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CALORIMETERS FOR DIAGNOSIS OF LASER-FUSION EXPERIMENTS

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REA

CALORIMETERS FOR DIAGNOSIS OF LASER-FUSION EXPERIMENTS

ABSTRACT

A variety of calorimeters have been developed for measuring ions, x-rays, and scattered radiation emanating from laser-pulse-imploded fusion targets. The ion and x-ray calorimeters use metal or glass absorbers to reflect or transmit most of the scattered laser radiation; the versions using metal absorbers also incorporate a differential construction to compensate for the fraction of the scattered laser radiation that is absorbed. The scattered-radiation calorimeters use colored glass to absorb the radiation and a transparent glass shield to remove ions and x rays. Most of the calorimeters use commercial semiconductor thermoelectric modules as the temperature sensors.

INTRODUCTION

In laser-fusion experiments, part of the radiation impinging on the target is absorbed and then reemitted mostly as heavy ions and as x rays, and part is scattered from the target without being absorbed. Various calorimeters have been developed at LLL for measuring these three forms of energy; this paper will describe in some detail their construction and operation.

Other detectors have been used extensively for all these measurements, but calorimeters have several characteristics that make their use attractive. Among these are relative insensitivity to the charge of ions, linearity of response with respect both to ion and x-ray energy and to flux density, and capability of absolute calibration. The sensitivity (threshold detection limit) is relatively low, but it is more than adequate for many measurements at the laser energies now in use. The time constants of calorimeters are very long compared to the time scale of the target implosion; the obtained information is for the integrated flux for the whole time span of the experiment, without time resolution.

Target-implosion experiments produce energetic heavy ions, electrons, x rays, and neutrons, always accompanied by scattered laser radiation. The energy in the electron flux is always small compared to that of the ions, and the neutron flux is below the level of calorimetric detectability. Three general categories of calorimeters have therefore been built for measurement of ions, x rays, and scattered radiation; the instruments are designed to discriminate to a considerable extent among these three fluxes. The ion

calorimeters are used for experiments where the ratio of x-ray energy to ion energy is low; however, they also measure most of the x rays and electrons accompanying the ions. The x-ray calorimeters are for experiments in which the ratio of x-ray energy to ion energy is high; they are used with various combinations of deflecting magnets and filters to remove at least part of the ion flux. Most of the ion and x-ray calorimeters discriminate against the scattered laser radiation by either a reflection-compensation method or a transmission method. In the compensation method, the difference in the temperature rise of two metal receivers is observed; both have a high reflectivity so as to absorb only a small part of the scattered laser radiation, and one has a glass shield to remove the ion and x-ray flux; the difference therefore represents the ion and x-ray flux. The transmission method uses glass disks to absorb the ion and x-ray flux while the scattered laser radiation passes through. The calorimeters for measurement of scattered radiation use glass shields in front of the absorbers to remove the ions and most of the x rays.

The numbering of the various models described below represents the approximate chronological order of development. Earlier designations of LC-1 to LC-14 and LC-20 are laser-beam calorimeters.^{1,2}

CALORIMETRIC PRINCIPLES

The methodology used with all of these calorimeters is known as the isoperibol (also "semiadiabatic" or "isothermally-jacketed") method. In this, it is assumed that the surroundings of the calorimeter are at a constant temperature and that the temperature of the calorimeter, in the absence of heat inputs other than heat exchange with the surroundings, follows the differential equation

$$dT/dt = -k(T-T_{\infty}), \quad (1)$$

where T_{∞} is the effective average temperature of the surroundings, which the calorimeter temperature approaches asymptotically. When a brief input of energy is made to the calorimeter, the temperature changes as shown in Fig. 1. A corrected temperature rise is operationally defined as

$$\Delta T = T_3 - T_1 + k \int_{t_1}^{t_3} (T - T_{\infty}) dt. \quad (2)$$

Fig. 1. Time-temperature curve of an isoperibol calorimeter.

This has been discussed in greater detail elsewhere.³ For present purposes, it is usually adequate to fit a straight line to an arbitrary section of the curve, t_3 to t_4 , extrapolate it to T_2 , and take $T_2 - T_1$ as proportional to ΔT . In either event, the method of comparative measurements is used (except for the glass calorimeters, LC-19 and LC-25, below): the ΔT produced in a target implosion experiment is compared with the ΔT produced in a calibration experiment by electrical heating or some other known amount of energy.

In the isoperibol method, k (the "thermal leakage modulus" or "cooling constant") is usually made as small as possible in order to minimize the last term in Eq. (2). This is the reason for the alternate designation, "semiadiabatic." If the last term were zero, the condition would be the same as that of an adiabatic calorimeter, in which the jacket temperature is kept equal to that of the calorimeter to eliminate heat transfer. The isoperibol method can be contrasted with the conduction ("heat-flow" or "steady-state") method, which is frequently used for measurements of both the power and energy of lasers. In this method, k is made larger; for CW power measurements, the steady-state offset $T_p - T_o$ (Fig. 2a) is proportional to the power, and for pulse-energy measurements the area under the time-temperature curve, integrated until it returns to the original value, is proportional to the energy (Fig. 2b).

In considering calorimeter characteristics, it is frequently convenient to use the cooling time constant, τ , which is k^{-1} , or the cooling half-time, $t_{1/2}$, which is $0.693 k^{-1}$.

Except for the glass disk calorimeters (LC-19 and LC-25) and the box calorimeter (LC-16), all these calorimeters are of twin construction. In some, this is partly for radiation compensation, as discussed above; but it also serves to improve the apparent temperature stability of the calorimeter. The twin construction involves the use of two calorimetric bodies, one with the working absorber and the other with a dummy of similar construction. The difference in temperature of the two, rather than the temperature of the working absorber alone, is measured; thus changes of calorimeter temperature resulting from changes in environmental conditions such as the temperature of the surroundings, are canceled out to the extent that these changes similarly affect the working and dummy sides.

Fig. 2. Time-temperature curves of a conduction calorimeter: (a) power measurement; (b) energy measurement.

THERMOELECTRIC MODULES AND TEST APPARATUS

All of the calorimeters except the glass-disk type use commercial semiconductor modules as the temperature sensors. These are manufactured primarily for use as Peltier coolers for electronic components but are also useful as high-sensitivity transducers for measurement of temperature difference. Compared with metal-wire thermopiles, they have the advantages of giving about ten times the voltage output per pair of thermoelements, and they are available as assembled multipair units that can be simply cemented into place.

A test apparatus, shown in Fig. 3, was built to measure the sensitivity and the thermal conductance of the modules. The module under test is placed between an aluminum base plate ($25 \times 254 \times 305$ mm) and a copper plate ($3.2 \times 51 \times 51$ mm) with thermal conducting grease on the surfaces. A wire heater is cemented to the upper surface of the copper plate, and a chromel-constantan thermocouple is provided with one junction on the copper and one on the aluminum. The heater is energized at a constant power to give a steady state temperature differential of about 20 K. In a comparison measurement, the copper plate is raised the same distance from the aluminum on small blocks of plastic foam, and the power necessary to give the same temperature differential is measured; the difference of the two powers divided by the temperature differential is the thermal conductance of the module. The module output, which is measured simultaneously during the first measurement, divided by the temperature differential is the thermometric sensitivity of the module.

This apparatus has also been used for measurement of the thermal conductivities of glasses, plastics, epoxy cements, thermal-conducting greases, and other materials used in laser calorimeters.

A similar apparatus was built for rapid measurement of only the thermometric sensitivity of large numbers of modules. A cylindrical aluminum block, 76 mm in diameter and 51 mm high, is fitted with a heater and maintained at a temperature about 20 K above that of a massive aluminum base plate; a thermocouple is used to measure the temperature differential. The modules are measured in groups of three; they are placed 120° apart between the lower face of the heated block, near its circumference, and the base plate, with thermal-conducting grease on the interfaces. The module outputs reach a constant value a few seconds after the system is assembled, and measurements are reproducible to about 1%.

Fig. 3. Test apparatus for thermoelectric modules.

Modules from two manufacturers were used: Nuclear Systems, Inc. (NSI) and Borg-Warner Corporation (BWC). Approximate values of the characteristics of the various models are given in Table 1. The modules all have sensitivities near 370 μV per degree per pair of thermoelements.

Table 1. Characteristics of thermoelectric modules.

Model	Height (mm)	Upper plate size (mm)	Pairs of thermo- elements	Sensi- tivity ($\mu\text{V}\cdot\text{K}^{-1}$)	Thermal conduc- tance ($\text{W}\cdot\text{K}^{-1}$)	Electrical resistance (Ω)
NSI-1AB	5.1	5.0 $\times$ 6.2	9	3500	0.009	0.80
NSI-2AD	3.4	4.2 $\times$ 4.2	7	2700	0.011	0.35
BWC-110-12	2.6	4.0 $\times$ 6.1	12	4100	0.009	1.13
BWC-930-7	5.1	8.5 $\times$ 8.9	7	2600	0.018	0.19
BWC-930-11	5.1	8.5 $\times$ 13.1	11	4100	0.027	0.31
BWC-930-17	5.1	13.1 $\times$ 13.1	17	6400	0.040	0.50

All have plates of beryllium oxide on both faces. In all of the present calorimeters, the plates are cemented to the adjacent surfaces with silver-loaded epoxy having a thermal conductance of about $0.010 \text{ W}\cdot\text{cm}^{-1}\cdot\text{K}^{-1}$. The thermal conductivity of the thermoelectric element material is about $0.015 \text{ W}\cdot\text{cm}^{-1}\cdot\text{K}^{-1}$, and the area-to-length ratio is much smaller for the thermoelements than for the beryllium plates and the silver epoxy; so most of the temperature difference between the calorimetric bodies and the base blocks appears across the thermojunctions in the module.

In calorimetry, such modules as these are most often used for conduction calorimeters where the thermal leakage modulus, k , is deliberately made quite large. In isoperibol calorimeters, it is desired that k be small; this implies that the modules should have long legs of small cross-sectional area. The commercially available modules, designed for a different purpose, are not ideal for the present application, but they are adequate and convenient.

METAL-ABSORBER ION CALORIMETERS

Four models of these have been built. The first three use aluminum absorbing surfaces; a literature survey suggested that aluminum would have

about the best practicable efficiency of absorption of ions (low losses of energy by sputtering, secondary electron emission, etc.). However, the literature is far from definitive for multiply-charged heavy ions over a range of energies; so the fourth model was built to compare the energy deposition in aluminum with that in other materials.

LC-15 Disk Ion Calorimeter

This was the first model developed, and it has been superseded by LC-17 and LC-18. The design is a twin, for thermal stabilization, somewhat similar to one version of the laser beam calorimeters,² but it has no compensation for scattered laser radiation. The construction is shown in Fig. 4. The copper base block is 25.4 mm in diameter and 12.7 mm long; the copper disks are 25.4 mm in diameter and 1.65 mm thick. The absorbers are aluminum, 12.7 mm in diameter and 1.60 mm thick. The thermoelectric modules are BWC-930-17.

The aluminum absorbers were burnished with fine abrasive paper, but the reflectivity was later found to be only about 65% at 1.06 μm . Because the design does not include compensation for scattered laser radiation, a correction has to be applied. Using photodiodes or other detectors, we base this correction on measurements of the scattered laser radiation near the calorimeter.

One side of LC-15-2 was fitted with an IRTAN-5 absorber, rather than with aluminum, to measure scattered radiation in 10.6- μm target irradiation experiments.

LC-17 Ring-and-Disk Ion Calorimeter

We will describe first the latest version of this calorimeter and then the minor differences of two earlier versions. Ten of the final version, designated LC-17-5 to -14, have been built. These are illustrated in Figs. 5, 6, and 7. The ion receiver is a disk, 19.05 mm in diameter; the compensating radiation receiver is a ring (22.28 mm i.d. and 44.09 mm o.d.). The absorbers are household aluminum foil, 0.025 mm thick, cemented with silver epoxy to copper plates, 3.18 mm thick. One thermoelectric module is cemented to the disk, and four, equally spaced, to the ring. The modules are NSI-1AB, except NSI-2AD for LC-17-11, -13, and -14. The modules are then cemented to an aluminum base block that is 50.8 mm in diameter and 25.4 mm thick. This assembly is

Fig. 4. LC-15.

Fig. 5. LC-17 ring-and-disk ion calorimeter.

Fig. 6. LC-17 ion calorimeter.

Fig. 7. LC-17 ion calorimeter.

mounted in a cylindrical aluminum jacket whose interior is grooved and black-anodized to minimize the effect of scattered laser radiation reflected from the walls.

The open end of the jacket supports an ion shield of WG-280 glass, 1.0 mm thick. This prevents ions and most of the x rays from reaching the ring. Since the shield is not antireflection coated, it experiences Fresnel reflection losses at two surfaces to give a transmittance of 92.5%.

The thermoelectric modules are connected as shown in Fig. 8. The 10- Ω resistors, R_1 , R_2 , R_3 , and R_4 , are matched within 0.1%; they serve to eliminate the effect of small differences in the resistance of the four thermoelectric modules on the ring. Resistor R_5 is also 10 Ω ; it serves to give a well-defined resistance that is later shunted by R_6 . The ring and disk are first calibrated separately by electrical heating; an appropriate resistance, R_6 , is then added to make the sensitivity per unit area of the disk equal to 92.5% of that of the ring. Since the reflectivity of the absorber at 1.06 μm is about 93%, even if the intensity of the scattered radiation is equal to the ion-energy intensity, a mismatch of 1% in the sensitivities per unit area of the ring in the disk or of 1% in the average intensity of scattered radiation on the ring and the disk will produce an error of only 0.07% in the measurement of the ion-energy flux. An inequality of 1% in the reflectivity of the ring and the disk under the same conditions would give an error of 1% in the measurement.

The first version (LC-17-1) used BWC 930-7 modules, and the second (LC-17-2, -3, and -4) used BWC 930-11. Both used a square base block, (50.8 $\times$ 50.8 $\times$ 25.4 mm). No external housing was provided; the shield, which was of 1.6-mm-thick Pyrex-7740, was supported by four small posts mounted on the base block near the corners. Resistors R_5 and R_6 (Fig. 8) were not used; the weights of the copper ring and copper disk and the sensitivities of the modules were selected so that the sensitivities per unit area of the ring and the disk were equal within 1 or 2%. This design does not allow for the Fresnel reflection losses of scattered laser radiation at the glass ion shield. Therefore, under conditions of flux intensity of ions equal to that of scattered laser radiation, a 0.56% error will result if we assume a 93% reflectivity for the aluminum. This is usually negligible, but a correction can be made from auxiliary measurements of the intensity of scattered laser radiation, as for LC-15.

Fig. 8. Electrical connections of
LC-17 ring-and-disk ion calorimeter.

In addition, the first version (LC-17-1) had another small defect. The inner edge of the copper ring was not undercut as shown in Fig. 5. A small amount of the scattered laser radiation would strike the resulting cylindrical surface; since the angle of incidence would be nearly grazing, only a small fraction of this would be absorbed, but a small — probably negligible — error would result.

LC-18 Three-Disk Ion Calorimeters

These fulfill the same function as the LC-17 design but are designed for use in situations where less space is available. As Fig. 9 shows, the receivers are 12.7 mm in diameter and mounted 17.5 mm apart on centers. The absorbers are household aluminum foil, 0.025 mm thick, cemented with silver epoxy to 1.6-mm-thick aluminum disks. The modules are BWC 110-12. The aluminum base is $26 \times 54 \times 35$ mm, with semicircular ends. The ion shields are 0.8-mm-thick Pyrex 7740 and are supported on posts.

The modules are connected in a circuit similar to that for LC-17 (Fig. 8). The sensitivity of the center receiver per unit area was adjusted to be equal to, rather than 93% of, the average of the end receivers, so, as for the first two versions of LC-17, there is a small error in the radiation compensation.

LC-24 Nine-Disk Ion Calorimeter

Shown in Figs. 10 and 11, this calorimeter consists essentially of three model LC-18s bolted together. The receivers are 12.7 mm in diameter and mounted 15.9 mm apart on centers. The six receivers of the two side groups, ABC and GHI, have absorbers of 0.025-mm-thick household aluminum. The three receivers of the center group, DEF, are to be fitted with whatever absorbing material is being compared with aluminum. The base blocks are 15.9×58.7 mm and 25.4 mm thick.

The ion shields are BK-7 wedged disks with 30' wedge angles. Each disk is 19.0 mm in diameter and 2.8 mm thick. A wedged glass shield has the advantage of eliminating any possible reinforcement or cancellation effects upon the transmission of coherent radiation.

The modules are NSI-1AB. Those in each group of three are connected in a circuit similar to that of LC-18. The trim resistors are selected to make the sensitivities of B, E, and H equal to 92% of the averages of A and C, of D

Fig. 9. LC-18 three-disk ion calorimeter.

Fig. 10. LC-24 nine-disk ion calorimeter.

Fig. 11. LC-24 ion calorimeter.

and F, and of G and I, respectively. The sensitivities of the pairs A and C, D and F, G and I, and B and H are made nearly equal.

The calorimeter is to be used with two readout systems, one for ABC and GHI in series and the other for DEF. To the extent that the ion flux varies linearly between B and H, the first readout then indicates the energy that would be deposited in an aluminum absorber at E, and the ratio of the two readouts gives the ratio of energy absorption in the experimental absorbing material on DEF to the energy absorption in aluminum. By comparing various metals in the ion and x-ray fluxes produced under various experimental conditions, the range of variation of energy absorption efficiency may be observed and some estimate may be made of the absolute efficiency of the best absorbers.

GLASS-ABSORBER ION CALORIMETERS

These have been built for use in two situations where the metal-absorber calorimeters are not applicable. The first is for measurements of the ion flux directed toward the irradiating laser beam without blocking much of the beam. The second is for measurements where space is not available for the compensated calorimeters; since the glass absorber transmits the scattered laser radiation, no additional calorimeter element is necessary for compensation and the calorimeter can be made almost arbitrarily small.

The energy absorption efficiency for ions in glass is even more poorly known than in aluminum, but the uncertainty is estimated to be less than 10%. The efficiency relative to that of aluminum could be determined using LC-24.

LC-19

These have been built with Pyrex-7740 disks, 0.9 mm thick and 12.4 or 10.0 mm in diameter. Two soldered thermocouple junctions of bare 0.13-mm-diam chromel and constantan are cemented to the disks (as shown in Fig. 12) with a small amount of epoxy, which was measured to have a low absorptivity at 1.06 μm . The disk is suspended in front of the converging lens of the laser system by means of the four thermocouple wires; the two thermocouples are connected in series with the reference junctions cemented to a massive mounting ring and shielded from the radiation and ion fluxes.

Fig. 12. LC-19 glass-disk ion calorimeter.

The disk is not fitted with a heater for electrical calibration; the sensitivity is derived from the measured thermometric sensitivity of the thermocouples and a calculated heat capacity. The glass disk is weighed before assembly; the masses of solder and epoxy are obtained by difference during assembly; and the mass of wire is obtained from measurements of the length of wire on the disk and the mass per unit length. The glass disk is the largest part of the heat capacity; a value of $0.76 \text{ J} \cdot \text{deg}^{-1} \cdot \text{g}^{-1}$ is used, based on measurements of similar glasses⁴; estimated values are used for the other specific heats.

The measured transmittance of the glass together with the known index of refraction indicates an absorptivity of $\sim 1\%$ at $1.06 \mu\text{m}$. In some cases, the energy absorbed from the laser beam in the glass wires and epoxy is excessive with respect to the ion energy being measured; a shield can then be used behind the calorimeter to remove part of the convergent $1.06\text{-}\mu\text{m}$ beam.

LC-25

This type was built for measurement of the ion flux through 5-mm holes in the ellipsoidal focusing mirrors⁵ of the JANUS laser irradiation system. The disk is Pyrex-7740, 0.7 mm thick and 6.0 mm in diameter. The soldered thermocouple junctions of 0.08-mm wire are cemented with epoxy to the edge rather than to the face of the disk. The disk is suspended on the thermocouple wires at the end of an aluminum tube (7.3 mm o.d. and 6.3 mm i.d.), as shown in Fig. 13. This tube is centered inside an outer tube (9.8 mm o.d. and 8.8 mm i.d.), which slides into a 10-mm mounting hole aligned coaxially behind the 5-mm hole in the mirror surface. Since the defining aperture is 5 mm in diameter while the disk diameter is 6 mm, the thermocouples and the outer edge of the disk are shielded from the ion fluxes. Computer heat-flow calculations show that the edge is within 1% of the final temperature 4 s after the flux is received.

X-RAY CALORIMETERS

Two models of these have been built; gold foil, 0.025 mm thick, is the absorbing material for both and is cemented to the aluminum backing disks with silver-loaded epoxy.

Fig. 13. LC-25 glass-disk ion calorimeter.

LC-22 Four-Disk X-Ray Calorimeters

This calorimeter has four receivers, 12.7 mm in diameter, mounted in a square pattern 19.0 mm apart on centers on a 50.8-mm-square aluminum base block that is 25.4 mm thick. The aluminum disks are identical to those of LC-18, 1.6 mm thick; the modules are NSI-1AB.

The calorimeter is designed for mounting in the target chamber of the ARGUS laser system,⁶ with the receivers 196 mm from the target point. Four rods mounted near the corners of the base block support a magnet mounting plate, with its surface 90 mm from the target point. Four black-anodized aluminum baffles ($76 \times 76 \times 0.4$ mm), each with four holes successively 9.5, 11.1, 12.7, and 15.9 mm in diameter, are arranged as shown in Fig. 14. These are intended to reduce the probability of ions passing near the magnet and being deflected toward the receivers.

Each of the receivers is to be connected to an independent amplifier and recorder. A glass shield may be placed over one of them to provide the correction for scattered laser radiation, if needed; filters of various thicknesses may be used over any or all of the four to gain information about the x-ray spectrum and to reduce the flux of ions not adequately deflected by the magnets.

LC-23 Two-Disk X-Ray Calorimeter

Shown in Fig. 15, these are compensated calorimeters basically similar to LC-18 but employing one compensation disk rather than two. Since the reflectivity of gold is about 97% at $1.06 \mu\text{m}$ compared with 93% for aluminum, the compensation for scattered laser radiation is less critical than for the ion calorimeters. The receiver diameter is 8.5 mm; this is nearly the smallest that would cover the NSI-1AB modules. A small diameter was desired to minimize the gap size of the magnet placed in front of the calorimeter to deflect ions; a small diameter also minimizes the angle through which ions would have to be deflected. The aluminum backing disks are 3.2 mm thick (rather than 1.6 mm as for the 12.7-mm-diam disks of LC-18, LC-22, and LC-24) in order to increase the mass and decrease the thermal leakage modulus.

The base block is 19.0×30.2 mm, and 25.4 mm thick. The two receiving disks are 12.7 mm apart on centers. The ion shield is a 19.0×2.8 -mm 30' BK-7 wedge, as for LC-24. The modules are connected in opposition,

Fig. 14. LC-22 x-ray calorimeter.

Fig. 15. LC-23 x-ray calorimeter.

and the sensitivity of the working (unshielded) receiver is trimmed with a shunting resistor to 93% of that of the compensation (shielded) receiver.

SCATTERED-RADIATION CALORIMETERS

Two types of these have been built for two different purposes. The first is to measure the radiation flux in a small, solid angle at some particular orientation with respect to the target and the irradiating laser beams; the second is to integrate, as completely as practicable, all of the radiation scattered from the target over 4π sr. Both use colored glass to absorb the radiation and convert it to heat, a method that has been well established for calorimeters that are used to measure short-pulse and CW laser beams in the visible and near-infrared^{1,2,7} and at $10\text{ }\mu\text{m}$.⁸ Schott NG-1 glass is suitable for 0.4 to $3\text{ }\mu\text{m}$, and BG-18 is particularly useful at $1.06\text{ }\mu\text{m}$.

LC-21

As shown in Fig. 16, these are essentially similar to LC-15, with a surrounding jacket added. They have been built with diameters of 12.7 and 19.0 mm . The NG-1 glass absorbers, 1.0 mm thick, are cemented with silver epoxy to aluminum disks, 3.2 mm thick. The aluminum disks are this thick in order to increase the heat capacity and decrease the thermal leakage modulus; the time required for equilibration of heat initially deposited near the front surface is much greater for glass 1.0 mm thick than for aluminum or gold 0.025 mm thick.

Although electrical heaters could be installed on the aluminum disks, this was not done; fifteen of the calorimeters have been constructed, and installing the heaters is a rather laborious operation. The calorimeters are easily calibrated by comparison with a reference beam calorimeter^{1,2} using a CW $1.06\text{-}\mu\text{m}$ split-beam system as described in the "Reflectivity Measurements" section below.

Filters can be used in place of the window in front of the calorimeter to gain information on the spectral distribution of the scattered radiation. In either case, a correction is necessary for the Fresnel reflection losses at the surfaces of the window or filter and of the NG-1 absorber.

Fig. 16. LC-21 disk radiation calorimeter.

LC-16 Box Radiation Calorimeters

The absorbers of these consist of six squares of BG-18 or NG-1 glass, 1.0 mm thick, forming a cube centered at the target. All are for two-beam irradiation systems; two opposite faces are pierced with holes of appropriate size to admit the converging beams. One was built for use with F:1 lenses at the JANUS system⁹ and a second for F:2 lenses at the CYCLOPS system¹⁰; both of these use 50.8-mm squares of BG-18. A third, for F:1 lenses at the ARGUS system,⁶ uses 101.6-mm squares of NG-1. The top face has a hole for the target holder, and the other three faces have holes for other diagnostic measurements.

The absorbers are cemented to 1.6-mm-thick copper plates with silver-loaded epoxy. Each of these is cemented to two thermoelectric modules (four for the ARGUS version) located about midway between the hole and opposite corners of the copper square. The modules in turn are cemented to aluminum base blocks, 6.35 mm thick. These are mounted with shims to give appropriate spacing inside a cubical aluminum jacket that is 9.5 mm thick and 101.6 mm on an outside edge (152.4 mm for the ARGUS version). Although the twin-calorimeter principle is not invoked here to reduce the influence of changes in ambient temperature, the construction is sufficiently massive to ensure that the temperature of the aluminum base blocks is adequately stable. A cross-sectional view is shown in Fig. 17.

To stop ions and most of the x rays from reaching the absorber, a thin-walled, cubical glass shield is centered in the absorber cavity. This is made of Pyrex-7740, 0.9 mm thick and 38.1 mm on an outside edge (WG-280, 1.0 mm thick and 71.9 mm on an edge for ARGUS). The six sides are fastened together with a small amount of transparent epoxy; each has a hole proportional to that in the corresponding absorber square. The shield is suspended by six 0.08-mm nichrome wires running radially from the corners to small holes near the corners of the jacket. On the first two versions, several thermocouples of fine chromel-constantan wire were cemented to the outside of the shield with a small amount of transparent epoxy; these were used to measure the temperature rise of the glass and obtain an approximate value of the local ion and x-ray flux.

The two (or four) thermoelectric modules on each side are connected in series. In the first two versions, the sensitivities of the six sides, in

Fig. 17. LC-16 box radiation calorimeter.

microvolts per joule, were made nearly equal by selecting modules of appropriate sensitivity and by trimming the copper plates; the modules of the six sides are then all connected in series. Alternatively, the six sides can be measured individually or in various combinations to secure some information on the angular distribution of the scattered radiation.

The six holes in the absorbers of the JANUS box calorimeter are 33.2, 33.2, 12.4, 9.8, and 6.2 mm in diameter; they subtend a total of 2.43 sr about the target. Gaps at the twelve edges of the cube subtend about 0.15 sr. So 20.5% of radiation scattered isotropically from the target would pass out of the calorimeter without hitting the absorbers. (In practice, other optical systems with beam-type calorimeters^{1,2} collect most of the radiation directed toward the large beam-entry holes.) In addition, some radiation will be lost through the holes after one or more surface reflections at the ion shield and absorbers. Ray-tracing calculations were performed as diagrammed in Fig. 18 to determine the solid angle subtended by each of the holes for rays undergoing one reflection from the first surface of the absorber (Fig. 18a) and from the two surfaces of the ion shield (Fig. 18b). These total 1.7% of isotropically-distributed radiation from the target point. The calculation is insensitive to angle of polarization because each hole receives reflections from four adjacent surfaces lying 90° apart. Losses by paths including two reflections from the absorber surface or ion shield are negligible. The losses would be about the same for the ARGUS calorimeter and substantially less for the CYCLOPS calorimeter, which has smaller beam-entry holes.

The third box calorimeter was made larger than the others because the ARGUS system delivers more energy; by having the ion shield and absorbers farther from the target, the ion- and radiation-flux densities are reduced and the probability of damage is decreased.

MISCELLANEOUS NOTES ON CONSTRUCTION

Attachment of Absorbers

The absorbers of LC-15 and LC-17-1 were attached to the copper backing disks (and ring for LC-17-1) with hard vacuum wax. This practice was discontinued because in using a hot-air blower to soften the wax there was danger of destroying the thermoelectric modules, which are assembled with low-melting solder. Furthermore, the thermal conductivity of silver-loaded

Fig. 18. Radiation losses from surface reflections in LC-16.

epoxy, which was used to attach the absorbers of all the other calorimeters, is higher. Silver-loaded epoxy was used to attach the thermoelectric modules in all cases.

Heaters

The rims of the copper or aluminum disks of LC-17, LC-18, LC-22, LC-23, and LC-24 and the copper rings of LC-17 are turned to a diameter less than that of the absorber except for a narrow lip immediately behind the absorbers. The aluminum disks are anodized to provide an electrically insulating surface, and one or two coats of varnish are applied to the copper disks and rings. Calibrating heaters of 0.101-mm-diam, formvar-coated, manganin wire are wound bifilarly on these undercut cylindrical surfaces and fastened in thermal contact by means of epoxy cement and varnish. The leads are 0.160-mm copper, also cemented to the cylindrical surface or the flat back surface near the rim for a considerable distance in order to be in thermal equilibrium during heatings.

The rims of the model LC-15 were not undercut, so the heater protruded undesirably beyond the edge of the absorber.

In the box calorimeters, heaters of the same wire (or 0.202-mm manganin for the ARGUS version) were distributed uniformly over the varnished backs of the copper plates and similarly cemented in place.

The current and potential leads for the heaters are in some cases permanently assembled with the calorimeter, but in most cases are simply taped to the base block during calibrations and soldered to the heater leads. The current leads are 0.160-mm copper; the potential leads are fine manganin, attached to the current leads midway between the base block and the point of attachment of the heater leads to the disk, ring, or plate.

Resistors

The resistors used in the thermoelectric module networks, such as that of Fig. 8, are of the metal-film type, LLL stock, 1/8-W rating. The resistances are checked with a portable Wheatstone bridge to 0.1% accuracy. All are also tested in a vacuum chamber: the change of resistance upon pumpdown and after several minutes is undetectable, and the rate of outgassing after two minutes of pumping is less than one micron-liter per minute.

CALIBRATIONS

For convenience, the calorimeters are calibrated in air, although they are used in an evacuated target chamber. Usually the calorimeter is placed in a 4-liter dewar flask, in a room whose temperature is well controlled. The calorimeter is allowed to stand for some time to approach thermal equilibrium. The heater is then energized for a known interval, usually a few tenths of a second, using a precision timing circuit, a DC power supply of about 10 ppm stability, and a standard resistor in series with the heater. The thermopile output is amplified and displayed on a strip-chart recorder to determine the temperature rise. The heater is later energized for a longer period at the same setting of the power supply and at the same time the voltages across the standard resistor and across the heater potential leads are measured with a digital voltmeter to determine the power dissipated in the heater. Typical values of the deduced total sensitivity, S_t , are given in Table 2; where pertinent, values of the sensitivity per unit area, S_a , are also given.

The initial parts of the time-temperature curve for the electrical-heating calibrations and for the irradiation experiments are somewhat different. This is particularly true for the LC-16 box calorimeters and would be similar for the LC-21 disk-radiation calorimeters if electrical heaters were installed for calibration. Heat is transferred rapidly from the heater to the copper plate, whose temperature is measured by the thermoelectric modules; heat is then transferred to the glass absorber; this causes the measured temperature to drop more rapidly than it does after the glass is in approximate equilibrium with the copper. During irradiation, on the other hand, the energy is deposited near the front of the glass, and the temperature of the copper rises more slowly. These effects are illustrated qualitatively in Fig. 19. The error, due to inexact realization of the method of comparative measurements, is, however, negligibly small if t_3 is taken late enough so that T_3 lies on the final exponential curve. Table 2 includes the values of t_3 and t_4 adopted for the various models. For LC-19 and LC-25, which are not calibrated, an approximate extrapolation of the exponential t - T curve is performed.

Table 2 also includes values for k , the thermal leakage modulus observed in air. Heat is transferred to and from the calorimeter by radiation, by conduction through the thermoelectric modules, and, during calibrations, by conduction through air, mainly to the base blocks. For most of the calorimeters using thermoelectric modules, the transfer through the modules

Table 2. Typical thermal characteristics of the calorimeters.

Model	Sensitivity		Thermal leakage modulus	After-drift interval	
	Total, S_t ($\mu\text{V}\cdot\text{J}^{-1}$)	Per unit area, S_a ($\mu\text{V}\cdot\text{J}^{-1}\cdot\text{cm}^2$)	k (s^{-1})	t_3 (s)	t_4
LC-15	1170	5930	0.0079	18	36
LC-17	1100	3135	0.0055	18	36
LC-18	11700	14800	0.033	6	12
LC-24	6200	7870	0.020	6	12
LC-19, 12.4 mm	630 ^a	761	-	-	-
LC-25	3400 ^a	670 ^b	-	-	-
LC-22	6900	8740	0.019	6	12
LC-23	6900	3930	0.020	6	12
LC-21, 12.7 mm	2600 ^c	3300	0.013	12	24
LC-21, 19.0 mm	1100 ^c	3140	0.007	12	24
LC-16, JANUS	414	-	0.0052	18	36
LC-16, CYCLOPS	421	-	0.0052	18	36
LC-16, ARGUS	130	-	0.005	18	36

^a Calculated.

^b For a defining aperture of 5.0-mm diam.

^c Calibration performed with a CW laser beam.

Fig. 19. Time-temperature curves for calibrations and irradiation.

is large compared with that through the air gap, so k in vacuum is not much less than in air. For LC-16, the area of the copper plates is larger relative to that of the modules, and the reduction of k in vacuum is therefore also larger.

In laser-beam calorimeters,^{1,2} the rather massive copper or aluminum disk cemented to the glass absorber has two functions. The first is to improve lateral distribution of heat and give a response that is largely independent of the location of energy deposition in the glass. The second is to give a calorimeter body with a well-defined physical boundary and a heat capacity large enough to make k and the last term of Eq. 2 small; although this reduces the sensitivity in microvolts per joule compared to that obtained with a thinner metal disk, the slope of the final time-temperature curve is lower and more temperature readings can be taken with an amplifier having a longer time constant and a lower noise level. The first objective does not apply to the present calorimeters (except for the box calorimeters) since the flux is expected to be nearly uniformly distributed on the absorbers; but the second does apply.

REFLECTIVITY MEASUREMENTS

Measurements of the absorption of CW 1.06- μ m radiation by the aluminum and gold surfaces of the ion and x-ray calorimeters were performed using a split-beam test arrangement (Fig. 20), which is similar to one previously described for short-pulse studies.¹ The laser beam is passed through a Glans polarizer, shutter, 3-mm aperture, and a splitter, which is a 30' BK-7 wedge. Three calorimeters are used: MC, the monitor calorimeter, and RC, the reference calorimeter, are beam calorimeters of the type previously described; EC, the experimental calorimeter, is the one under investigation. The beam energy ratio, E_{RC}/E_{MC} , was first measured with the shutter opened for one or two seconds; this ratio was 3.13, and the power into RC was typically 1 W. The experimental calorimeter, EC, whose sensitivity had been electrically calibrated, was then inserted in place of RC. The ratio of the ratios $(E_{EC}/E_{MC})/(E_{RC}/E_{MC})$ is then the absorptivity of the surface of EC.

The reflectivity of three of the LC-17s was measured. With each, measurements were performed at eight points: four near the middle of the ring, 90° apart, and four on the disk, midway between the center and edge, 90° apart. At each position, measurements were done in duplicate; these

Fig. 20. Split-beam test facility.

generally agreed within 1%, which is about the limit of the strip-chart recorders. The absorptivity values ranged from 0.065 to 0.082, with an average deviation from the mean of 0.004.

Measurements of the absorptivities of one LC-22 and one LC-23 with stock gold-foil surfaces were also performed in duplicate at two points on each of the six disks; the absorptivities at the twelve points ranged from 0.025 to 0.031. Two other LC-23s, in which a layer of 0.5- μ m-thick gold had been evaporated in vacuum onto the stock gold surface, were also tested; the absorptivities at eight points ranged from 0.0162 to 0.0179. The evaporated gold overcoating evidently both reduces the absorptivity and improves its uniformity.

In the compensated calorimeters, it is more important that the absorptivities of the aluminum or gold surfaces be uniform than that they be low. To improve the probability of achieving this, the working and dummy absorbers were always cut from adjacent sections of the stock foil.

The compensated calorimeters also depend upon the average intensity of the scattered laser radiation being nearly equal at the working and dummy absorbers. Because of the lower absorptivity of the gold surface, this requirement is less stringent for the x-ray calorimeters than for the aluminum-surfaced ion calorimeters. The uniformity can also be improved by making the calorimeters smaller or moving them farther from the target so that they subtend a smaller solid angle, but this reduces the signal level.

PERFORMANCE

For large signals, the energy absorbed by the calorimeters can be determined to 1% or better. For the scattered radiation measurements, this is about the limit of absolute accuracy.^{1,2} But for the ion and x-ray measurements, a higher limit is imposed by uncertainties in the efficiency of absorption of energy.

For small signals, the limit is imposed by the signal-to-noise ratio. The noise level depends not only on the characteristics of the calorimeter but also on environmental perturbations and on the characteristics of the electronic amplifier. The target chambers, massive and evacuated, are a rather favorable environment. Various types of amplifiers have been used; the baseline stabilities with the better ones are such that small temperature rises of most of the calorimeters can be measured to a precision of 0.01 μ V or better.

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