREMENTS

A traditional central role for NBS has been widely recognized to be: "promoting accurate, meaningful, and compatible scientific and technical measurements". Paralleling the expanded public interest in coordinated approaches to various public and national problems, NBS is re-examining its role in cooperating in this endeavor. One example of a broadened view of the NBS role in "promoting" such measurements is the present study.

2. PROMOTING MORE EFFECTIVE USE OF SCIENCE AND TECHNOLOGY

The recent rapid development of photon sources and photon detectors has been described. Opportunities to use these new tools in a more effective manner have also been noted. Appropriate strengthening of the measurement system will be required if these new tools are to be utilized to fulfill their promise.

3. PROMOTING STRENGTH IN THE ECONOMY AND EQUITY FOR BUYER AND SELLER IN TRADE

The economic impact of improved measurement technology for optical radiation falls in two broad areas identified in the earlier Technical Note [1]. Within this country, if the buyer is to make intelligent decisions, whether he be an individual buyer in a supermarket or the economically more important large scale commercial purchaser, he requires such data as the luminous flux provided by various manufacturers. This data must be of sufficient accuracy for reliable comparison of dissimilar objects designed to meet a given performance criterion.

Abroad, the growth of international trade in the rapidly growing electro-optics industry has been widely recognized. "I have travelled through every country that sells our products and talked to each of our representatives, and their story is the same. We must have improved light measurement traceability to the National Bureau of Standards" [22].

And finally, in the development both of domestic and of international agreements, authoritative participation is highly desirable if the U.S. is to respond to the coordinated approach displayed by other countries. We are being asked to achieve a higher degree of coordination than that which has characterized our activity in the past [21,27].

4. STANDARDS AND TEST METHODS FOR PROTECTION OF THE PUBLIC FROM SPECIFIC HAZARDS

In the preceding Technical Note [1], several pieces of relatively new legislation were cited. Three of these bear directly on hazards. The first is the Federal Hazardous Substances Act, 15 US Code Chapter 30. More recently has come the Radiation Health and Safety Act of 1968, Public Law 90-602. And finally there is the Occupational Safety and Health Act of 1970, Public Law 91-596. These establish very broad powers for the Secretary of Health, Education and Welfare and the Secretary of Labor. Emphasis will naturally be placed in certain spectral regions and at specific levels. It is in anticipation of increased activity in these areas that the national measurement system must be designed.

5. TECHNICAL INFORMATION SERVICE

Because of the state-of-the-art nature of most measurements in this area, information resulting from radiometric research is awaited with keen anticipation throughout the industry. In areas where commercial factors may influence technical objectivity, users require access to relatively unbiased information.

6. EXPERIMENTAL TECHNOLOGY INCENTIVES PROGRAM

Because of the technical complexity and vast extent of the effort of required for improvement in the measurements, symbiotic approaches by government and industry might be explored. One path is the NBS Experimental Technology Incentives Program. Both because of the rapid march of technology in electro-optics and because of a heavy defense orientation in the past, a number of new commercial opportunities exist that have not been fully realized in this area. The civilian application of highly advanced, and previously classified, areas of technology presents an opportunity for the solution of national problems, both social and economic. This challenge may lead to a very new and complex interaction with industry.

APPENDIX G

A Comprehensive Approach to the Measurement System

A reliable measurement system consists of two parts: (1) research and (2) the interaction between this research and routine measurement.

1. THE RESEARCH REQUIRED

Since radiometry and photometry consist of the measurement of electromagnetic radiation generated, transmitted, and detected by optical system components, the system can readily be approached in terms of these elementary functions.

a. Source Characterization

The characterization of a source by a system user typically involves three separate elements: the realization of a scale, its transfer to secondary standards, and the development of techniques for extension of these standards to the generally dissimilar object to be measured. For the characterization of a source in the U.S., a second source typically embodies the scale and a third source the secondary standard. But detectors may well be used increasingly for these purposes.

(1) Realization of the scale

The realization of radiometric scales by sources for the characterization of other sources has been a widely recognized accomplishment of the NBS program in radiometry. NBS leadership in source blackbodies is acknowledged. One important area remains to be developed within the system as a whole however: the characterization of large area blackbodies. Both space and ground requirements have led to a need for the full characterization of sources with an area of many square centimeters. A number of designs have been proposed and used under a variety of conditions. A full analysis remains to be performed however.

(2) Transfer of scales to secondary standards

The transfer of blackbody scales to secondary standards is another area where NBS has already provided acknowledged leadership. Comparable standards of spectral radiance are available nowhere else. A major fraction of the emphasis of the present NBS program is still in this area. Substantial NBS work is being directed to the transfer of scales to particular standards in a definitive way at the 1-2% level: standards of spectral irradiance, luminous intensity, and luminous flux.

A fundamental question remains to be examined. For important new standards is it preferable for the system to operate with additional secondary standards, or rather to generate the additional measurement capability by the establishment of reliable techniques for the extension of present standards. The second approach is considered by many to be preferable for large systems. Three system elements can be defined in the area of secondary standards:

(a) Characterization of present standards

Because of the complexity of the measurements, some NBS standards and most others remain to be fully characterized. More complete characterization of its standards has a high priority now at NBS. Particularly as other countries develop similar standards it will be important for NBS standards to receive full, documented quantitative characterization.

(b) Improvement of present standards

The best U.S. secondary standards are spectral radiance standards, to which is ascribed an uncertainty of between 1 and 3%. Requests are already being received for radiometric accuracy better than 1%, and planning should start, at least, for the generation of new standards better by at least by a factor of 2. But in view of the requirements in other areas, this area probably will not receive high priority at the moment. Areas receiving primary attention at NBS now are spectral irradiance and luminous flux.

(c) Description of procedures for present standards

The utilization of present standards has been hampered in the field by lack of a complete description of procedures recommended for their use. Such description ideally consists of two parts. A complete characterization of the standards involves a description of the variation of the measured output with respect to the various parameters of the lamp. One example important for some lamps is the variation with orientation. A second set of parameters deals with the influence of the environment, such as temperature and humidity. Until such descriptions are supplied with the lamps, the user will still be left with an unnecessarily large job to do and one whose performance would be redundant if performed in a large number of laboratories.

(3) Extension of present standards

The major thesis of Chapter II was that many different types of measurements were to be made. These can be made either by substitution or by extension, as just noted in Section 2. For example, most source standards are incandescent lamps, whereas a major fraction of radiometric and photometric measurements are made on non-incandescent sources. One approach would be to generate an enormous series of non-incandescent standards so that all field measurements can ultimately be made by substitution with similar standards. Alternatively, one could generate a set of techniques whereby present standards could be used reliably to calibrate a wide variety of lamps. If the system were relatively small, the former approach would inevitably be economical. But for a large system with great diversity of measurements there are probably fewer *aspects* that need to be characterized than there are different lamp types to be measured. Lamp production is so varied that even a subset, for example, fluorescent lamps, are probably more economically standardized against incandescent standards then by direct substitution standards for each type of fluorescent lamp.

This general approach may also be advisable even for smaller systems where work is destined ultimately for comparison with that on dissimilar objects. Such is increasingly the case for artificial illumination and its comparison with natural daylight. If two dissimilar measurements are to be made on a comparable basis then one must understand in detail the nature of the measurements. With proper attention to design, it is to be expected that measurements providing for extension of given standards to dissimilar areas can be made sufficiently convenient that economic procedures can be developed. Such a system has the further advantage that it can be extended with minimal effort as the field grows.

The optimum system may involve the establishment of a few additional secondary standards in areas where a large number of measurements are relatively similar to each other but very dissimilar from the secondary standards presently available. But such a conclusion must be drawn with extreme care. Two dominant factors in such an evaluation will be the stability of the contemplated new standards and their similarity to the various objects that they are to serve as standards. These questions both arise, for example, with respect to proposed LED standards.

b. Detector Characterization

(1) Realization of scales

Work in a number of national laboratories on electrically calibrated radiometers is demonstrating that this approach to the realization of radiometric scales is perhaps the most certain, particularly where spectral information is secondary in importance. One extremely promising approach to absolute detector radiometry arises in the development of pyroelectric detector technology. Several vigorous programs in the development of this technology are already underway at NBS [66].

(2) Transfer of scales to secondary standards

Several new detectors seem to promise the stability required of secondary standards. Pyroelectric detectors are already under active investigation. Several solid state quantum detectors are also extremely promising, primarily silicon in the visible region. Although experience on the stability of, and environmental effects on, these detectors remains to be accumulated, preliminary indications are extremely encouraging. The high sensitivity of new detectors is especially important in permitting detailed spectral response information to be obtained. Both photometry and radiometry can be expected to undergo a revolution through this new technology.

(3) Extension of present standards

Vacuum diodes and multipliers have traditionally been considered to be too unstable to act as primary or secondary standards. Their response must be characterized however and techniques must be developed for doing so reliably. The National Research Council of Canada has a strong program in this area. There is a renewed interest in photomultipliers now that photocathodes composed of elements from the third and fifth periods of the periodic table (III-V compounds) have been shown to display a remarkably flat response throughout the visible and into the near ultraviolet and infrared spectral regions.

c. Techniques

There is wide agreement that the proper generation and use of physical standards require close attention to specific measurement techniques. Similar attention to the extension of present standards to dissimilar measurement objects is greatly needed.

One conspicuous example is the detailed characterization of attenuation. In a recent poll of members of the CIE international Subcommittee on Detectors, for example, the dominant concern expressed was for linearity [20]. Although a review article has appeared [14], the field is so extensive that an even more detailed review of various techniques with high precision has been requested.

A second general problem, particularly in photometry, is the characterization of spectral techniques, especially as applied to spectral lines. With increasing interest in spectral information, small, convenient, and reliable instrumentation is desired. Fourier interferometric techniques offer a number of attractive advantages for dealing with such spectral problems. They have been exploited for spectroscopy, where wavelength information is the quantity of primary interest. Their radiometric suitability remains to be determined.

A third general area is that of pulsed measurement. The measurements are so heavily dependent on the particular time scale of the pulses in question that a general approach may not be feasible.

A fourth area of concern is polariation. Interest in this area will probably continue to be focused on the characterization of specific components, rather than a general approach. Although some good reviews have been prepared [23-24], the sheer extent of the effect leaves much still to be done.

A fifth general area of optical radiation measurement is spatial distribution. Although the description of inhomogeneities is of greatest significance with respect to sources and detectors (q.v.), general techniques for determination of inhomogeneities would be useful for the system.

Diffraction is a sixth area of concern. Since the quantitative importance of diffraction can be determined meaningfully only with respect to an entire system, individual components clearly cannot be so characterized. Their degree of coherence is important though. The significance of diffraction is beginning to be recognized [67], and further work will be appearing. A full understanding of diffraction will be coupled with some basic questions of coherence in radiometry.

2. SYSTEM COORDINATION

Unless research continues to be based on up-to-date input from the measurement system on the one hand and, on the other hand, unless the results of the research are effectively coupled into the system, the research may be remote and its value, questionable. Thus interaction with the measurement system is of importance comparable to that of the research itself. Two types of interaction are involved. First, there is conceptual communication, either oral or written. Equally important is experimental assessment of measurement performance, a measurement assurance program, and dissemination of standards. Both conceptual and measurement communication are essential to a smoothly functioning system.

a. Coordination of Information

The importance of strong interaction between the NBS program management and the community that it serves is widely recognized. In addition to individual bilateral interaction, a number of more systematic channels must be employed. The professional societies provide facilities for communication of the type already described in Chapter III. These must be utilized. A more structured format providing for the achievement for coordination of effort is also extremely important. The organization of the Council for Optical Radiation Measurement for this purpose has been described and is analyzed in detail in Appendix E.

There is an additional type of important interaction. This is the normal initiative taken by those outside of NBS who would like to have various services performed by NBS, either routine or special. Many call on NBS for specific services. Some continuing compilation and evaluation of the kinds of service they are asking for would be highly desirable. Although some of these contacts occur at a non-technical level, attempts will be made to generate specific information on the use and utility of standards being requested.

b. Coordination of Measurements

The specific coupling of optical radiation measurements to NBS standards is achieved in one of two ways. Traditionally, calibrated objects have been disseminated by NBS. This is the simplest and the cheapest form for the provision of this interaction. It also provides the least information.

Either alternative or complementary to this calibration service is the establishment of intercomparison programs in which NBS can play a role. If NBS calibrates one of the objects used in the intercomparison, then this object can fulfill the function of a calibration. But in addition it can play a more rounded role. If the object is carefully chosen, its intercomparison can also assist in the determination of the performance of the measurement system and thereby provide a firmer basis for the prediction of system performance than can a calibrated object in itself. Such an approach essentially constitutes the performance of research in a parallel fashion in a number of laboratories. The great effort required must be balanced on a case-by-case basis against the expected benefits. Because of the extensive requirement for resources in such a program, critical planning must play a strong role in this work. Goals must be clearly established and articulated in advance. The intercomparisons must be carefully designed to achieve their goals with close attention to costs both at NBS and in cooperating laboratories. By means of such intercomparisons, one can both provide the basis for the measurement system and demonstrate that it is indeed performing satisfactorily. Moreover, the impact of system improvements can be clearly demonstrated. The immediate effect both of research and individual services can thus be measured in quantitative fashion. NBS is developing such an intercomparison program, but because of budgeting restrictions its realization will be very slow.

EXECUTIVE SUMMARY

The ultimate users of the optical radiation measurement system fall into four major categories: industry, government, the academic community, and the general public. All are facing severe problems.

Light emitting diode manufacturers, for example, have found spreads of the order of 40% among measurements. Such differences are clearly visible and intolerable commercially. But the complexity of the measurement means that, without outside assistance, companies making reliable measurements face very high measurement costs. Not only will highly trained people be involved, but at present a great deal of time for research will be required. The exceedingly high costs thus involved are simply not feasible for this fragmented industry. It is currently much cheaper to argue a case of disagreement in court, if it comes to that, rather than to set up a research laboratory to solve the problems on an individual basis.

The varied authority for enforcement of new Federal regulation is increasingly important. First was the Federal Hazardous Substances Act, 15 U.S. Code Chapter 30. More recently has come the Radiation Health and Safety Act of 1968, Public Law 90-602. And finally there is the Occupational Safety and Health Act of 1970, Public Law 91-596. The Departments of Health, Education, and Welfare, Labor, and Commerce are involved. Furthermore, the Environmental Protection Agency is responsible for an area of rapidly expanding concern.

In the past, the measurement systems of the various countries have been quite independent. But as international commerce in electro optics grows, foreign standards will probably impinge increasingly upon the U.S. measurement system.

Public concern for energy has led to activity in areas that depend on optical radiation measurement. There is growing public sensitivity both to power conversion and to the efficient utilization of energy. A review article summarized the situation with respect to energy conversion recently: "Whatever method is being pursued, the electro-optics community is very firmly entrenched in the search for new energy sources. The long- and short-term goals discussed in these pages seem destined to keep a great many of us diligently at work for a good many years to come." The efficient utilization of power is also receiving attention. Since lighting takes 25% of the electric power generated, measurement of efficiency in lighting becomes important to improving the efficiency of power utilization as a whole.

Pollution of the environment must be monitored if it is to be controlled in a realistic fashion. Remote sensing approaches are being explored. Problems of pollution are coupled with energy problems through the wide availability of hydrocarbon fuels that contain relatively large amounts of sulphur, a serious pollutant. Another specific interest in monitoring attempts to control pollution is connected with substantial changes in the earth's atmosphere. Serious climatic changes may follow increased pollution as a long term effect. In the short term, the amount of ultraviolet light, which is controlled by ozone in the upper atmosphere, may be affected. Meteorology in fact is providing some of the tightest requirements in radiometry.

The study of the measurement system leads to a number of conclusions. The first is the grave need for coordination of activity. What channels for concerted action can be utilized? In addition to bilateral interaction between NBS and the various other institutions already involved, a number of more elaborate systematic channels must be employed. The professional societies provide facilities for communication of a type described. These must be utilized. A more structured format providing for this coordination of effort is also extremely important. The establishment of the Council for Optical Radiation Measurement for this purpose has been described and analyzed in detail. Coordination in the dissemination of commercial standards and procedures developed by American and international standards organizations remains to be tackled.

A number of technical conclusions are also drawn. Source and detector characterization are called for as well as greater attention to technique building blocks. Monitoring of the performance of the entire system and of its basic measurements are called for. Improved methods of transfer of measurement technology must be developed. And last, a mechanism for the establishment of priorities in the development of an extremely complex technology is urgently needed.

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The electro-optics industry and the public that depends on it are part of an informal but influential system for optical radiation measurement. The growth of this undustry and of public concerns related technically to it have put severe new strains on this measurement system. The system itself must therefore be analyzed. The state of the art, on which the measurement system depends, is surveyed in terms of basic measurement parameters. The measurement system is analyzed in terms of its three basic components: the flow of physical standards, the generation of procedural standards, and the funding framework. The roles of the professional society and of the Council for Optical Radiation Measurement are reviewed. New requirements of the system are identified. Finally, the methodology of the study is reviewed in detail.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Measurement system; photometry; professional societies; radiometry; standards.

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