Determination of the Constants of Total Radiation From a Black Body

This paper [1] presents a critical review of the state of knowledge about the constant of nature that relates the quantity of radiant heat and light to the temperature of the radiant object. Studies of this issue at the beginning of the 20th century ultimately led to the discovery of quantum mechanics, the keystone of modern physics. The continuity of this work at NIST for the remainder of the century also led to fundamental changes in the way that optical metrology is now carried out.

In 1905 Samuel W. Stratton, the Director of the National Bureau of Standards, persuaded a young research associate at the Washington Carnegie Institute to come to the NBS laboratories to undertake research programs in infrared spectroscopy. Thus William Weber Coblentz began a nearly 40-year career at NBS that resulted in over 400 publications in diverse areas of optical research. Stratton's original intent was to use Coblentz as an assistant in his own laboratory, but these demands were modest and Coblentz was able to pursue his own interests in infrared spectroscopy and radiometry, begun as a graduate student at Cornell. One of the suggestions offered by Stratton led to the work cited here and to the establishment of the science of radiometry at NBS.

The first decade of the 20th century was a very important time in the development of concepts in modern physics. One of the of the great mysteries of the era was the underlying principle behind blackbody radiation, the heat and light emitted from hot objects. (Black objects are studied in order to eliminate the effect of reflection.) Max Planck in Germany had developed a theory that appeared to explain the phenomenon in proper detail, but it required the introduction of a revolutionary new idea. In Planck's theory, the energy of light and other electromagnetic radiation was quantized in discrete increments. The proportionality between the energy increment and the frequency of the radiation became known as Planck's constant.

The spectral distribution of blackbody radiation, that is, its radiance at different wavelengths, is determined by its temperature. Early on, the quantitative details were described by presuming two constants of nature, which became known as the first and second radiation constants. Additionally, the total energy of the radiation emitted was shown to be proportional to the fourth power of the temperature. This proportionality constant was named the Stefan-Boltzmann constant after the theoretical physicists who first calculated the relationship. The Stefan-Boltzmann constant can be expressed in terms of the other radiation constants or the fundamental constants now known as Planck's constant, the Boltzmann constant, and the speed of light. This process of unifying basic phenomena and verifying the ideas with accurate experiments was central to the development of physics at the turn of the century.

On a visit to Europe, Stratton observed that a number of the national laboratories in Europe were expending considerable effort in measuring the radiation constants for describing the spectral distribution and total radiation from blackbody sources. Stratton suggested to Coblentz that it would be good if NBS could contribute to this effort and recommended that Coblentz direct his efforts in this regard.

The accuracy that Coblentz was able to achieve with his early instruments is a testimony to his diligence, rare experimental insight, and scientific capability.

During 1914–16, Coblentz developed an absolute radiometer, measured the Stefan-Boltzmann constant, and reported the results in the review article [1]. To perform this measurement he constructed a thermopile-based electrically calibrated radiometer to measure the total power from a blackbody radiator [2]. The temperature of the blackbody varied between 1000 K and 1400 K, and hence most of the radiation was in the infrared region of the spectrum. Based upon designs by Ångström and others, Coblentz designed a radiometer incorporating an electrical heater so that the optical power could be measured by comparing it to an equivalent amount of electrical power, each causing the radiometer to rise to the same temperature. A thermopile consists of an array of thermocouple junctions that are connected in series and parallel to produce a changing voltage as their temperature changes. Coblentz experimented with various arrangements of joining the thermocouple junctions in order to improve their sensitivity and response time. He was able to achieve a sensitivity of about 10 nW [3].

Using these thermopile detectors, Coblentz was able to measure the radiation constants to within 0.5 % of their presently accepted values. His result for the Stefan-Boltzmann constant was within 1 % of its present value, and he was able to calculate a value for Planck's constant that differed from the modern value by only 0.8 %. His results were among the best in the world at that time, and additionally, he was able to show that the shape of the blackbody spectrum, its intensity as a function of wavelength, agreed with Planck's theory.

In carrying out these difficult measurements he used the expertise he gained in graduate school while making infrared measurements of the absorption spectrum of various gases and materials. He knew how to account correctly for the effects of atmospheric water and carbon dioxide, as well as impurities that could cause anomalous absorption. He designed and built both absolute and relative detectors, and he constructed monochromators appropriate to the task of performing the spectral measurements of blackbody radiators. The manufacture of these devices required exquisite and detailed work, with small receivers and intricate wiring of the thermopiles.

Coblentz is considered the originator of molecular infrared spectroscopy in the United States, and a society named after him, the Coblentz Society, arranges scientific meetings and other activities for specialists interested in the infrared region of the spectrum for a variety of analytical and other purposes [4]. His body of spectroscopic work during his career at NBS is too extensive to review here—in these and other fields, he published more than 400 papers in leading scientific journals.

Coblentz also had a life-long interest in astronomy. He actively participated in astronomical observations until his retirement in 1945, and he contributed significantly to the art of stellar observations by developing sensitive radiometers that could be used for stellar photometry [5]. These were used in many observatories throughout the United States.

Coblentz applied his technology to the early NBS efforts in human visual photometry and developed an early experiment to determine the so-called mechanical equivalent of light. To do this he measured the visual wavelength response of a number of observers and then calculated the radiant luminous efficiency of a blackbody source at known temperatures [6,7]. His early work in photometry, including work on standard sources and human visual response, helped set the stage for the work of Tyndall and Gibson that resulted in the modern system of photometry used throughout the world. The photometric units of luminous flux and luminous intensity were maintained by the world's national laboratories using candles, gas flames, and incandescent lamps until the candela was defined in 1979 by the CIPM in terms of optical power. The work Coblentz performed in the Stefan-Boltzmann and other blackbody studies was the progenitor of the detector development used in the visual photometry efforts.

In the late 1960s, scientists sought a more precise value of the Stefan-Boltzmann constant by utilizing new technology. Blevin and Brown at the CSIRO in Australia developed a more precise experiment and measured the total radiation at the gold melting point to obtain a value within 0.1 % of that calculated from the fundamental constants [8]. At NBS, Ginnings and Reilly built a new version of the classic Coblentz experiment, but with a modern innovation—their electrical-substitution radiometer operated at liquid-helium temperature in order to gain sensitivity and reduce noise [9]. For a variety of reasons, including the difficulty in correcting for diffraction and scattering effects, Ginning and Reilly did not achieve the accuracy they desired. However, in the attempt they developed a new type of radiometer, the cryogenic radiometer, that has ignited a modern revolution in radiometric accuracy.

Using ideas from the Ginnings and Reilly work, Quinn and Martin at the National Physical Laboratory (NPL) in the United Kingdom developed a new cryogenic instrument and succeeded in measuring the Stefan-Boltzmann constant to within 0.02 % of the value calculated from the fundamental constants [10]. This landmark work by Quinn and Martin, and further work by the NPL team, provided a basis for establishing the cryogenic radiometer as the fundamental high-accuracy instrument for all radiometric standards work [11]. NIST's work in cryogenic radiometry was continued by Yokley, who built a very highly sensitive cryogenic radiometer for calibrating very low level, low temperature thermal sources [12].

The cryogenic radiometer and its inherent accuracy of 0.05 % or better has revolutionized optical and photometric measurements. No longer do we think in terms of primary, standard sources of light. Instead, the best standards work is based upon measurements and comparisons of detectors of light [13, 14]. The 1979 redefinition of the candela in terms of optical power takes full advantage of cryogenic radiometry to put modern photometric standards on a detector basis [15]. Cryogenic radiometry, together with new technology in silicon photodiodes, low-noise amplifiers, and precision optical filters, has spawned new types of standards for the candela, lumen, and lux. Further developments have placed the spectral radiance and irradiance scales on an absolute detector base through the accurate measurement of the temperatures of blackbody sources with narrow-band filtered photodetectors. All of these will continue to improve over time as further improvements to filters and the detectors are anticipated.

The fundamental strategy originated at NBS by Coblentz in making radiometric and photometric measurements with electrically calibrated optical detectors set the stage at NIST for the present-day and future standards work. The continued importance of better measuring the Stefan-Boltzmann constant spurred the development of the modern cryogenic radiometer, which is found today in most national standards laboratories throughout the world. The legacy of Coblentz's work in the early 20th century to develop even more sensitive optical detectors is a continuing effort to keep pace with such needs. The accuracy that Coblentz was able to achieve with his early instruments is a testimony to his diligence, rare experimental insight, and scientific capability. His work is the cornerstone of radiometry, photometry, and infrared spectroscopy at NIST.

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