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STUDIES OF CALORIMETER ABSORBERS FOR CW AND PULSED CO₂ LASERS

Stuart R. Gunn

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STUDIES OF CALORIMETER ABSORBERS FOR CW AND PULSED CO₂ LASERS

Abstract

Solid and liquid absorbers, used in calorimeters to measure the power and energy of CW and pulsed CO₂ lasers, have been studied from 9.24 to 10.76 μm (CW) and near 10.588 μm (pulsed).

The principal materials used were magnesium oxide, lithium fluoride, polystyrene, polytetrafluorethylene, carbon tetrachloride and kerosene.

Introduction

The volume-absorbing calorimeters described in a previous paper¹ can be used to measure radiation of any wavelength for which suitable absorbing materials can be found, but most materials satisfactory in the visible and near infrared are not suitable in the middle infrared. The original studies of the calorimeters were done at 1.06 μm ,¹ and absorbers for 0.46 to 0.69 μm were studied later.² The present work was undertaken mainly to establish suitable materials for high-power, short-pulse lasers in the vicinity of 10.59 μm , but was also extended to cover other carbon dioxide laser lines from 9.24 to 10.76 μm . Most of the work was done with a CW laser, since the pulsed system was less readily available and only operated near 10.59 μm .

If the absorption process in a volume-absorbing material consists of excitation of an initial absorbing state to some excited state, which is nonabsorbing but decays back to the initial state with some characteristic relaxation time, then one would expect the apparent absorptivity of the material for short pulses to be less than that

for CW if the radiation density were sufficient to excite a substantial fraction of the initial absorbing species to the nonabsorbing upper state and if the relaxation time were not short compared with the pulse duration. This possibility can be investigated empirically by comparing CW and short-pulse measurements and by varying the energy density in the absorber. Previous measurements of three absorbing glasses at 1.064 μm showed the transmittance, specular reflectance, and total reflectance (specular reflectance, plus thermal reradiation loss) to be the same for CW² and for converging beams of 200-ps pulses at energy densities up to the damage threshold.¹

If the absorptance of the absorbing material does not change with pulse duration, one would expect the heat losses from the calorimeter to be the same for very short pulses and for pulses up to a duration where heat transfer within the absorbing material during the pulse is significant — of the order of a second, depending on the material.

Apparatus

MATERIALS

The following absorbing materials and sources were used:

- MgO – Eastman Kodak* Intran-5, hot-pressed compact, polished disks.
- LiF – Harshaw optical crystal, polished disks.
- PS – polystyrene sheet, LLL stock No. 9330-33805, clear, extruded, rigid per spec L-P-396, type III, class 2, ESR No. 326.
- PTFE – polytetrafluoroethylene sheet, LLL stock No. 9330-33838, molded, type I, grade B, per MIL-P-22241 and ESR No. 323.
- Kerosene – "Chevron Pearl Kerosene."
- Other liquids – reagent-grade chemicals.

CALORIMETERS

Two side-by-side calorimeters¹ with MgO absorbers, 38 mm diam and 2.0 mm thick, were used as the monitor calorimeter (MC) and reference calorimeter (RC). A back-to-back calorimeter, also of 38 mm diam, was used as the experimental calorimeter, EC. The block temperatures were not regulated, since the room temperature was found to be sufficiently stable to give adequately low noise, drift, and changes of sensitivity.

The stirred-liquid calorimeter was as previously described¹ except that the window was polished sodium chloride, 2° wedge angle, attached with epoxy cement.

The reflectance calorimeter was as previously described¹ except that the aluminum disk holding the absorbing specimen was fitted with a four-pair

thermopile instead of a thermistor; the reference junctions were mounted in the massive support ring.

CW TEST ARRANGEMENT

The CW laser used was a Coherent Radiation Model 42, fitted with an adjustable grating to permit selection of single lines. The output was horizontally polarized, and the beam was passed through a germanium plate at Brewster's angle to further reduce any vertical component. A mirror on a translation stage was arranged for ready insertion into the beam to bring the beam into a spectrometer (Optical Engineering, Inc., Model 16-A) for the purpose of checking the line wavelength.

The CW split-beam test facility was similar to that previously described.¹ The beam passed through an adjustable iris about 2 m from the laser output mirror. A power meter behind this iris was used to monitor the laser power between measurements. A f-m focal length sodium chloride lens, with sodium fluoride coating, was placed in a heated mount 620 mm from the iris. A shutter was placed close behind the lens. A 2° germanium wedge, which served as a splitter, was placed 140 mm from the lens. The angle of incidence at the splitter was 36°. Only the first-surface-reflected and first-transmitted beams were used, directed to MC and to EC or RC, respectively; the ratio of the energies in the transmitted and reflected beams at 10.59 μm was 1.93.

The iris was normally set at 10 mm diam. Decreasing the diameter to 5 mm reduced the transmitted power by about 50%; it is estimated that its central intensity was three times the average intensity over the 10-mm diam. Irradiations were typically performed for an interval of 1 to 1.5 s, giving about 2 to 3 J in the transmitted beam. The normal position of RC and the closest position of EC were with the

*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. Energy Research & Development Administration to the exclusion of others that may be suitable.

absorbers 500 mm from the lens; the central energy density here may then be estimated as roughly 30 J/cm^2 , increasing to 50, 85, 190, and 750 J/cm^2 at distances of 600, 700, 800, and 900 mm from the lens. The normal position of the MC receiver was 540 mm from the lens.

Central-stop tests were performed to make certain that there was not an excessive amount of radiation scattered near or beyond the edges of the 38-mm absorbers. The stops were disks of PTFE, 13- or 19-mm diam with aluminum foil cemented to the back side. They were suspended by thin wires at the face of the aluminum block of the calorimeter, 110 mm in front of the calorimeter absorber and centered on the axis of the absorber. A 19-mm stop in front of MC (which was moved 70 mm to the rear of its normal position) reduced the energy ratio E_{MC}/E_{RC} to 0.5% of its normal value. A 13-mm stop in front of RC, 450 and 800 mm from the lens, and a 19-mm stop, 500 and 800 mm from the lens, reduced E_{RC}/E_{MC} to 1.0, 0.8, 0.4, and 0.4% of the normal value.

PULSED TEST ARRANGEMENT

The pulsed laser used was the Valkyrie system,³ consisting of a mode-locked oscillator with single pulse switchout, a preamplifier, a beam-expanding telescope, and three amplifiers. The pulse width is 1 to 2 ns, which was checked intermittently during the present work. The system is known to operate on one or a few lines near $10.588 \mu\text{m}$; this was not checked spectrometrically during the present work, but the transmittance measurements reported hereinafter are all consistent with the assumption of a wavelength near 10.588 and most are inconsistent with the assumption of a wavelength near 10.244 , 9.350 , or 9.269 .

The beam was limited by a 19-mm-diam circular aperture positioned about 1 m from the output window of the last amplifier. A 1.98-m focal length sodium chloride lens, with sodium fluoride coating,

was placed 790 mm beyond the aperture and a sodium chloride splitter was located 150 mm beyond the aperture and a sodium chloride splitter was located 150 mm beyond the lens. The splitter was 254 mm in diameter and 38 mm thick, with a wedge angle of 30 min; only the rear surface was antireflection coated with sodium fluoride. The angle of incidence on the splitter was 45° ; the plane of incidence was perpendicular to the plane of polarization. Only the first-surface-reflected beam was directed to MC and only the first-transmitted beam to RC or EC.

The calculated first-surface reflectance at a 45° angle of incidence is 0.0897 of the incident energy. The sodium fluoride coating was investigated at three points on the surface by temporarily reversing the splitter and measuring the reflectance at the same angle of incidence; it varied considerably, but was about 0.013. Using this figure for the second-surface reflectance of the splitter, the calculated energy ratio of the two beams is 0.0998; the experimental value was 0.0969. The agreement is within the limits imposed by the imprecision of the measurement of the angle of incidence.

The output beam of the laser system was considerably larger than the 19-mm aperture; the energy density through the aperture was approximately uniform, as estimated from burn patterns. The sharp-edged (nonapodized) aperture accordingly gave a diffraction pattern in the beam. The magnitude of this and scattered radiation was checked by placing a 25-mm central stop in front of EC at 60 and 150 cm from the lens; the E_{EC}/E_{MC} ratio in both cases was reduced to about 0.6% of its normal value.

The energy in the transmitted beam ranged from approximately 1.0 to 2.5 J in the shots used. The energy density D at a transmittance specimen or at the receiver of RC or EC was calculated from

$$D = (E_T/2.85)(200/(200-d))^2, \quad (1)$$

where E_T is the transmitted energy, 2.85 cm^2 is the aperture area and d is the distance in centimeters from the lens; this neglects diffraction effects.

The laser system was occasionally fired with the pulse switchout turned off to check for energy in par-

astic oscillations. Under the conditions used through most of this work the energy found was negligible

CW Results

TRANSMITTANCE

Transmittances of solids were determined by measuring the energy ratio E_{RC}/E_{MC} with two calorimeters in the split-beam test facility, with and without a specimen of the material interposed in the beam to RC. The ratio of these two ratios is the external transmittance; this is divided by $(1-R_s)^2$, where R_s is the specular reflectance from Table 3, to correct for the reflective losses at two surfaces and to obtain the internal transmittance (Table 1).

The transmittances of the liquids were measured similarly. The cell employed two polished sodium chloride windows that had a 2° wedge angle. The measured transmittance of the empty cell at 10.588 μm was 0.85, which agrees with the calculated loss at four NaCl-air interfaces. The measured external transmittance of the liquids was divided by $(1-R_s)^2$ where R_s is the specular reflectance from Table 3, to account for losses at two NaCl-air interfaces. The indexes of refraction of the liquids were

not available, so losses at the two NaCl-liquid interfaces were neglected.

The results for MgO are in good agreement with the data of Eastman Kodak, which show a hump peaking at about 10.6 μm and interrupting the otherwise monotonic decrease in transmittance from about 6 to 10.3 μm . This hump and the preceding valley have the effect of giving a low slope of transmittance vs wavelength in the vicinities of 10.6 and 10.2 μm .

The results for the liquids are in reasonable agreement with earlier measurements in which an infrared spectrophotometer was used. However, in the cases of methylcyclohexane, benzene, and chlorobenzene, some of the listed wavelengths lie on the side of steep absorption peaks and the slope of transmittance vs wavelength is very large. Also, the absorptivities of the latter two are excessively high at two wavelengths. Kerosene and carbon tetrachloride were selected for further use, one being relatively opaque and the other relatively transparent at all

Table 1. CW transmittances.

Material	Thickness (mm)	Wavelength (μm)			
		9.269	9.550	10.244	10.588
		Transmittance			
MgO	1.05	0.281	0.149	0.0019	0.0114
LiF	1.21	0.165	0.094	0.0089	0.0030
PS	0.71	<0.0003	0.0073	0.0026	0.0031
PTFE	0.81	<0.0003	0.0064	0.0321	0.0145
Kerosene	0.81	0.076	0.090	0.024	0.035
CCl ₄	0.81	0.68	0.81	0.117	0.76
CCl ₄	9.1	0.013	0.086	<0.0004	0.057
Methylcyclohexane	0.81	0.089	0.38	0.003	0.33
Benzene	0.81	0.23	<0.0003	0.029	0.19
Chlorobenzene	0.81	<0.0004	0.038	0.024	0.043

four bands. The depth of the cup of stirred-liquid calorimeter was 18 mm; even at $9.550\ \mu\text{m}$, CCl_4 absorbs 98.8% of the beam before it strikes the back.

TOTAL REFLECTANCE

The reflectance calorimeter was used to measure the combined specular reflection and thermal reradiation loss (R_T) from specimens of MgO, LiF, PS and PTFE (2.08, 1.91, 0.74, and 0.81 mm thick, respectively). The absorber was slanted at an angle of 15°

to the beam, but the calorimeter housing was inclined so that the plane of incidence was 45° from the plane of polarization, thus, the specular reflectance was essentially that for normal incidence. R_T as given in Table 2 is defined as the ratio of the sum of the reflected and reradiated energy to the incident energy.

The test specimen in the reflectance calorimeter was 620 mm from the lens. For MgO, LiF, and PTFE, measurements were also performed at $10.588\ \mu\text{m}$ with the specimen 720 and 820 mm from the lens; there was no significant change in R_T .

Table 2. CW total reflectances.

Wavelength (μm)	MgO		LiF		PS	PTFE
	Series I	Series II	Series I	Series II		
9.247		0.025	0.003	0.004	0.071	0.065
9.269	0.022	0.024	0.003	0.004	0.071	0.064
9.291	0.022	0.023	0.003	0.004	0.074	0.064
9.315	0.024	0.023	0.003	0.004	0.074	0.062
9.455	0.020		0.003			
9.486	0.021	0.023	0.003	0.003	0.073	0.060
9.517	0.020	0.021	0.003	0.003	0.072	0.058
9.550	0.020	0.021	0.003	0.003	0.072	0.055
9.584	0.020	0.020	0.003	0.003	0.070	0.056
9.619	0.019	0.020	0.003	0.003	0.071	0.055
9.655	0.018	0.020	0.003	0.003	0.070	0.053
10.166		0.014	0.000	0.000	0.072	0.047
10.192	0.012	0.014	0.000	0.000	0.071	0.047
10.217	0.013	0.013	0.000	0.000	0.073	0.046
10.244	0.013	0.012	0.000	0.000	0.072	0.046
10.272	0.012	0.013	0.000	0.000	0.072	0.046
10.301	0.011	0.012	0.000	0.000	0.071	0.047
10.331	0.011	0.012	0.000	0.000	0.071	0.047
10.473	0.010	0.010	0.000	0.000	0.070	0.044
10.510	0.009	0.010	0.000	0.000	0.072	0.046
10.549	0.010	0.010	0.000	0.000	0.072	0.045
10.588	0.008	0.009	0.000	0.000	0.071	0.046
10.629	0.007	0.008	0.000	0.000	0.070	0.046
10.672	0.007	0.008	0.000	0.000	0.070	0.046
10.716	0.007	0.008	0.000	0.000	0.067	0.046
10.761	0.007	0.007	-	-	0.066	0.046

All measurements were performed in duplicate with the beam centered on the test specimen, except that for each specimen four measurements were performed at 10.588 μm with the calorimeter successively displaced 3 mm up, down, left, and right to establish that there was no perturbation resulting from a fringe of the beam striking the reflectance cup. The splitter was not present during these measurements; irradiations were for about 1 s at about 2 W. The precision in R_1 is about ± 0.001 .

Series I for MgO and LiF was performed with another laser of the same type, but with a different beam arrangement. The power density was approximately equal to that given by the system used in the remainder of the work at a distance somewhere in the region 600 to 800 mm from the lens. Since R_T was found to be insensitive to the variation of energy density in this region, it is unlikely that any substantial error is due to the change in irradiation conditions.

The MgO specimen was remeasured at a few wavelengths after exposure to the room atmosphere for 17 days; no significant change was found. The MgO and LiF specimens were then stored in an atmosphere of 80% relative humidity for 49 and 47 days, respectively, before performance of Series II. This was done to determine if there might be any slow change in the reflectance characteristics resulting from the formation of surface films by reaction with atmospheric moisture. It may be seen from Table 3 that the change, if any, is barely significant; however, in the remaining work the calorimeter openings were plugged when not in use, with a package of desiccant in the interior.

SPECULAR REFLECTANCE

The lens was removed from the split-beam system and the test specimen was mounted about 605 mm from the former position of the lens, at an angle of 13.2° . The energy ratio E_{RC}/E_{MC} was measured first with RC in the beam reflected from the test

specimen and then with RC in the beam between the splitter and test specimen. The ratio of the two ratios is given in Table 3 as R_1 , the reflectance at an angle of incidence of 13.2° with the plane of polarization parallel to the plane of incidence.

The results are corrected to normal incidence and tabulated as R_2 , and the derived values of the index of refraction are given. The values of the total reflectance, R_T , are also given. The difference between R_1 and R_2 may be taken as the thermal reradiation. However, the surface of the PTFE is sufficiently rough that the values of R_1 , R_2 and n may be low.

The NaCl value is for the stirred-liquid calorimeter, which was filled with kerosene and arranged to measure mainly the first-surface reflectance. However, it is possible that a little of the second-surface reflection, due to nonequality of the indexes of refraction of NaCl and kerosene, might be reflected from the black-painted bore of the aluminum block of the RC and reach the absorber. The derived values of n agree with literature values within experimental error, however, suggesting that such an effect was not significant.

The reflectance measurements were performed in duplicate: the reflecting specimen was moved between the measurements so that the beam struck a different spot. The reproducibility of R_1 was typically ± 0.0005 .

ABSORBER COMPARISONS

Split-beam comparisons were performed using 2.14-mm MgO, 2.11-mm LiF, 0.72-mm PS, 0.81-mm PTFE, kerosene, and carbon tetrachloride as the absorbers in EC. A typical sequence of measurements was:

1-6:	Calibrate MC, RC, and EC electrically, twice each.
7,8:	RC, 9.269 μm
9-12:	EC, 9.269 μm
13,14:	RC, 9.269 μm

15-22: Repeat 7-14 at 9.550 μm
 23-28: Repeat 1-6
 29-36: Repeat 7-14 at 10.269 μm
 37-39: RC, 10.588 μm
 40-43: EC, 10.588 μm
 44-45: EC, 10.588 μm
 46,47: EC, 10.588 μm , $d = 700$ m
 48,49: EC, 10.588 μm , $d = 800$ m
 50,51: EC, 10.588 μm , $d = 900$ m
 52,53: EC, 10.588 μm
 54-56: RC, 10.588 μm
 57-62: Repeat 1-6

The receiver of RC and EC was at a distance $d = 500$ mm from the lens, except for 46-51. At each wavelength RC and EC were moved so that the

beam struck the receiver at four spots, 3 mm above or below and 3 mm left or right of the center; this was done so that any substantial variation in the absorptivity of the surface from one spot to another would be evident. For 44-53, however, the beam was aimed at the center of the receiver; these measurements were made to detect any nonlinearity of response with increasing energy density in the convergent beam.

The observed energies were divided by $1-R_T$, from Table 2 ($1-R_S$ for NaCl from Table 3, in the case of liquids) to correct for total reflectance. The individual values of (E_{RC}/E_{MC}) and (E_{EC}/E_{MC}) at each wavelength were averaged. The ratio of the averages is given in Table 4 for the four wavelengths

Table 3. CW specular reflectances.

Material	Property	Wavelength (μm)			
		9.269	9.550	10.244	10.588
		Property values			
MgO	R_i	0.0215	0.0191	0.0121	0.0086
	R_s	0.0233	0.0207	0.0132	0.0094
	R_t	0.023	0.020	0.012	0.008
	n	1.360	1.337	1.260	1.215
LiF	R_i	0.0041	0.0031	0.0011	0.0005
	R_s	0.0046	0.0034	0.0012	0.0006
	R_t	0.004	0.003	0.000	0.000
	n	1.144	1.124	1.072	1.048
PS	R_i	0.0404	0.0431	0.0414	0.0431
	R_s	0.0434	0.0463	0.0445	0.0463
	R_t	0.071	0.072	0.072	0.071
	n	1.527	1.548	1.535	1.548
PTFE	R_i	0.0382	0.0324	0.0265	0.0249
	R_s	0.0411	0.0350	0.0287	0.0270
	R_t	0.064	0.055	0.046	0.046
	n	1.508	1.460	1.408	1.393
NaCl	R_i	0.0381	0.0375	0.0368	0.0362
	R_s	0.0410	0.0404	0.0396	0.0390
	R_t	—	—	—	—
	n	1.508	1.503	1.497	1.492

with a fixed beam position and in Table 5 for 10.588 μm with increasing energy density. The precision in the measurement of the energy ratios was about 0.1% for solids and 1% for liquids.

A surface-absorbing tubular calorimeter previously described⁴ was also used as the EC for series at 9.269 and 10.588 μm only, with the opening of the calorimeter 790 mm from the lens. It was moved alternately to three positions with the beam cen-

Table 4. CW split-beam absorber comparisons.

Absorber	Wavelength (μm)			
	9.269	9.550	10.244	10.588
	$E_{\text{EC}}/E_{\text{RC}}$			
MgO	—	—	—	0.999
LiF	1.002	1.001	0.999	0.999
PS	0.993	0.996	0.991	0.995
PTFE	1.002	0.999	1.001	1.001
Kerosene	0.988	0.989	0.988	0.992
CCl_4	1.004	1.001	1.001	1.015

Table 5. CW split-beam absorber comparisons at 10.588 μm in convergent beam.

Absorber	Distance (mm)			
	500	700	800	900
	$E_{\text{EC}}/E_{\text{RC}}$			
MgO	0.999	0.998	0.993	0.994
LiF	0.999	0.996	0.996	0.993
PS	0.997	0.983	0.986	0.988
PTFE	1.004	1.000	0.979	0.963

tered or 1.5 mm left or right of the center of the opening of the tube. The precision of the measurements of $E_{\text{EC}}/E_{\text{MC}}$ was about 0.15%. Assuming zero for the reflectance of the tubular calorimeter, the ratio $E_{\text{EC}}/E_{\text{RC}}$ was 1.000 at 9.269 μm and 0.990 at 10.588 μm . The reflectivity of metals generally increases with increasing wavelength in the infrared, and part of this discrepancy may be due to more scattering back out of the tube from scratches and other irregularities at the longer wavelength.

Pulse Results

TRANSMITTANCE

All of the individual transmittance measurements are listed in Table 6. The specimens of material used were the same as for the CW measurements.

The first two MgO values, the first two LiF values, the first two CCl_4 values, and all of the PS and PTFE values were measured with preliminary setups and are less precise. The observed values were divided by $(1-R_s)^2$, where R_s is the CW specular reflectance from Table 3, to obtain the internal transmittances listed in Table 6.

It may be seen that the transmittances decrease significantly beyond about 3 J/cm². They are therefore labeled "apparent" because it is probable that the lower values are due to loss of energy in the air and not to increased absorption in the mate-

rial (see the following section). The values at low energy densities are in substantial agreement with the CW results. The largest discrepancy was for LiF; the available specimen of LiF was only 25 mm in diameter, and it is probable that some pulse energy passed outside this diameter to the calorimeter. The same effect might have affected the CW results to a lesser degree. No evidence of damage was found on the test specimens.

ABSORBER COMPARISONS

Split-beam comparisons were performed using, in EC, the same specimens of MgO and PTFE used for the CW measurements. Unfortunately, the laser system suffered a breakdown after two PTFE measurements and the program was terminated. Table 7

Table 6. Pulse transmittances (apparent).

Material	Thickness (mm)	Distance, d (m)	Energy density, D (J/cm ²)	Transmittance
MgO	1.05	1.00	2.2	0.0107
		1.00	4.1	0.0100
		1.00	2.5	0.0113
		1.30	6.9	0.0079
		1.60	18.3	0.0042
		1.60	19.6	0.0043
LiF	1.21	1.00	2.4	0.0049
		1.00	3.0	0.0049
		0.60	1.7	0.0063
		1.00	3.5	0.0046
PS	0.71	0.40	1.4	0.0025
		0.40	1.5	0.0027
		1.00	1.4	0.0031
		1.00	2.5	0.0032
		1.30	3.0	0.0027
		1.30	3.7	0.0028
		1.70	33.2	0.0011
PTFE	0.81	0.37	1.0	0.0148
		1.00	1.8	0.0145
		1.00	2.0	0.0138
		1.30	1.4	0.0145
		1.30	2.0	0.0138
		1.30	3.5	0.0134
		1.70	27.9	0.0050
		1.70	30.7	0.0057
CCl ₄	9.1	0.60	1.6	0.047
		0.60	2.0	0.048
		0.60	1.0	0.051
		0.60	1.5	0.052

lists the results of all the individual runs. The observed energy values were divided by $1-R_t$, where R_t is the CW total reflectance. Ten E_{RC}/E_{MC} measurements were interspersed; the mean was 10.32 ± 0.06 (uncertainty interval twice the standard deviation of the mean). All of these measurements were done with the RC receiver 60 cm from the lens and energy densities of 0.6 to 1.7 J/cm².

The results for the EC with MgO are plotted in Fig. 1. Note that beyond 2 or 3 J/cm² the apparent energy received falls off rapidly. During the transmittance measurements, a flash was observed at the surface of Irtran-5 when the calculated energy density exceeded about 2 J/cm². When the specimen was moved further back in the converging beam, a series of sparks — a "chain of beads" — appeared

Fig. 1. MgO pulsed converging-beam comparison.

for some distance in front of the specimen. It is thus highly probable that the decrease in energy observed in the calorimeter here and in several of the transmittance measurements is due to the loss of energy by breakdown in air.

Three years earlier a series of comparisons was performed using the same type of stirred-liquid calorimeters and similar solid-absorber calorimeters. The laser system⁵ produced pulses that were about 100 ns wide. A split-beam test arrangement with a converging lens was used to give energy densities of about 0.5, 2.5, and 18 J/cm² at the receiver of EC. At 0.5 and 2.5 J/cm², PS, PTFE, polyvinyl chloride

Table 7. Pulse split-beam absorber comparisons in convergent beam.

Absorber	Distance, d (m)	Energy density, D (J/cm ²)	F _{EC} /F _{EC}
Mg	0.60	1.3	1.034
	0.60	1.4	0.991
	0.60	1.6	0.994
	0.60	1.9	1.009
	0.90	2.0	0.990
	0.90	2.6	0.984
	0.90	2.8	0.979
	1.00	2.7	0.988
	1.00	2.8	0.987
	1.10	3.8	0.936
	1.20	5.5	0.832
	1.30	5.9	0.796
PTFE	0.60	0.32	1.028
	0.60	0.32	0.995

(PVC), Plexiglas (PG), kerosene, CCl₄, methylcyclohexane and chlorobenzene all gave values of F_{EC}/F_{EC} in agreement within $\pm 5\%$ (except that PVC showed damage and gave a lower value at 2.5 J/cm²). All showed much lower values at 18 J/cm² (the stirred-liquid calorimeters had sodium chloride windows that sometimes cracked). The transmittances of 0.76-mm PVC and 1.60-mm PG were both < 0.002 (the PG absorber used in the EC was 0.79 mm thick).

Discussion

The general agreement of the three types of calorimeters — solid volume-absorption with four materials, liquid volume-absorption with two materials, and the tubular surface absorption — indicates that the measurements of CW beams can be made accurate to 1% or better. A similar solid volume-absorbing calorimeter using NG-1 glass was

compared at the National Bureau of Standards with their C-series calorimeters; agreement was within 0.6%.^{1,2}

The MgO and LiF absorbers showed no damage after any of the tests. The PS specimen used in the reflectance calorimeter showed definite evidence of surface melting spots, about 3.5 mm in diameter, at

the four spots which were struck only once; the damage was only moderately greater at the central spot, which was struck 48 times. The PS specimen used in EC showed similar damage at the four spots irradiated at a distance of 500 mm, and a deeper pit at the central spot irradiated at distances up to 900 mm. The PTFE specimens showed a similar pattern of smaller and less intense spots. It is evident that MgO and LiF are the preferred solid absorbers because of their lower reflectances, higher damage threshold, and linearity to higher energy densities. However, they are rather expensive in large sizes, and the plastics are adequate for most purposes. The properties of commercial plastics may be expected to vary from one batch to another

or from one manufacturer to another. The specimens used in this work were cut from large sheets, which one may hope to be reasonably homogeneous; absorbers for numerous future calorimeters could be cut from these sheets.

The measurements with nanosecond pulses are less complete and the earlier measurements with 100-ns pulses are less precise than would be desirable. However, all of the data obtained — particularly the nanosecond-time transmittances — show no significant differences from the CW observations and imply that all the materials are usable up to 2 J/cm^2 or $2 \times 10^9 \text{ W/cm}^2$. Stirred-liquid calorimeters could be used for very high-energy long-pulse or CW lasers.

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