

DOD/ANSI/EIA

Fiber Optics Standardization Symposium

PROCEEDINGS

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.D44

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December 7-10, 1987

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1987

NBS STANDARDS FOR OPTICAL POWER METER CALIBRATION

by

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Introduction

The measurement of optical power in the microwatt to milliwatt power range at NBS is based upon a standard reference laser calorimeter called the C-series calorimeter. The C-series calorimeter, which is used as a national standard for the measurement of laser power or energy, was designed to be rugged, easy to use, and capable of measuring energy over a wide range of laser wavelengths. This calorimeter, in conjunction with various laser sources and a calibrated beamsplitter measurement system, is used to calibrate transfer standards which are, in turn, used to calibrate other optical power meters. This paper will review the operation and capabilities of this standard calorimeter and associated measurement system, and will summarize the uncertainties associated with these energy calibration measurements.

Standard Calorimeter

To measure laser power or energy accurately, the typical characteristics of laser radiation (for example, coherence, nonuniform intensity spatial profile, and potentially high irradiance levels) must be considered and accommodated. Designed specifically to measure the radiation emitted by lasers, the C-series calorimeters (Refs. (1) & (2)) were developed at NBS in the early 1970's and are still in use today as national reference standards for the measurement of laser energy. These devices were built to measure the radiation of lasers operating at wavelengths and powers commonly used in industry and the military and thus are able to support a wide variety of laser types. The calorimeters have a relatively simple structure and, consequently, their behavior can be analyzed in a straight-forward manner starting with first principles of thermodynamics or by linear system analysis.

The basic operation of these calorimeters involves absorption of the laser radiation with concurrent conversion of the electromagnetic energy to thermal energy. The subsequent temperature increase is monitored by a thermal sensor (thermocouples) which produces a corresponding electrical

voltage. The calorimeters are built so that electrical energy (which can be measured more easily and accurately than optical energy) can also be used to generate thermal energy inside the device. This electrical heater provides a means to determine the electrical voltage response relative to the amount of electrical energy input. If optical energy deposition has the same effect on the calorimeter as does the electrical energy deposition (this possible error source will be discussed later), the calorimeter can be used to compare the electromagnetic energy from a laser to the amount of electrical energy which causes an equivalent voltage response.

The calorimeter consists principally of an absorbing cavity suspended inside a temperature controlled metal jacket. The purpose of the absorbing cavity is to capture all the laser radiation and convert it to thermal energy. To collect all the energy of the laser beam the cavity must be large enough (in diameter) to allow the whole beam to enter and also configured to minimize the amount of radiation that is scattered or reradiated back out the cavity. The absorbing cavity has a heater wire attached to provide a means of heating the cavity with electrical energy. The temperature controlled jacket which surrounds the absorbing cavity provides an operating environment which does not vary with time. Due to this constant temperature environment the calorimeter is often referred to as an "isoperibol" calorimeter. Temperature sensors are used to measure the temperature difference between the absorbing cavity and the temperature controlled jacket.

The C-series calorimeters were designed specifically to measure CW (continuous wave) radiation of low to medium power laser sources (1 mW to 1 W). As shown in the cross sectional view in Fig. 1, the calorimeter consists of a double cylinder absorbing cavity suspended by thermocouples inside a temperature controlled jacket. The two cylinders which compose the calorimeter itself are made of thin-walled (≈ 0.1 mm) copper and are connected to each other by a copper ring near the midsection of the two cavities.

The inside surface of the absorbing cavity is coated with a flat black paint which acts as the laser energy absorber for this device. The cavity is 9.5 mm in diameter and 19 cm in length. The back wall is angled so that the incoming laser beam has an angle of incidence (relative to the surface normal) of 30° and thus directs any specular reflection component to the paint on the side wall. The flat black paint has an absorptivity of about 97-98% for the wavelengths of concern and most of the radiation not absorbed is diffusely scattered with a hemispherical distribution from the point of contact at the back of the cavity. Any radiation scattered, reflected, or reradiated back out of the cavity will consequently not contribute to heating the cavity and will cause an error in the measurement process if not accounted for. The cavity length is a compromise between minimizing the amount of escaping radiation and maximizing the sensitivity of the calorimeter. As the cavity length is increased the amount of escaping radiation is reduced, but because of increased thermal mass the sensitivity decreases. In addition, a longer cavity increases the time constant of the calorimeter system and thus increases the time required to perform energy measurements. The time constant of the system using the dimensions listed

above is approximately 15 min and sequential measurements are made at about 45 min intervals.

The temperature of the calorimeter is monitored by thermocouples that are connected in series and have one junction attached to the surface of the outer shield cavity and the other junction attached to the temperature controlled jacket. The thermoelectric voltage produced by the thermopile is thus proportional to the temperature difference between the shield cavity and the temperature controlled jacket. This temperature controlled jacket is made of copper and its temperature is controlled to better than 0.0001°C by a resistance bridge circuit which balances at a temperature of about 33°C .

The entire volume inside the temperature controlled jacket is evacuated ($\approx 10^{-6}$ Pa) and accordingly a window is needed at the front of the calorimeter. The windows currently in use are made of fused silica and each has a wedge angle of 1° . The wedge is necessary to prevent interference effects caused by the coherent radiation from affecting the window transmittance. The inner surface of the temperature controlled jacket as well as the surfaces of the shield and absorbing cavities (except for the black paint surface) are gold plated to minimize and stabilize the radiative heat flow between the surfaces.

To allow electrical energy deposition, a manganin heater wire ($\approx 100\ \Omega$ resistance) is wound around the inner absorbing cavity near the location where most laser energy is absorbed. Electrical calibration measurements on these calorimeters have shown that best results are obtained if the energy deposition time is kept below 300 s. This constraint combined with the maximum usable energy determine the limits of this device. The maximum power density which can be safely absorbed by this model is limited by the damage threshold of the black paint absorber and is about $200\ \text{W}/\text{cm}^2$. Although the black paint is highly absorbing over the wavelength band of $0.4\text{--}25\ \mu\text{m}$, the fused silica windows limit the operating range to approximately $0.4\text{--}2\ \mu\text{m}$.

The electrical calibration of this device is accomplished by putting a constant, DC electrical current through a heater wire thermally bonded to the absorbing cavity and then monitoring the output voltage response of the temperature sensor as a function of time. The power dissipated by the heater is obtained by monitoring the voltage across the heater wire along with the voltage across a calibrated reference resistor connected in series with the heater wire.

For either an electrical measurement or a laser measurement, the voltage output of this calorimeter (shown in Fig. 2) can be expressed mathematically as an infinite series of exponential terms whose relative contributions change during the measurement. Eventually, after energy deposition has been discontinued, the voltage curve is predominately characterized by a single exponential term and at this time the exponential coefficient is defined as the "cooling constant." The cooling constant has units of s^{-1} and is the reciprocal of the time constant of the instrument. Once the cooling constant and the area under a portion of the voltage curve have been determined, the amount of absorbed energy can then be calculated (Ref. (3)).

Measurement System

To measure laser energy and to compare other detectors to the primary standard discussed above, the measurement system shown in Fig. 3 is used. The laser beam transmittance is controlled by a timed shutter which allows the laser beam to enter the measurement system for a predetermined time interval. When the shutter is open, the beam is incident onto a wedged beam splitter where the specular reflection from the first surface of incidence is directed into one detector and the main transmitted beam passes to another detector. The reference calorimeter is placed in one of either of the two beams and the meter to be compared is placed in the other beam. Before a calibration measurement, the ratio of energy in the transmitted beam relative to the amount of energy in the reflected beam is determined for the particular beamsplitter at the wavelengths being used. The energy measured by the standard calorimeter, in conjunction with the beamsplitter ratio is used to calculate the energy incident upon the test meter. The output response of the test meter is then compared to the calculated incident energy.

The function of the beamsplitter is to allow simultaneous measurement of the laser radiation by the two detectors being compared and thus eliminate the dependence on a stable laser (assuming both detectors are measuring energy). The beamsplitter also extends the range of the standard calorimeters since the beamsplitter ratios typically used at NBS vary from 10:1 to 27:1. The splitters are wedged ($\approx 1^\circ$) to preclude interference effects and to spread the emerging transmitted and reflected beams sufficiently apart so that they can be used or treated individually. To minimize ageing effects and to facilitate cleaning, the beamsplitters in use have no optical coatings. The splitters are positioned so that the angles of incidence are kept as small as possible ($\approx 1^\circ$) in order to reduce laser beam polarization effects on the splitter ratio. Because of the small angle of incidence the distance between the detectors and the splitter is made as large as possible to allow the various beams to spread enough that detectors can be placed into the beam being used without interfering with any other beams in that area.

The beamsplitter is calibrated by performing two sets of measurements for each wavelength for which the splitter will be used. With two detectors in the configuration shown in Fig. 3, a set of beamsplitter measurements are recorded and an average ratio is calculated by dividing the reading of the meter in the transmitted beam by the reading of the meter in the reflected beam. The two detectors are then interchanged and another set of beamsplitter ratio measurements are made and a second ratio is calculated. The absolute beamsplitter ratio is then determined by calculating the square root of the product of the two beamsplitter ratios.

Ideally, all systematic errors will cancel; therefore, as long as the detectors are linear they need not be calibrated to obtain the beamsplitter ratio. The same number of measurements are performed in each of the two configurations and any ancillary electronic equipment is interchanged along with the detectors with which they are used. Table 1 lists the beamsplitter ratios presently used in the C-series measurement system.

TABLE 1**C-SERIES MEASUREMENT SYSTEM PRIMARY BEAMSPLITTER**

<u>Material</u>	<u>Wavelength</u>	<u>Beamsplitter Ratio</u>	<u>Standard Deviation (%)</u>
Sapphire	488.0 nm	11.43	0.09
	514.5 nm	11.44	0.07
	632.8 nm	11.53	0.07
	1.06 μm	11.66	0.08
	1.32 μm	11.74	0.11

When it is necessary to perform measurements below the power levels achieved using the primary standards and the beamsplitters listed above, a precision multiple reflection attenuator (Ref. (4)) is used. The precision attenuator (see Fig. 4) is a wedged beamsplitter which has high optical purity and ultra-smooth, polished surfaces. Using the values for (1) the refractive index of the material, (2) the splitter wedge angle, (3) the angle of laser beam incidence, and (4) the laser beam polarization state, the relative powers of the reflected and transmitted beams can be calculated using Fresnel's laws of reflection. Thus, if the main transmitted beam is monitored with a standard detector at a relatively high power, the powers contained in the other emerging beams can be calculated and used for low power measurements. The optical wedge used in this manner is a precision attenuator which allows calibrated measurements to be performed at low levels of power or energy. By experimentation, it has been observed (12) that the wedge attenuator technique (using fused silica) is suitable for attenuations in the range of 1-25 000. The absolute power levels of the high order, internally reflected beams which have attenuations greater than about 25 000 cannot be determined as accurately due to surface scattering effects and thus are not normally used for calibration measurements.

Measurement Uncertainties

The uncertainty estimates for the NBS laser energy measurements are represented and combined using a method frequently called the PTB approach (Refs. (6) & (7)). Using this approach as a guideline, the uncertainty estimates are accomplished by assessing and combining the limits or bounds of the various error components which apply to a particular measurement process. To establish these limits, the errors are separated into (1) systematic or bias errors whose magnitudes are determined by subjective judgement and (2) random errors whose magnitudes are obtained from analyzing the precision of a series of measurements. The assumptions and procedures for defining these error limits are as follows:

- a) All the systematic error components are assumed to be independent and have rectangular or uniform distributions (that is, each has an equal probability of being within the region, $\pm\delta_1$, and zero probability of being outside that region). If the distribution is rectangular, an approximation to the standard deviation, σ_1 , for each systematic error component is equal

to $\delta_i/3^{\frac{1}{2}}$ and the total "standard deviation" is approximated by $(\sum \sigma_i^2)^{\frac{1}{2}}$ where the summation is performed over all systematic error components.

b) The random errors are assumed to be normally distributed and consequently the standard deviation for each component is

$$S_r = ((\sum x^2 - (\sum x)^2/N)/(N-1))^{\frac{1}{2}}, \quad (1)$$

where the x values represent the individual measurements and N is the number of x values used for a particular random error component. The standard deviation of the mean is $S_r/N^{\frac{1}{2}}$, and the total standard deviation of the mean is $(\sum (S_r^2/N))^{\frac{1}{2}}$, where the summation is carried out for all the random error components.

c) The total uncertainty is determined by combining the random and systematic uncertainty estimates in quadrature and multiplying this result by a factor of three. The multiplicative factor of three is commonly used by NBS in quoting total uncertainties. The total uncertainty is

$$\text{Total Uncertainty} = 3(\sum \sigma_i^2 + \sum (S_r^2/N))^{\frac{1}{2}}. \quad (2)$$

d) The number of decimal places used in the final reported values obtained from a series of measurements (for example, calibration factors or beamsplitter ratios) are determined by expressing the total NBS uncertainty to two significant digits (18) & (19). For example, if a reported value of 94.27162, has an estimated total uncertainty of $\pm 2.32\%$ the uncertainty (expressed to two significant digits) is 1.9 and consequently, one decimal place would be used to report the final number (94.3).

The major error sources in the standard calorimeter have been separated into the following categories:

- a) Thermal Inequivalence
- b) Absorptivity
- c) Electrical Heater Leads
- d) Ancillary Electronics
- e) Window Transmission
- f) Electrical Calibration Factor Precision.

The error sources in categories a-e may consist of both systematic and random components while the error source in category f is considered as purely random (the systematic components of electrical calibrations are contained in the other categories).

a) Thermal Inequivalence: The characteristic voltage response of a calorimeter can be affected by changes in the location and spatial distribution of the thermal energy source within the absorbing cavity. This situation can potentially occur when using both electrical and laser energy to generate heat within the cavity if they each generate the heat in

different physical locations. Using laser beams with different spatial power density profiles and/or different alignments relative to the calorimeter may also contribute to this error source. To minimize the influence of energy source location, the C-series calorimeter was designed with a shield cavity surrounding the absorbing cavity. The thermal sensors for these units are located on the shield cavity, thus forcing the heat, no matter where it has been generated within the absorbing cavity, to travel to the shield cavity through the connecting ring which joins the two cavities. As a result, the connecting ring appears to the thermal sensors as a secondary thermal source and minimizes the inequivalence effect.

The measurement of internal energy change (during the period when the voltage can be expressed as a single exponential term) is not affected by the thermal source location, thus, the inequivalence error can be minimized by reducing the amount of the heat transferred from the calorimeter relative to its change in internal energy. This is accomplished by gold plating the surfaces inside the calorimeter to reduce the radiative heat transfer and by evacuating the calorimeter chamber thus decreasing convection heat transfer inside the calorimeter. The heat transfer uncertainty is also minimized by beginning a measurement after the calorimeter has cooled until the voltage is changing slowly with time. For optimal results, time intervals of at least three to four time constants between successive measurements are normally used.

The magnitude of the inequivalence error for the C-series calorimeter was estimated by performing electrical calibrations using heaters mounted at different locations within the cavity. The resulting variation of the electrical calibration factor is then used as a measure of the laser and electrical inequivalence error as well as the error due to using laser beams of different alignments and intensity profiles on the same device. In the C calorimeter the normal heater is mounted near the closed end of the absorbing cavity while the auxiliary heater used to test the inequivalence is mounted near the midsection of the same cavity.

b) Absorptivity: Any laser radiation which enters the calorimeter cavity but is reflected, scattered, or reradiated out will not contribute to heating the calorimeter and thus will generate an error in an energy measurement. The standard calorimeter cavities are designed to minimize this backscattered or escaping radiation by coating the absorbing surfaces with highly absorbing black paint and by making the cavity lengths sufficiently long that the solid angle window to the outside world as seen by the energy absorption area is kept small. The back absorbing wall of the C-series instrument is angled so that any specular reflection component is directed to the wall of the painted cavity. Due to the nature of the absorbing paint, this device loses radiation mainly by diffuse scattering.

The magnitude of the radiation loss error has been estimated by mounting an auxiliary calorimeter to the front of the main calorimeter and then performing a laser measurement with the two-calorimeter configuration (Ref. (10)). The auxiliary calorimeter has (at its center) a small hole through which the laser beam can pass and be absorbed by the cavity of the main calorimeter. The radiation coming back out of the main calorimeter is

detected by the auxiliary calorimeter, taking into account its reflectance and the hole through its center. The temperature increase of the auxiliary calorimeter will be due not only to the radiation scattered and reflected back out of the calorimeter but also to the radiation radiated from the absorbing surface. Because the laser energy is deposited over a smaller area on the absorbing surface than the electrically generated energy, the resulting localized temperature increase during a laser measurement is greater and thus causes relatively more energy to be radiated from the surface than when performing an electrical measurement at the same power level. This energy radiated from the absorbing surface is minimized by avoiding power density levels which cause large temperature increases.

c) Electrical Heater Leads: This error is due to heat lost in the electrical leads of the calorimeter heater during electrical calibrations. The electrically generated heat calculations assume that all heat corresponding to the voltage change as measure across the heater is deposited on the outer surface of the absorbing cavity of the calorimeter in close proximity to the location where the laser radiation is absorbed. Since the electrical leads of the heater wire have a resistance value, some heat is generated in these wires and can thus cause a perturbation in the heat flow pattern. To minimize this error the potential leads are attached midway between the surface of the calorimeter and the inner surface of the surrounding temperature controlled jacket. The magnitude of this error is estimated by calculating the joule heating occurring in the leads and then assessing the distribution of this heat within the calorimeter.

d) Ancillary Electronics: This uncertainty category accounts for the errors introduced into the measurement process by the electronic equipment used during electrical and laser calibration measurements. Primarily, these instruments consist of digital voltmeters, nanovolt amplifiers, digital timers, and standard resistors. These devices are calibrated against NBS-traceable standards and have uncertainties much smaller than most of the other calorimeter uncertainties.

e) Window Transmittance: The C-series calorimeters contain windows whose spectral transmittance properties must be determined before use so that the energy actually incident on the front surface of the window can be determined. The spectral transmittances of the fused silica windows now in use in these devices were measured by the Radiometric Physics Division of NBS and their results are currently used for the uncertainty estimates. It is expected that future transmission values and uncertainty estimates will be obtained in our laser calibration laboratory using appropriate laser sources along with fast, linear detectors to reduce the magnitude of this error source.

f) Electrical Calibration Factor Precision: The electrical calibration factor (K_e in Table 2) for each standard calorimeter is obtained by calculating the mean of a number of electrical deposition measurements which have been performed over a period of time. The fluctuations of the individual measurement results are assumed to be random and, therefore, the uncertainty is estimated by calculating a standard deviation (S_e in Table

2). The current electrical calibration values used for the NBS C-series calorimeters are summarized in Table 2.

TABLE 2
ELECTRICAL CALIBRATION RESULTS

<u>Series</u>	<u>Serial No.</u>	<u>Amplifier Gain</u>	<u>Energy Range (J)</u>	<u>No. of Measurements</u>	<u>From</u>	<u>To</u>	<u>K_o (J/mV)</u>	<u>S_r (%)</u>
C	41	10 ⁵	0.2- 0.7	27	1976	1987	4.2506	0.13
		10 ⁴	1.4- 2.8	25	1976	1987	4.2504	0.05
		10 ³	8.2-22.6	17	1976	1987	4.2416	0.05
	44	10 ⁵	0.3- 0.7	19	1976	1987	4.8583	0.07
		10 ⁴	1.5- 4.2	24	1976	1987	4.8601	0.10
		10 ³	8.5-23.3	18	1976	1987	4.8515	0.08
	46	10 ⁵	0.3- 0.6	28	1976	1987	4.9450	0.10
		10 ⁴	1.6- 4.3	24	1976	1987	4.9465	0.06
		10 ³	8.6-23.7	20	1976	1987	4.9443	0.05

g) Uncertainty Summary: Table 3 summarizes the magnitudes of the uncertainty estimates for the errors sources discussed above for the C-series calorimeters. The uncertainty totals as well as some of the uncertainty categories listed below consist of both random and systematic error components, but for convenience, these were combined to obtain the values listed in Table 3. In practice, the random and systematic uncertainty components are treated separately until the total measurement uncertainty is determined then they are combined with the other pertinent measurement uncertainties as discussed in the error analysis section above. The uncertainty values used for a particular measurement process (at a specific wavelength and energy level) may vary slightly from the representative values listed in the table.

TABLE 3
CALORIMETER UNCERTAINTIES

<u>Source</u>	<u>Magnitude</u>
1. Inequivalence (δ_1)	0.19 %
2. Absorptivity (δ_2)	0.01 %
3. Heater Leads (δ_3)	0.01 %
4. Electronics (δ_4)	0.02 %
5. Window Transmission (δ_5)	0.12 %
6. Electrical Precision (S_r)	0.08 % (N=26)
Total Uncertainty	0.39 %

Besides the uncertainties of the standard calorimeter the other major source of uncertainty is the beamsplitter ratio. Since the beamsplitter ratio is determined by the interchange method described earlier, its uncertainty is assumed to be composed of only a random component, the systematic components having cancelled during the interchange calibration process. Typical standard deviation values for the NBS C-series system beamsplitter are listed in the last column of Table 1. Whenever possible, polarized beams are used to perform the energy measurements; however, when unpolarized beams are used, an associated uncertainty of the beamsplitter ratio must be included. This polarization uncertainty is estimated by assuming that the effect on the beamsplitter ratio due to polarization changes must be less than the ratio change between a vertical linear polarization state and a horizontal linear polarization state. The ratio change for these two polarization states is then calculated (for the appropriate angle of incidence and wavelength) and is used for this worst case estimate.

The random uncertainty of the beamsplitter ratio may be eliminated from separate consideration by performing the calibration measurements in two sets in similar fashion to that used in calibrating the beamsplitter itself. In this procedure, a set of measurements are made with the reference standard and test meter in one configuration and then another set of measurements are performed with the meters interchanged. If the two meters are linear, the beamsplitter ratio value is constant but is not explicitly used and thus does not enter into the uncertainty calculation as a separate error source. This technique is not normally used for NBS laser calibration measurements due to the awkwardness of moving the standard calorimeters and because the meter being calibrated often does not have sufficient dynamic range. The uncertainties associated with the fused silica precision attenuator for the typical NBS measurements range from 0.04 to 0.69 % (Ref. (11)).

In performing comparison measurements using the standard calorimeters and the laser measurement system to characterize a test meter, typically a set of ten measurements are performed and the mean value of the results of those ten measurements is used as the reported calibration factor for that

instrument. The measurement uncertainty for that determination includes the uncertainties discussed above plus an uncertainty of the mean value due to the random scatter of the ten measurements. Thus, a standard deviation, S_r , is calculated and combined with all the other pertinent random uncertainties. In addition, if any other electronic instruments (such as amplifiers and voltmeters) are used to modify or monitor the test meter signal, their estimated uncertainties must also be included. If the test meter has an analog meter display that is read by an operator, an estimated reading error is also included in the total uncertainty estimation.

Since the standard calorimeters measure energy, laser stability (within operational limits) does not affect the measurement accuracy as long as the test meter also measures energy. However, if the test meter measures power, then laser stability may contribute to the inaccuracy of the calibration since an energy measurement of the standard then must be compared to the power measurement of the test meter. Integrating the analog voltage output of a power meter allows an energy measurement to be used (Ref. (12)) to determine the calibration factor and thus eliminate this possible error source. If no analog output of the power meter is available (or if the instrument owner does not want it used), the power reading must be compared to the energy reading of the standard by converting that energy reading to average power (that is, dividing the energy by the laser exposure time). This comparison of the calculated average power to the power measured by the test meter has an associated uncertainty which depends on the degree of laser stability and thus must be estimated and included in the error analysis. If the laser fluctuations are random, the consequential effects will presumably be imbedded in the randomness of the results and thus the calculation of the standard deviation for a large number of measurements may include this error source.

Measurement Services and Capabilities

Using the standard calorimeters and the laser measurement system discussed above, NBS offers two formal services to the public for laser power and energy measurements: a) regular calibrations and b) Measurement Assurance Program (MAP) intercomparisons.

The regular calibrations are accomplished by comparing a customer's laser radiation detector to the appropriate standard calorimeter using the wavelength and power or energy specified by the customer. In some cases a transfer standard is used as the reference standard for these comparison measurements. The measurements are performed at cost and typically it takes one to two days to accomplish a set of ten measurements at a particular wavelength and power level.

The MAP intercomparisons (Ref. (13)) are performed by sending a well-characterized transfer standard to the participant who then calibrates this device using his standard and measurement system. The transfer standard is then returned to NBS along with the measurement data. Both before and after the transfer standard is shipped, NBS performs calibration measurements on the instrument to assure continuity. This program inherently provides a more thorough analysis of the participant's measurement capability than merely

calibrating a standard since the entire measurement process used by the participant is compared to that of NBS.

Both of these services listed above are available for the wavelengths and power or energy ranges contained in Table 4.

TABLE 4

MEASUREMENT CAPABILITIES

<u>Standard</u>	<u>Wavelength Range</u>	<u>Power Range</u>	<u>Typical Uncertainty</u>
C	488.0, 514.5 nm	1 μ W - 1 W	0.5 - 1.0 %
	632.8 nm	1 μ W - 20 mW	
* 830.	nm	100 μ W - 100 mW	
	1.06 μ m	1 mW - 1 W	
	1.32 μ m	100 μ W - 100 mW	
* 1.53	μ m	1 μ W - 1 mW	

* being established

In addition to the laser calibration capabilities listed in the table above, NBS also maintains calibrated and characterized transfer standards specifically to support the optical fiber community. These transfer standards are available by special arrangement with NBS. More information on measurement services offered by NBS can be obtained from Ref. (14).

The uncertainty estimates described earlier represent the results of a recent reevaluation of the error magnitudes of the C-series calorimeter and associated measurement system. The original uncertainty estimates were assessed during the initial implementation of the calorimeter system and due to the lack of measurement data at that time, a conservative approach was used. The recent reevaluation effort was undertaken to review the original estimates in light of the accumulated measurement history and to establish realistic and credible uncertainty assessments without being overly conservative. Efforts to reduce the error magnitudes associated with our present standards are continuing, and new detector designs are being investigated for possible use as absolute standards for optical power measurements.

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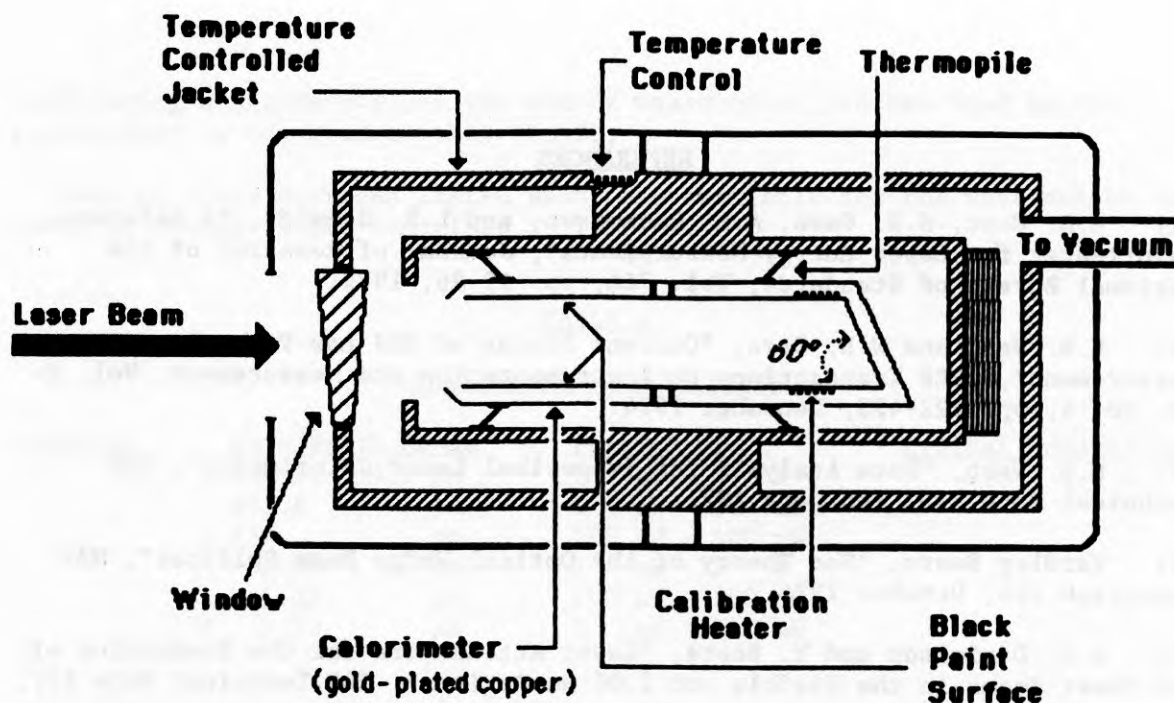


Figure 1. C-Series Calorimeter Cross Section

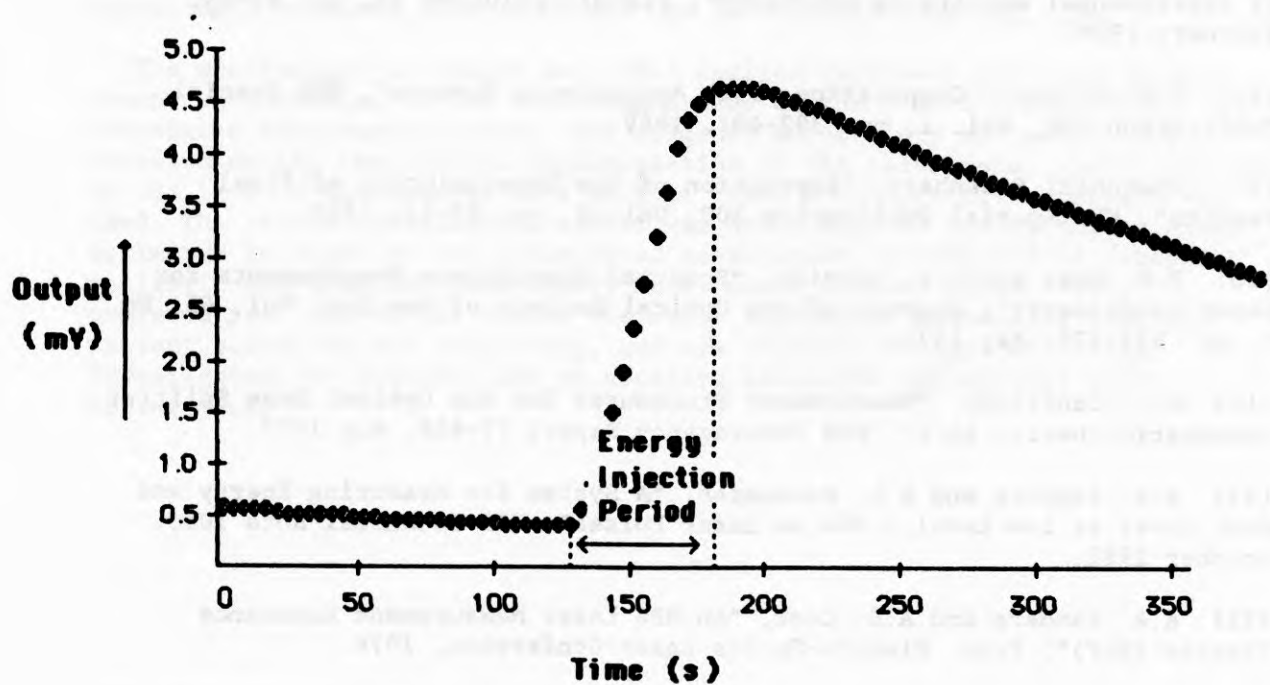


Figure 2. Calorimeter Voltage Output

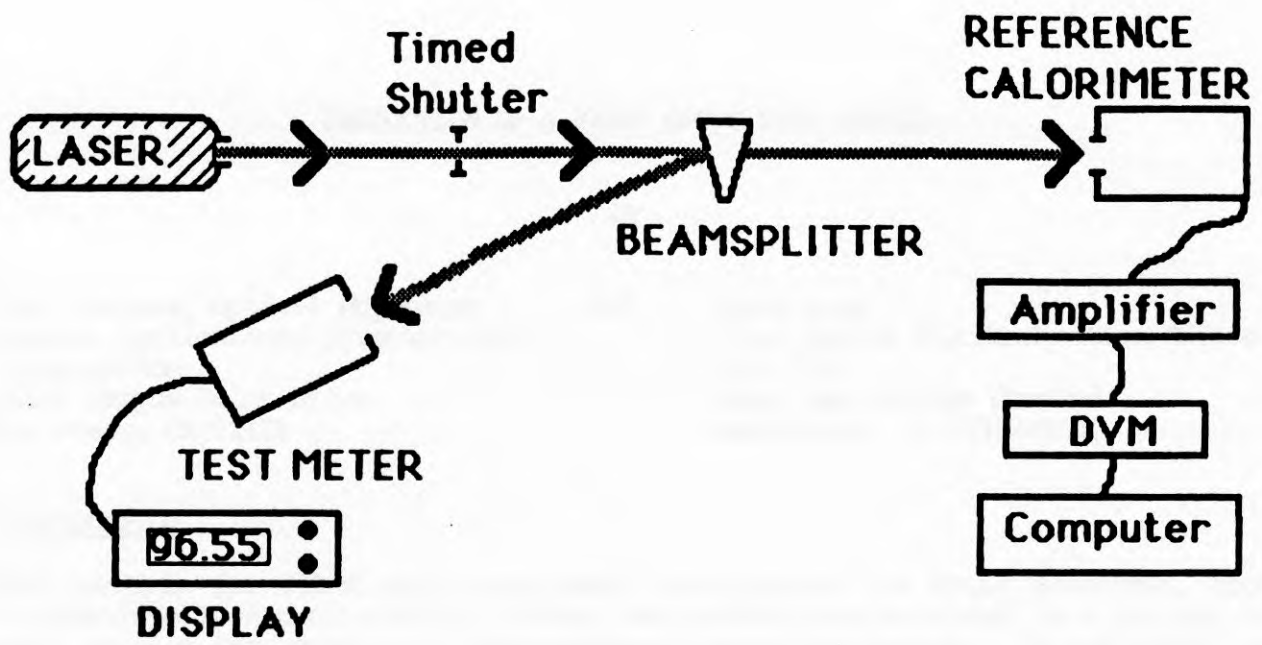


Figure 3. Measurement System Configuration

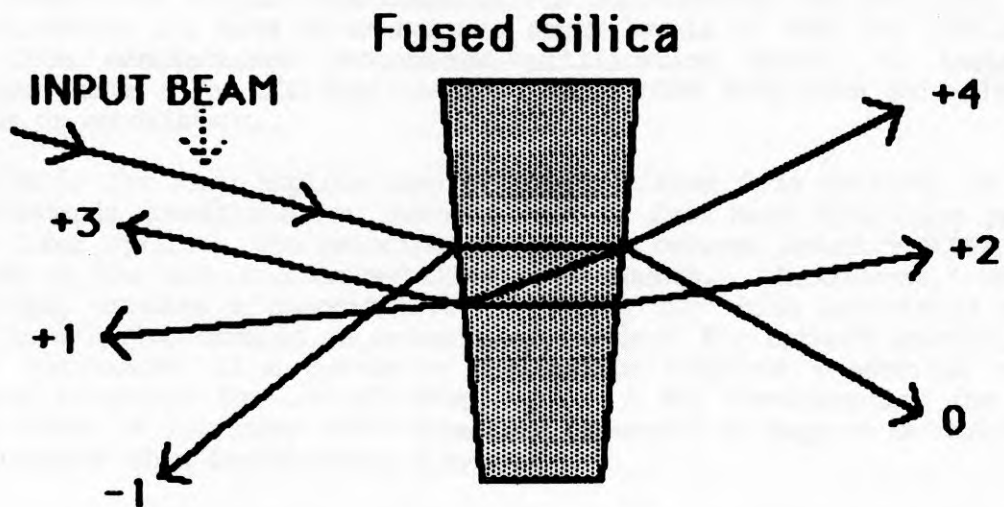


Figure 4. Precision Attenuator