Theory of Isoperibol Calorimetry for Laser Power and Energy Measurement

This paper [1] describes the first and most thorough analysis concerning the behavior of isoperibol calorimeters developed at NIST and used by NIST (and other laboratories) as standards for laser power and energy measurements. For over 30 years, instruments based on the principles described in the paper have been used as primary standards to relate absorbed laser energy to dissipated electrical energy and thus to provide traceability to SI units. A family of such instruments provides the basis for calibrations that span a wide range of laser types and power ranges—wavelengths from 193 nm in the ultraviolet to 10.6 μm in the infrared, and power levels from nanowatts to over 100 kW. New instruments based on the same principles continue to be developed as NIST capabilities are extended to meet emerging needs. In some cases (e.g., certain wavelengths or power levels), NIST is the only national metrology laboratory with the capability to provide needed laser calibrations, and, consequently, it provides traceability to organizations throughout the world.

Lasers, as opposed to other sources of electromagnetic radiation, typically emit light in a well-defined beam that may have very high irradiance and a nonuniform irradiance profile. Laser light also has very high spatial and temporal coherence. Although these properties contribute to the usefulness of lasers for many applications, they also can complicate the performance of accurate measurements of laser power and energy.

In the early 1960s, during the period of initial development of the laser, NBS began developing standards and appropriate measurement techniques to characterize laser radiation. The very first NBS laser energy standard was a "liquid cell calorimeter" developed by Don Jennings [2]. It used an aqueous solution of $CuSO_4$, contained in a cell with a quartz window to absorb the radiation from pulsed lasers such as ruby and Nd:glass. A small amount of dark ink was added to the solution to increase the wavelength absorption range. Thermocouples were used to measure the corresponding temperature increase from laser light absorption. An electrical heater, immersed in the liquid, provided a means to calibrate the responsivity of the device electrically. Although designed for measuring the energy from pulsed lasers, the liquid-cell calorimeters also worked well for measuring the energy or average power from continuous (cw, as opposed to pulsed) laser sources. For a number of years, these liquid-cell calorimeters were used as primary standards at NIST and at military primary standards laboratories for calibrating laser power and energy meters.

In July of 1969, Dale West, Chief of the Heat Measurements Section of the Heat Division, who had been working for a number of years in the field of high-temperature calorimetry, moved from NBS in Gaithersburg to NBS in Boulder to join Don Jennings' Quantum Electronics Section of the Quantum Electronics Division. As leader of the Laser Power and Energy Project, West applied his knowledge of "bomb calorimetry" (a technique for measuring the energy released by a combustion reaction that produces a large increase in temperature and pressure) to the task of measuring the amount of power and energy contained in laser radiation. He quickly recognized that isoperibol calorimeters would make excellent primary standards for this application and would allow increased accuracy over the liquid-cell calorimeters in use at that time. The term "isoperibol" refers to a calorimeter in a constant temperature environment. In 1970, West and Kenneth Churney wrote and published *Theory of Isoperibol Calorimetry for Laser Power and Energy Measurements* [1] in which they developed the underlying concepts for isoperibol laser calorimetry. Thereafter, until his retirement in 1974, West designed and built various models of laser calorimeters that implemented the principles established in this paper. He also published numerous other papers in which he discussed various aspects of laser power and energy measurements.

In this seminal paper [1], West and Churney start with the first law of thermodynamics and, in a logical sequence, develop the equations that govern the resulting thermal response of an isoperibol calorimeter when exposed to laser radiation. They clearly explain the assumptions and conclusions that lead to their final formula for the "corrected temperature rise" of the calorimeter. West and Churney showed that the corrected rise is proportional to the stored thermal energy in the calorimeter minus the heat energy lost during the measurement. In further papers, West gives more detailed guidance (and even a software program [3]) that enables the reader to apply the corrected-rise calculations to actual data acquisition and analysis. These analytic techniques are still used today for many situations in laser-measurement laboratories. The clear and thorough treatment of the calorimeter behavior enabled timely and widespread public acceptance of these devices as primary standards for laser energy measurements.

West was known for his rigorous, meticulous approach to metrology and uncertainty analysis. Before building any final devices, he built numerous test fixtures and samples to evaluate thoroughly the heat-flow patterns, with special emphasis on the equivalence of electrical and laser energy deposition. The isoperibol calorimeters that West designed for laser measurements basically consist of cylindrically shaped absorbing cavities surrounded or enclosed by temperature-controlled metal jackets. The jackets provide the isoperibol (i.e., constant temperature environment) conditions necessary as prescribed in the paper. During use, laser radiation enters the absorbing cavity (typically coated with a black paint or other highly absorbing material) where the absorbed optical energy is converted to thermal energy. The resulting temperature increase is then monitored with thermal sensors (e.g., thermocouples or resistors). Heater wires are thermally attached to the cavities to calibrate the instruments by injection of known amounts of electrical energy. Using West and Churney's equations developed in the paper, the characteristic output of the temperature sensors can then be quantitatively correlated with the measured amount of injected electrical energy.

The first significant calorimeter that West produced based on these principles was the C-series calorimeter [4,5], which was designed to measure the output of low to medium power (1 mW–1 W) lasers. Assisted by William Case and Alvin Rasmussen for certain aspects of the construction, such as the temperature control circuitry and the electrical wiring, West did much of the construction at his desk (e.g., attaching the thermocouples and positioning the cavity inside the temperature-controlled jacket). The calorimeter worked amazingly well and its output reproduced the characteristic behavior pattern predicted in the paper. The C-series calorimeters are still used on a daily basis over 30 years later. A cross-section of this calorimeter design is shown Fig. 1.

To accommodate higher powers (up to 1000 W), West then designed and built several larger calorimeters, designated as the K-series [6]. The absorbing cavities for these calorimeters used cone-shaped mirrors to spread the laser radiation over a large area of the absorbing surface to reduce the irradiance and thus

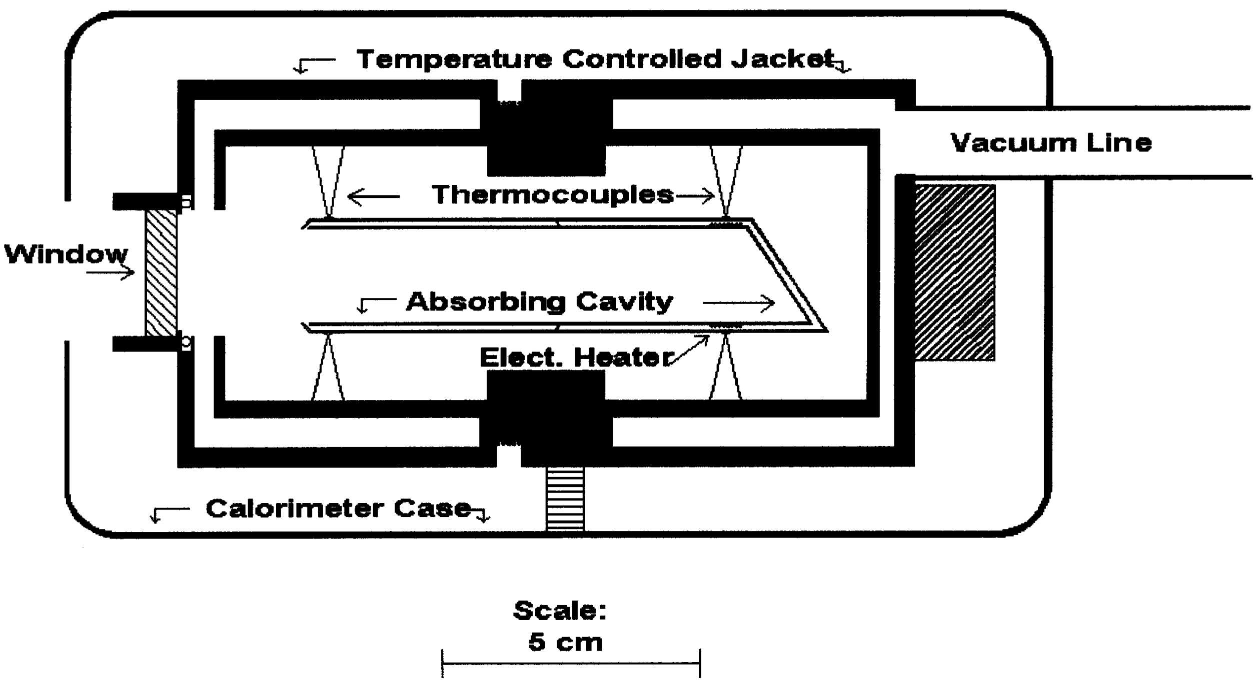

Fig. 1. Cross-section of C-series isoperibol laser calorimeter.

prevent damage of the absorbing paint. At about this same time (i.e., early 1970s), Douglas L. Franzen and Leonard Schmidt, with West's technical oversight and advice, designed and built a type of isoperibol calorimeter called the Q-series [7] to measure pulsed laser radiation. As with Jennings' liquid cell calorimeter, the Q-series devices use a volume absorbing technique to distribute the absorbed energy throughout the absorbing material. In particular, Franzen used neutral-density absorbing glass having specific absorption coefficients to absorb safely the pulsed laser radiation of Q-switched Nd:YAG lasers. Then, in the mid-1970s, two large (400 kg) calorimeters, called the BB-series [8,9], were built by Richard Smith, George Chamberlain, and Phillip Simpson to measure military lasers having powers up to 100 kW (cw). Although these large, massive calorimeters were inherently different from the earlier, smaller calorimeters in many respects, their outputs are, nevertheless, governed by the isoperibol-calorimeter equations developed in West and Churney's paper.

More recently, Rod Leonhardt, Chris Cromer, Marla Dowell, T. R. Scott, and David Livigni have developed specific models of isoperibol calorimeters for measuring the pulsed, ultraviolet radiation emitted by excimer lasers [10,11]. The inherently high photon energies and large peak powers of these lasers complicate accurate measurement, which is one reason why no other national laboratories have such capability at this time. The NIST calorimeter cavities contain specially selected glass which can absorb the radiation without suffering damage or degradation while keeping fluorescence to a minimum. Again, analysis of the calorimeter output uses the algorithms developed in West and Churney's papers. For special high-accuracy laser-power measurements at low power or energy levels, many national metrology laboratories, including the NIST Optoelectronics Division [12], now use cryogenic radiometers to compare laser power to electrical power with very low associated uncertainties (<0.01 %). At cryogenic temperatures, the thermal properties (such as specific heat capacity and thermal conductivity) of the metal cavity change rapidly with temperature; consequently, the temperature response is not sufficiently linear to apply West's isoperibol calorimeter principles. However, the essential structure of these devices in many ways mirrors the basic construction of West's original C-series calorimeter (i.e., a cylindrical cavity surrounded by a constant temperature environment and having an electrical heater attached).

Today, 30 years later, West and Churney's corrected-rise equation and associated isoperibol-calorimeter analysis described in this paper still permeate the field of laser power and energy measurements. The array of calorimeters described above, whose behaviors are governed by the principles discussed in the paper, are still in operation, many on a daily basis. In addition, almost all standard calorimeters for mea-suring laser power and most radiometers (even those that are not isoperibol) are designed using the same basic structure of West's C-series, his first isoperibol calorimeter.

Prepared by Thomas R. Scott.

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