Appendix B
Material Damage Thresholds

B1. Limits for Absorbers

For absorptive filters there will be strong absorption at the test wavelength. In some cases, the absorption is inherent to the substrate, for example, most glasses and plastics at the CO_2 wavelength. In other cases, the absorption is due to an additive or dye mixed into the substrate material to strongly absorb the wavelength of interest. Much laser-induced material/substrate damage data is derived from exposures to a CO_2 laser, especially for exposure periods longer than a few milliseconds. The mechanism of damage in such exposures is the thermal result of absorbed energy. To at least a first approximation, such damage is independent of the laser wavelength, requiring only that incident laser energy be strongly absorbed in the material. Thus, the data derived from CO_2 laser exposures is relevant to all exposures at wavelengths where the laser is highly absorbed. It must be recognized that the laser induced damage threshold (LIDT) and the actual damage level will be a function of the irradiance diameter and the absorption coefficient of the material. These two parameters taken together, determine the volume within which the energy is deposited. Figure B1 presents available data that varies in both parameters.

The data as shown in Figure B1 helps to quantify the damage thresholds for various substrate materials. In all cases, LIDT is proportional to $t^{0.5}$ for exposures longer than a few microseconds to milliseconds, depending on the material. It might be expected that this relationship would extend down to a few nanoseconds, but at least in the case of the plastics, for example, acrylics or polycarbonate, effects such as material flow and plume formation protect the material for shorter exposures. Data for absorbing glass and fused silica substrates are limited for shorter exposures. It would be expected there would be large thermal gradients in these materials that would lead to surface damage for short exposures. Table B1 supports the data in Figures B1 and B3.

B2. Limits for Reflectors

Determining the limits for reflective technologies is different in that the substrate is generally transparent at the wavelength of interest, and in the absence of significant absorption, laser-induced thermal damage occurs only at very high radiant exposures or if there are imperfections, such as dust or dirt in the substrate. The more useful measure is the threshold for damage to the generally non-absorbing, very thin metal, or multilayer dielectric coatings on the substrate. These coatings are specifically designed to reflect the incident radiation and in doing so, significantly reduce the level of absorption within the coating and substrate. Reflective devices are in general very resistant to damage for exposures longer than a few milliseconds, simply because of the very low absorption of the energy required to thermally degrade the material.

Figure B2 presents current understanding of the LIDT for highly transparent materials. The curves are adapted from Wood, SPIE Vol 3578:201-211, 1999. They show that for fused silica, the LIDT scales directly as the time and inversely to the irradiance diameter for exposures longer than 10^{-8}

seconds, and then scales as the square root of time for exposures from 10^{-11}s to 10^{-8} s. Below 10^{-11} seconds the LIDT remains constant or perhaps even increases. Damage data that exists only for short duration exposures agree with the curve. Damage levels for reflective coatings are not easily determined, but it is not expected that they would be any higher than the substrate damage threshold.

Figure B3 compares the LIDT for absorbing and transparent substrate materials. For exposures longer than one microsecond, transparent materials are more resistant to laser-induced damage than absorbing materials. Transparent materials appear to be more susceptible to damage for shorter exposures, though in part, this is because the curves for transparent materials represent a more subtle level of damage than do the curves for absorbing materials. This might result in a requirement to test clear materials at or above their LIDT, but that is a conservative approach.

B3. Limits for Barriers, Curtains, and Windows

Reflective technologies, in general, are not found in large area protection such as curtains, canopies, large blocks, and windows. The cost of fabrication precludes such application. These are the applications most likely to be subjected to potentially damaging radiant exposures. The useful damage variable for these devices is the burn-through time, which is a function of incident power, material thickness, and material type.

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Table B1. Selection of Failure Threshold Values (TV) by Substrate Type.

Material Type	**TV_{max} (J/cm^2)**		
	$<10^{-6}$ s	10^{-6} to 10^{-3} s	$> 10^{-3}$ s
soft plastic (acrylic)	3	3	$100 \cdot t^{0.5}$
polymeric plastic (polycarbonate)	10	10	$300 \cdot t^{0.5}$
glass	1	$1000 \cdot t^{0.5}$	$1000 \cdot t^{0.5}$
quartz	2	$2000 \cdot t^{0.5}$	$2000 \cdot t^{0.5}$

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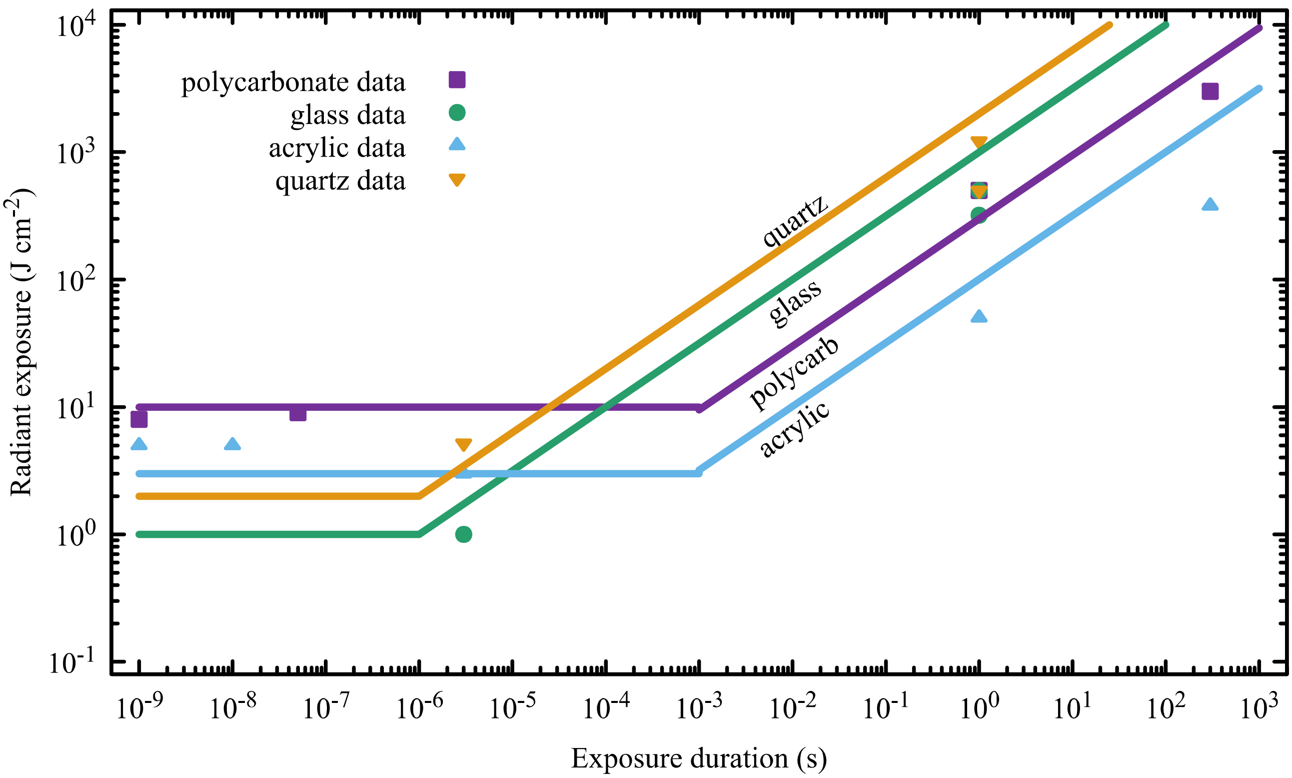

Figure B1. LIDT for Absorbing Substrates.

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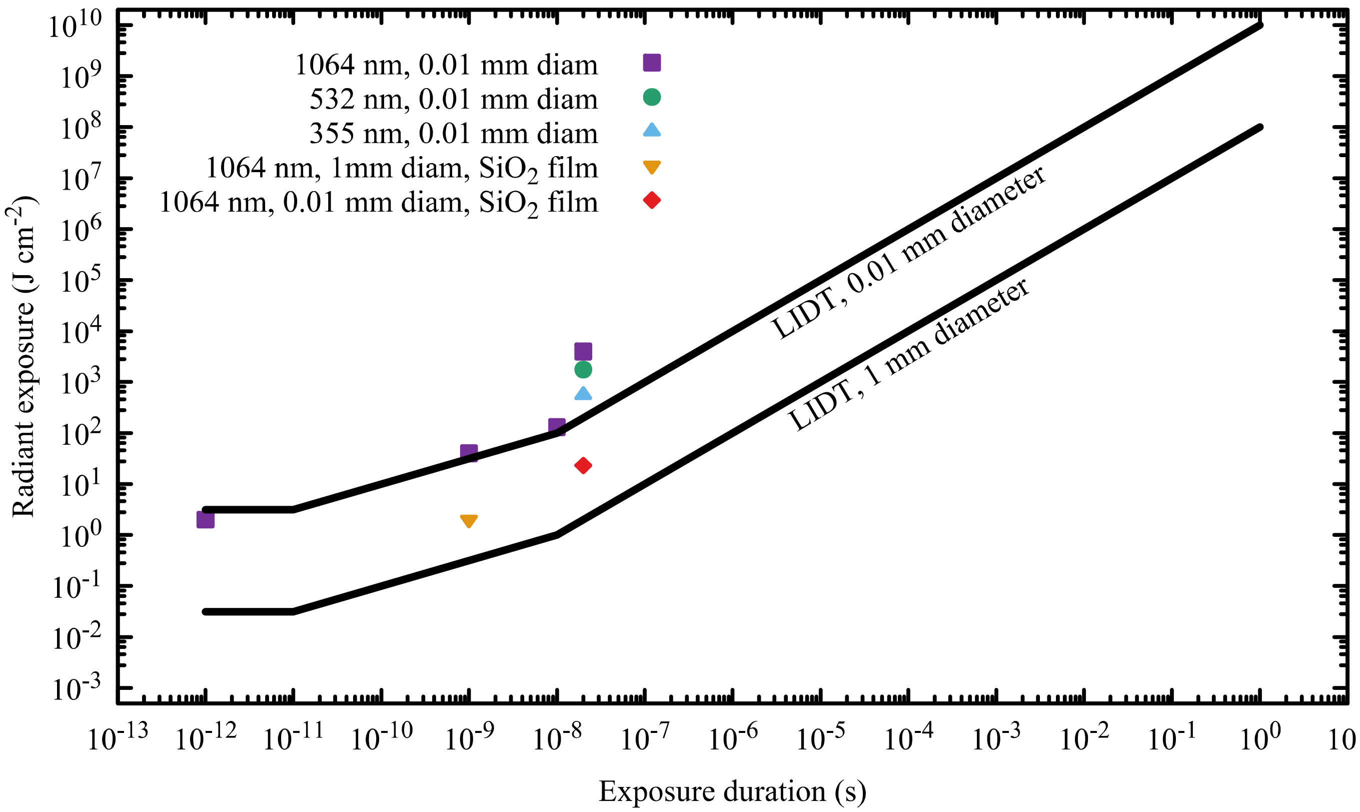

Figure B2. LIDT for Transparent Substrates.

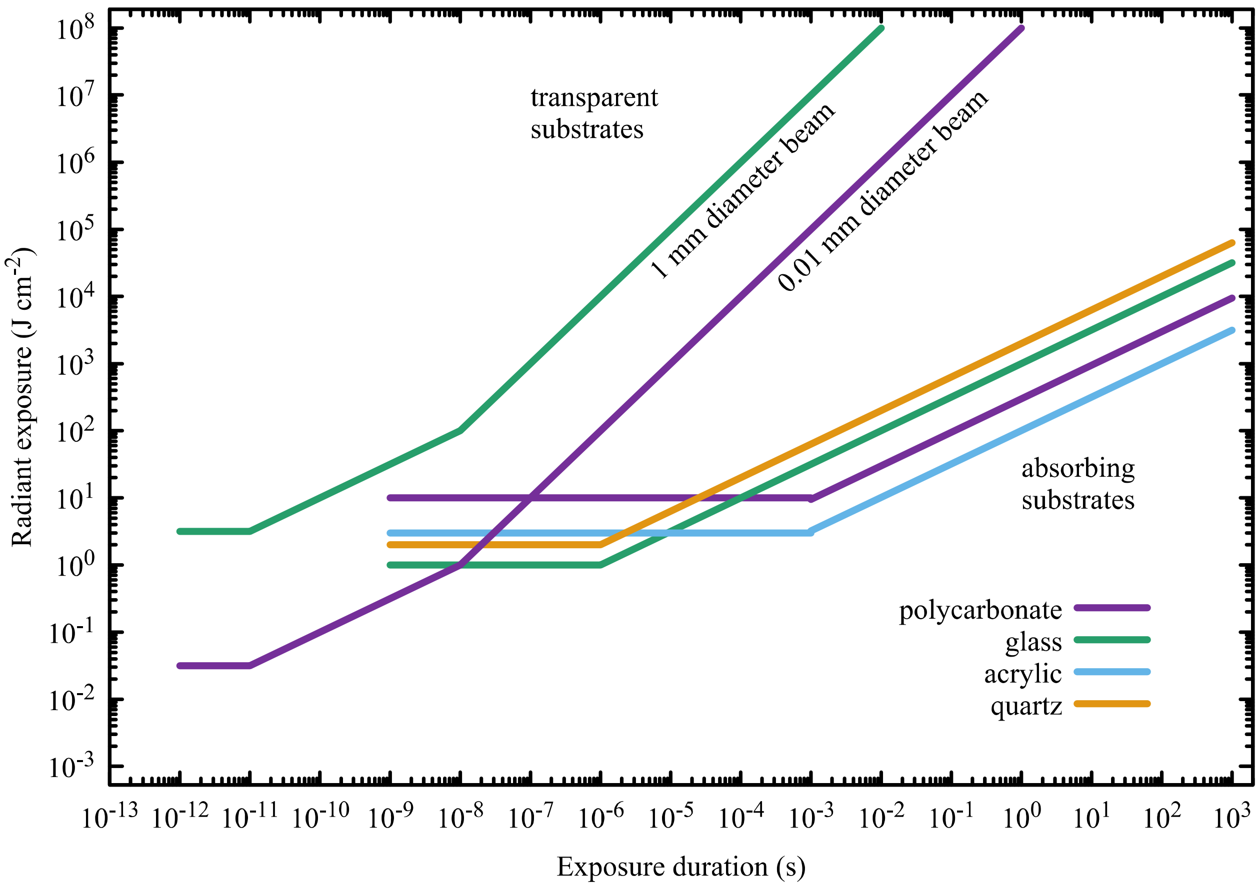

Figure B3. A Comparison of LIDTs for Absorbing and Transparent Substrates.

Appendix C
Procedure for Laser Based Testing of Optical Density for Absorptive Filters

C1. Introduction

This SOP describes a method to measure the OD of a sample by direct comparison to a neutral density (ND) filter of a known OD. This is not the only possible procedure to measure sample OD, but has the advantage of limiting the range of energy/power at the detectors to ensure that they remain well within their linear range. A sample apparatus configuration for determining OD is shown in Figure C1. See Figure C1 for a list of acronyms used in this section.

The laser is chosen to yield the required wavelength, pulse duration, and energy/power. The laser, beam BE, and AP4 produce a collimated beam of known profile, top-hat or Gaussian, such that the peak and average irradiance/radiant exposure at the target can be accurately determined. A wedge BS reflects a portion of the beam into a Detector B to provide the data necessary to normalize the pulse-to-pulse or time-dependent variation of the laser output. The BS prevents interference between the front and back surface reflections, and is insensitive to small changes in incidence angle. The reflectance of the BS is dependent upon the plane of polarization of the incident beam; therefore, the beam must be polarized.

Properly placed apertures (AP2, AP3) ensure that the detectors see only the power/energy passing through the sample or ND filters. Beam limiting apertures must be placed before the BS.

The detectors should be selected to match the laser wavelength and pulse duration to ensure sufficient sensitivity with minimum and maximum energy to measure the transmitted power/energy. ND filters, ND1 and ND2, are chosen to ensure that the detectors are operating within their linear range. A calibrated BP filter of the appropriate wavelength is inserted prior to the transmitted power detector to ensure only the transmitted radiation is collected. Filters ND1, ND2, and BP must be chosen to ensure that there is no saturable absorption at the specified irradiance, or radiant exposure, for pulse durations used for testing. The transmission of the sample is determined by direct comparison to ND3, a calibrated ND filter of known OD.

When stacking absorptive filters of any type, care should be taken to place filters of the lowest attenuation closest to the laser source. This is to reduce the potential to damage a filter. For example, placing a 1.0 OD filter in front of a 2.0 filter reduces the laser power by 90 % then again by 99%. If the order were switched, the initial filter would be absorbing more of the initial laser energy (99%) and potentially increasing the possibility of damage. Pin-hole baffles of appropriate size should also be placed between each filter to reduce reflections.

Pulse duration has a significant effect on the protective qualities of filters. When qualifying a filter using ultrashort pulsed lasers, the duration of the pulse and the spectral bandwidth of the laser must be carefully quantified and should be indicated in the test documentation. Generally, at U pulse durations, the spectral bandwidth of the laser emission will be broader than the spectral bandwidth of CW or Q-switched lasers. Nonlinear effects are known to exist at U pulse durations, including self-focusing and continuum generation. It is recommended that a user test the protective filter against the laser with which it will be used to determine that a filter actually protects against the exact wavelength profile of the laser.

C2. Procedure

a) Calibration.

1. Verify the laser wavelength.
2. If the laser is pulsed, measure the pulse duration.
3. Measure the beam profile at the sample position. The beam diameter should be ≥ 1.0 mm measured at the diameter at which the intensity falls to 1/e of the peak intensity.
4. Determine the irradiance/radiant exposure at the sample position.
5. Select a calibrated ND3 filter to match the estimated OD of the sample.
6. Calibrate the system by inserting reference ND filters at the sample location and measuring the OD using the procedure below.
7. Compare the measured values to the known reference values.

b) Measure the OD of the sample.

1. Ensure that the beam is perpendicular to the sample surface and that all transmitted energy reaches the detector. Ensure that there is no potential lensing/optical wedge or clipping by the sample.
2. Simultaneously measure the energy/power at detector A (sample) and detector B (reference).
3. Determine the ratio $\Re_{A3} = \left(\frac{Q_A}{Q_B}\right)_{A3}$ with calibrated attenuator ND3 in place.
4. Determine the ratio $\Re_S = \left(\frac{Q_A}{Q_B}\right)_S$ with sample in place.
5. Calculate the transmission/OD of the sample.

$$\tau_S = \tau_{A3} \cdot \frac{\Re_S}{\Re_{A3}} \tag{C1}$$

$$OD_S = OD_{A3} + \log_{10} \frac{\Re_{A3}}{\Re_S} \tag{C2}$$

c) Test for saturation/nonlinear absorption.

Saturable absorption is evident when the OD at high irradiance levels is lower than the OD at low irradiance levels. Saturable absorption occurs under high irradiance and will only be observed for Q-switched or ultrashort pulse lasers. The measurement requires that the OD be determined for low irradiance where only linear absorption is possible and at a high irradiance where nonlinear absorption occurs.

For this measurement, the ND1 filter should have a high OD that is consistent with measuring sufficient energy levels at the detector for accurate measurement.

1. Low radiant exposure: Place the ND1 filter before the sample as shown in Figure C1. Measure the transmission /OD of the sample as in Section C2.
2. High radiant exposure: Place the ND1filter between the sample and the detector. Measure the transmission/OD of the sample as in Section C2.

If the results of steps 1 and 2 are different, nonlinear absorption is indicated.

d) Procedure to estimate the OD of the sample if it is above the measurement capability of system. This procedure is used when the energy/power transmitted through the sample is below the linear range of the sample detector.

1. Measure the response of the system to determine the measured OD for filters of known OD values.
2. Using computer software, generate a simple polynomial fit for the data generated in step 1, letting x be the known ODs and Y the measured ODs. The resulting polynomial equation should be of the form:

$$Y = a + bx + cx^2 + dx^3 + ex^4 \tag{C3}$$

   The curve fitting software will generate the coefficients *a, b, c* and so forth. To generate a curve that matches the values in step 1, use as few terms as needed as a high order polynomial will be highly oscillatory and be of little use.

3. Determine the measured OD of the sample.

4. Insert the measured OD" into the equation developed in step 2 as the Y value. Solve for x to find the actual value of the sample. This can be done numerically through iterative substitution of approximate values of Y into the polynomial, graphically, or by generating a lookup table.

C3. Calibration Example

A range of known filters were measured. Results are shown in Table C1.

The equation for this data is:

$$Y = -0.00925 + 1.13x - 0.119x^2 + 0.0311x^3 - 0.00271x^4 \quad \text{(C4)}$$

A lookup table can then be easily prepared to compare known to calculated OD. A portion of a sample table is shown in Table C2.

The graph of this equation is shown in Figure C2.

Eventually the system will be unable to differentiate ODs as the curve has flattened off. In this example, known OD 7.00 and 8.00 both generated a measured OD of 6.20 that indicates the system cannot differentiate between 7.00 and 8.00 OD. This means that 7.00 is the highest value that the calibrated system can reliably measure.

Care should be taken to carefully quantify uncertainty of the measurement, both the linear region and the calibrated nonlinear region of the measurement system. This can be done by assessing the uncertainty of each individual component and propagating through to the end result. NIST Technical Note 1297 (Taylor & Kuyatt, 1994) provides guidance on this.

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