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MODEL LC-13 LASER CALORIMETERS USING COMMERCIAL THERMOELECTRIC
MODULES

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October 22, 1974

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Prepared for U. S. Atomic Energy Commission under contract no. W-7405-Eng-48

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MODEL LC-13 LASER CALORIMETERS USING COMMERCIAL THERMOELECTRIC
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ABSTRACT

Twin-disk laser calorimeters using semiconductor thermoelectric modules are described. Comparisons with a previous type indicate agreement within 1%. The new type is simpler and more economical to construct.

INTRODUCTION

The laser calorimeters previously described¹ have proven to be quite satisfactory in use. They are, however, rather expensive and laborious to construct; and they are more accurate, especially with respect to lack of variations of response with variations of beam size and position, than is necessary for most routine uses. Multi-arm laser systems may use a large number of calorimeters, and fabrication expenses will be significant.

Accordingly, the present work was undertaken to develop a design which would be more economical to construct but which would still give adequate, though perhaps lower, performance. This has been accomplished mainly through three modifications:

- Commercial semiconductor thermoelectric modules are used rather than soldered Chromel*-constantan wire thermopiles.
- The calibrating heaters are not covered.
- The jacket construction is based on standard tubing and plate sizes and requires substantially less machining than the earlier types.

Another advantage which obtains with the present instruments is that the thermopile response, in voltage output per unit temperature rise, is about one order of magnitude greater and the thermopile resistance is nearly two orders of magnitude smaller than the earlier types. This does not mean that the useful sensitivity of the calorimeters is greater; the base-line drift and noise level, which depend in large part on thermal fluctuations in the calorimeter and its environment, are also enhanced. But it does mean that in principle amplifiers of lesser sensitivity and higher noise level, and therefore presumably lower cost, can be used.

1. S. R. Gunn, Rev. Sci. Instrum. 45, 936 (1974).

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

CONSTRUCTION OF THE CALORIMETERS

To date, 11 of the calorimeters have been constructed: two model LC-13-1.0, two model LC-13-1.5, one model LC-13-2.0, one model LC-13B-2.0, one model LC-13-3.0, and four model LC-13-5.0. The final number in the model designation is the receiver diameter in inches. The "B" in LC-13B-2.0 refers to a variation in the construction which will be described below.

A cross section of a calorimeter is shown in Fig. 1. Diameters given in the following discussion are for calorimeters with receivers up to 3-in. diameter. For 4- and 5-in. calorimeters, diameters are 2 in. larger; for 6- and 7-in. calorimeters (none yet built), diameters are 4 in. larger. Lengths and thicknesses are the same for the larger calorimeters. The material is aluminum unless otherwise specified.

The outer jacket has a 6.00-in. o.d., a 0.125-in.-thick wall, and is 8.50-in. long. The outer end plate is 0.50-in.-thick Bakelite and is held in place by four set screws through the outer jacket. The inner jacket has a 5.00-in. o.d., a 0.25-in.-thick wall, and is 7.00-in. long. It is held in place by eight set screws through the outer jacket. The inner end plate (0.50-in. thick), center plate (copper, 0.50-in. thick), and entry aperture (3.00-in. thick) are free-sliding fits into the inner jacket; each is held in place by four set screws through the inner jacket. The bore of the entry aperture is of diameter $(D + 0.10)$ in., where D is the diameter of the receiver; the bore is painted with Nextel flat black paint. The center plate and inner end plate are joined, with 1.75-in. separation, by three 3-in., No. 10-32 steel screws (only one is shown in Fig. 1) so that they may be inserted and removed as a unit.

A number of commercial lines of thermoelectric modules are available. Some characteristics of those selected for the present calorimeters are given in Tables 1 and 2. For calorimeters LC-163 and LC-164, three modules were used on each side, centered 120° apart on a 3.00-in.-diameter circle; the three were connected in series. The modules are cemented to the center plate and disks with a silver-loaded epoxy cement.

Table 1. Thermoelectric modules used in calorimeters.

Calorimeter		Module	
Serial No.	Model	Number	Model
165 and 166	LC-13-1.0	2	Borg-Warner 930-1.7
167 and 168	LC-13-1.5	2	Borg-Warner 930-35
169	LC-13-2.0	2	Borg-Warner 930-35
170	LC-13B-2.0	1	Borg-Warner 930-35
160	LC-13-3.0	2	Asarco TH 0812/P
161 and 162	LC-13-5.0	2	Borg-Warner 930-35
163 and 164	LC-13-5.0	6	Borg-Warner 930-17

Fig. 1. Cross section of model LC-13 calorimeter.

Table 2. Characteristics of thermoelectric modules.

Model	Face plates		Thickness, in.	Sensitivity, $\mu\text{V}/\text{deg}$	Conductance, W/deg	Resistance, Ω
	Material	Size, in.				
Asarco TH 0812/P	Al	0.91×1.02	0.28	14,000	0.087	1.6
Borg-Warner 930-17	BeO	0.52×0.52	0.20	6,400	0.040	0.5
Borg-Warner 930-35	BeO	0.52×1.06	0.20	13,000	0.075	1.0
Borg-Warner 930-71	BeO	1.18×1.18	0.20	25,000	0.142	2.1

Alumina-loaded epoxies of similar thermal conductivity are available and would be preferable, since they are electrically insulating and accidental contact of the cement with the thermojunctions at the edge of the plates would therefore be less damaging.

The receiver and dummy disks are of copper. The normal design is 0.125-in. thick and has a groove about 0.100-in. wide and 0.020-in. deep around the rim. The groove is varnished; the heater, of No. 34 enamelled Manganin wire, is wound bifilarly in a single layer, and two more coats of varnish are applied. Number 34 copper leads are attached to the winding, brought over the flange at the rear edge of the disk, and laid on the rear face near the rim, around about half of the circumference; they are cemented in place with epoxy to improve the thermal contact. The disk of calorimeter LC-161 is 0.312-in. thick for a diameter of 2.50-in. at the center; the remainder of the 5.00-in. diameter is 0.062-in. thick. The heater is wound on the step at the 2.50-in. diameter. The disks of calorimeter LC-163 have a groove 0.20-in. wide and 0.100-in. deep around the rim; this was filled with epoxy and the heater was wound in it.

The absorbers for all of the present calorimeters are Schott BG-18 glass, 0.040-in. thick. These are pressed onto both the receiver and dummy disks over a layer of thermal-conducting grease.

There are three electrical cables, one for the thermopiles and one for each of the heaters, which enter the calorimeter through slots at the rim of the outer end plate and through holes near the edge of the inner end plate. The cable wires are held to the inner end plate by a cable clamp of aluminum plate, $0.25 \times 2.00 \times 3.00$ in. To improve the thermal contact, the space between the clamp and the end plate is filled with epoxy cement. The wires are cut off just beyond the clamp.

The thermoelectric modules under the two disks are connected in opposition. The leads from them and the current leads from the heaters are No. 34 copper, cemented with epoxy over strips of electrical tape on the center plate. Number 35 Manganin potential leads are attached to the heater current leads midway between the center plate and the disks, and likewise cemented. The leads from the receiver disk pass through the center

plate in small holes lined with plastic spaghetti. The upper spacing screw is wrapped with electrical tape; the 10 leads are wrapped loosely around it and soldered to the cable wires.

In model LC-13B, the copper center plate is eliminated and the two disks are cemented on opposite sides of a single thermoelectric module. The disks are also joined by three 0-80 stainless-steel screws (0.057-in. o.d.), equally spaced near the rim of the disks. Braided nylon fish line is tied to the center of each of these screws and used to suspend the assembly centrally between the three supporting screws.

An entry tube is used to reduce the effect of air currents and varying background radiation. Typically, this is a thin-walled aluminum tube of diameter equal to the outer jacket tube, 8-in. long for receiver diameters to 3.0-in. and 12-in. long for LC-13-5.0. Five or six apertures are fitted in the interior; these are of Bakelite, 0.030-in. thick, with holes of diameter $(D + 0.12)$ in., painted black. The interior of the tube between the apertures is lined with sponge rubber, 0.38- or 0.50-in. thick, painted black.

TESTS AND PERFORMANCE

The instruments are treated as isoperibol calorimeters, and the corrected temperature rises are calculated with the same programs used for the calorimeters described earlier.¹ This turns out to be an adequate approximation even though physically the calorimeters are a poorer approximation to the idealized single-body calorimeter model. Also, the single thermoelectric module (or the three modules for LC-163 and LC-164) does not give the same temperature-averaging effect as obtained with the 12- or 21-pair wire thermopiles. If a pulse of radiation is received near the module, there is a large overshoot in the output, which rapidly decreases as the temperature of the disk equilibrates.

To investigate systematic errors in the calorimeters, a split-beam arrangement similar to that previously described was set up.¹ The reference calorimeter, RC, was a 1.5-in.-diameter, side-by-side type with laboratory designation LC-3E. The beam was supplied by a CW YAG laser; no converging lens was used. An iris ahead of the splitter limited the beam to a 6-mm diameter (8-mm for the 5-in. calorimeters). The power through the splitter to EC or RC was about 1W. An electrically controlled shutter was used to give a 2-s irradiation interval (5-s for the 5-in. calorimeters). The same interval was used for the electrical heating calibrations.

A typical pattern for the EC-RC comparisons was as follows:

- Calibrate MC, RC and EC twice each;
- Perform three or four measurements of E_{RC}/E_{MC} with the position of RC varied slightly;
- Perform six to twelve measurements of E_{EC}/E_{MC} with EC moved between measurements so that the beam struck various points on the receiver disk;
- Perform three or four more measurements of E_{RC}/E_{MC} ; and

- Perform two more electrical calibrations of each calorimeter.

The results for each EC measurement are expressed as a ratio R,

$$R = (E_{EC}/E_{MC}) \times (S_{RC}/S_{EC})/R_{RC},$$

where S_{RC} and S_{EC} are the average sensitivities of RC and EC deduced from the electrical-heating calibrations, and R_{RC} is the average value of (E_{RC}/E_{MC}) . Thus R represents the ratio of the energy deduced from measurements with EC to the energy deduced from measurements with RC, for the same actual incident energy; and RC is a type of calorimeter whose performance has been well established in other studies.^{1,2} The results of these comparisons are tabulated in Table 3.

After an electrical heating or absorption of a laser pulse, when the temperature of the receiver disk has nearly equilibrated, the decrease of temperature with time is approximately exponential according to the equation

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

where k is the thermal leakage modulus, and T_{∞} is the steady-state temperature which is approached asymptotically. If a laser pulse strikes a small area of the receiver near a thermoelectric module, that region temporarily becomes considerably hotter and the temperature "overshoots" — that is, it temporarily rises above the exponential curve and then approaches it from above. If the laser spot is far from any module or if the disk is heated electrically at the rim, the temperature approaches the curve from below. (LC-161 does, however, show an overshoot with electrical heating.) In either event, a rough idea of the speed of equilibration of the disk is given by observation of the time after the end of an electrical heating period (t_e) or laser irradiation period (t_r) at which the temperature comes within 0.01 ΔT of the final exponential curve, ΔT being the corrected temperature rise for the experiment. The value of t_r of course depends to some extent on the location of incidence of the laser beam; values given in Table 4 are approximate averages for the locations previously described. Approximate values of k, the thermal leakage modulus, and s, the sensitivity, are also given.

DISCUSSION

In practice, one prefers to use the smallest calorimeter that will accommodate the beam being measured, in order to maximize the signal-to-noise ratio. The receiver disk is then irradiated much more uniformly than was the case in the tests reported here; the effective value of R would be approximately an average of those found with the small spot, and t_r would be reduced. It thus appears that the results given by these calorimeters would generally be within 1% of those given by the calorimeters described earlier. It also appears that, at least to a first approximation, the noise and drift of these calorimeters under similar environmental conditions are comparable.

2. S. R. Gunn, Studies of Laser Calorimeters Using Glass Absorbers and Black-Painted Absorbers from 0.46 to 1.06 μ m, Lawrence Livermore Laboratory, Rept. UCRL-51613 (1974).

Table 3. Test results, model LC-13 laser calorimeters.

Unit	Location of measurement	R^a	
LC-166 (LC-13-1.0)	Beam at center	0.999	
		1.000	
	Beam at four positions 90° apart, 2.2 mm from the center	0.996	
		0.995	
		0.996	
LC-169 (LC-13-2.0)	Along two radii of the receiving disk, 90° apart, about 35° and 55° from the long axis of the rectangular thermoelectric modules, at three distances from the center.		
	Along radius 35° from the long axis:		
	At 0 mm from the center	1.008	
	8	1.005	
	16	1.002	
	Along radius 55° from the long axis:		
	At 0 mm from the center	1.008	
	8	1.008	
	16	1.004	
LC-170 (LC-13B-2.0)	Along two radii of the receiving disk, 90° apart, about 25° and 65° from the axis of the module.		
	Along a radius 25° from the axis:		
	At 0 mm from the center	1.005	
	8	1.003	
	16	1.003	
	Along a radius 65° from the axis:		
	At 0 mm from the center	1.009	
	8	1.004	
	16	1.008	
LC-160 (LC-13-3.0)	At the center:	1.012	
		1.008	
		1.012	
		1.010	
		1.010	
	Along three radii, 90° apart, at four distances from the center.		
	Along first radius:		
	At 13 mm from the center	1.008	
	25	1.003	
	29	1.002	
	32	1.001	
	Along second radius:		
	At 13 mm from the center	1.006	
	25	1.000	
	29	0.999	
	32	0.995	
	Along third radius:		
	At 13 mm from the center	1.008	
	25	1.001	
	29	0.999	
	32	0.997	
LC-161 and LC-162 (LC-13-5.0 with heater on step at 1.25-in. radius)	At the center:	LC-161	LC-162
		1.005	1.011
		1.005	1.020
		1.004	1.025
	Along four radii 90° apart, 25 mm from the center:	1.005	1.008
	Along four radii 90° apart, 51 mm from the center:	0.998	1.002
		1.000	0.996
		0.996	1.013
		0.998	1.002
		0.988	0.998
		0.986	0.999
		0.987	0.989
		0.989	1.000

Table 3. (Continued)

Unit	Location of measurement	R ^a	
LC-163 and LC-164 (LC-13-5.0, three modules)	At the center:	LC-163	LC-164
		1.002	0.997
		1.001	0.999
		1.000	0.996
	Along four radii 90° apart, lying 0°, 30°, 30°, and 60° from the center of the nearest thermoelectric module.	1.001	0.997
	At 25 mm from the center:		
	At 51 mm from the center:		

^aSee text for definition of R.Table 4. Characteristics of LC-13 Calorimeters.^a

Model	t _e , s	t _r , s	k, min ⁻¹	S, μV/J
LC-13-1.0	3	5	0.38	915
LC-13-1.5	3	—	0.33	825
LC-13-2.0	4	8	0.22	480
LC-13B-2.0	2	7	0.44	485
LC-13-3.0	6	10	0.13	237
LC-13-5.0 (161)	20	23	0.10	155
LC-13-5.0 (162)	14	17	0.10	144
LC-13-5.0 (163,164)	5	10	0.90	116

^aSee text for definitions of t_e, t_r, k, and S.

Although the LC-13B model is slightly simpler and cheaper to build, it might be disadvantageous in situations where measurements were being repeated at frequent intervals. Lacking the massive copper center plate, both disks rise in temperature, being cooled mainly by air conduction and convection to the inner jacket. When their temperature elevation above the jacket becomes large enough, the randomness of convection might introduce excessive variability in the temperature drift rates; also, the thermopile sensitivity might change significantly at the higher temperature.

The stepped design of LC-161 does not appear to be advantageous. The six-module design of LC-163 and LC-164 does appear to be substantially superior to the two-module LC-161 and LC-162 and will be preferred for calorimeters over 3 inches in diameter.

In principle, one expects a calorimeter with an uncovered surface heater to give a slightly high result for radiation measurements because heat losses from the heater during calibration lead to a slightly high apparent energy equivalent. These losses occur because the heater wire must superheat somewhat with respect to the surface of the disk on which it is wound. The magnitude of the effect may be visualized as the ratio of the thermal conductivities from the center of the heater wire to the jacket (by the mechanisms of radiation and air conduction) and to the surface of the disk. The reference calorimeter used in this work has a covered heater, as do all of the earlier-described calorimeters over 1-inch diameter; since the values of R are near unity, the effect cannot be large. Also, there is no substantial difference between LC-163, with the heater buried in a deep, narrow groove, and LC-164, with a normal surface heater.

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