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Safety Guidelines for Laser Illumination on Exposed High Explosives and Metals in Contact with High Explosives with Calculational Results

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SAFETY GUIDELINES FOR LASER ILLUMINATION ON EXPOSED HIGH EXPLOSIVES AND METALS IN CONTACT WITH HIGH EXPLOSIVES WITH CALCULATIONAL RESULTS

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ABSTRACT

Experimental tests have been undertaken to determine safe levels of laser exposure on bare high explosive (HE) samples and on common metals used in intimate contact with HE. Laser light is often focused on bare HE and upon metals in contact with HE during alignment procedures and experimental metrology experiments. This paper looks at effects caused by focusing laser beams at high energy densities directly onto the surface of various bare HE samples. Laser energy densities (fluence) exceeding 19 kilowatts/cm^2 using a 5-milliwatt, 670 nm, cw laser diode were generated by focusing the laser down to a spot size diameter of 4 microns. Upon careful inspection, no laser damage was observed in any of the HE samples illuminated at this fluence level. Direct laser exposure of metals directly contacting HE surfaces was also tested. Laser energy densities (fluence) varying from 188 Watts/cm^2 to 12.7 KW/cm^2 were generated using an 11-Watt, 532 nm frequency-doubled Nd:YAG cw laser with focal spot size diameters as small as 100 microns. These measurements look at the temperature rise of the surface of the metal in contact with HE when laser energy is incident on the opposite side of the metal. The temperature rise was experimentally measured as a function of incident laser power, spot size, metal composition and metal thickness. Numerical simulations were also performed to solve the two-dimensional heat flow problem for this experimental geometry. In order to simplify the numerical simulation to allow representation of a large number of physical cases, the equations used in the simulation are expressed in terms of dimensionless variables. The normalized numerical solutions are then compared to the various experimental configurations utilized. Calculations and experiment agree well over the range measured. Safety guidelines for alignment laser illumination upon bare HE are outlined.

INTRODUCTION

In the High Explosives Application Facility (HEAF) at the Livermore National Laboratory (LLNL), laser beams are routinely focused onto HE samples. There has been some concern expressed that exposing HE to focused beams of low power and high power lasers for optical alignment and non-contact profilometry might initiate reactions that progress to deflagration and/or detonation. The question is how much laser intensity does it take? What are the limits of safely exposing HE to laser light? Three cases were explored experimentally to try to answer these questions. In addition, numerical calculations were performed to provide some guidance in determining safety limits for manned operations where laser beams illuminate HE samples.

Case 1) High power cw laser illumination on metal-cased explosives

The alignment laser sometimes consists of a high-power laser that will be used in an experiment during detonation but is operated at a much-reduced power for alignment purposes. The most common modes of operation with these lasers are when the laser beam impinges upon an explosive encased in a metal shell. Safety questions arise, however, when multiple-laser spots are focused onto the experiment simultaneously and when the laser spot size becomes very small, on the order of 100 microns or less.

Calculations can be made to estimate the maximum laser power that will initiate a reaction. While calculations should play a significant part in determining the safe level of operation, they need to be verified by experiment before they are relied upon for safety purposes. Only after a set of calculations has been experimentally verified should one consider using similar calculations to estimate power levels in a new experimental configuration. This is prudent only if a strict set of calculational parameters pertaining to the new configuration is used in conjunction with experimentally verified safety considerations.

Case 2) High power cw laser illumination on bare explosives

High power lasers used in detonation diagnostic experiments, are frequently reduced in power and aimed onto bare HE as part of the pre-alignment process. Many of the lasers operated in the alignment mode are of low enough power so as not to be of concern to experimenters during manned operation. However, concern arises when a high-power laser is being utilized in an attenuated mode for alignment purposes. It is important to consider the maximum credible power that could reach the sample in a worst case failure mode of the laser or the attenuation mechanism.

Case 3) Low power cw laser illumination on bare explosives

Low power lasers are focused onto HE samples during optical alignment procedures prior to some HE experiments. Although total power is low, the fluence can be in the tens of thousands of Watts/cm^2! It is important to determine the maximum credible fluence that could reach the sample during the alignment process.

Non-contact surface profilometry measurements of HE samples are routinely performed prior to experimental testing. These operations involve focusing low power laser beams onto exposed HE surfaces. Again, with extremely tight focus, the fluence can be in the kilo-Watts/cm^2. Measurements were taken to verify that no damage or heating to HE will result with normal operation of laser profilometers.

EXPERIMENT #1 -- High power laser on encased high explosives

When the HE is encased in suitably thick metal layer, the only credible way for the CW alignment laser to create a problem is by heating the metal to a temperature that could cause a reaction to begin in the HE. The most thermally sensitive of the common explosives used at LLNL is PETN, which does not show significant exothermic reaction below a temperature of 150° C. It is possible to establish a set of safe, practical exposure guidelines by determining what laser and experimental parameters will produce temperatures of this order on the surface of the metal in contact with the HE.

In simulating temperature rise from laser exposure, it is not necessary to utilize actual HE as long as a material that simulates its thermal conductivity is placed upon the back surface of the metal under laser illumination. These experiments explore the temperature rise of the surface of a metal plate opposite the laser irradiation as a function of incident laser power, laser spot size diameter, type of metal in contact with the HE, and the thickness of the metal. The experimental arrangement is shown in Figure 1. A 7.62 x 7.62 cm square of metal is clamped to an aluminum holder that serves as a heat sink for the sample. The distance from the irradiated spot to the holder is 3.5 cm. A 1.0 cm thick piece of Styrofoam is epoxied to the back of the metal to simulate the worst-case thermal conductivity of typical explosives. A type K thermocouple junction is placed on the back surface of the metal, under the Styrofoam, directly behind the position of the irradiated spot on the opposite surface of the metal. A small dab of vacuum grease is placed on the thermocouple junction- metal interface to aid in the thermal contact. The junction itself is 1.0 mm in diameter.

First, very low laser power is used to align the beam spot upon the target metal. Next, the sample holder was removed and a Coherent Beamcode analyzer was put in its place to measure the spot size. This is repeated for various sample positions along the optical rail and the rail position is subsequently marked for various spot sizes. The beam diameters are measured at full width, 10% maximum. The Beamcode detector was then removed, permitting the beam to be collected by a Coherent 210 power meter and the laser power adjusted to the desired level. The laser was shuttered and the sample holder put back into place. The shutter is then opened and temperature readings are taken for the defined duration of time.

The laser used in these experiments is a Spectra Physics Millennia X, 532 nm frequency doubled Nd:YAG CW laser. The laser is capable of an output of 11 Watts, which translates to about 8.6 Watts maximum on the samples after accounting for losses in turning mirrors and lenses.

The strategy of this method is to map the parameter space in a way that could identify important dependencies without measuring every possible experimental permutation.

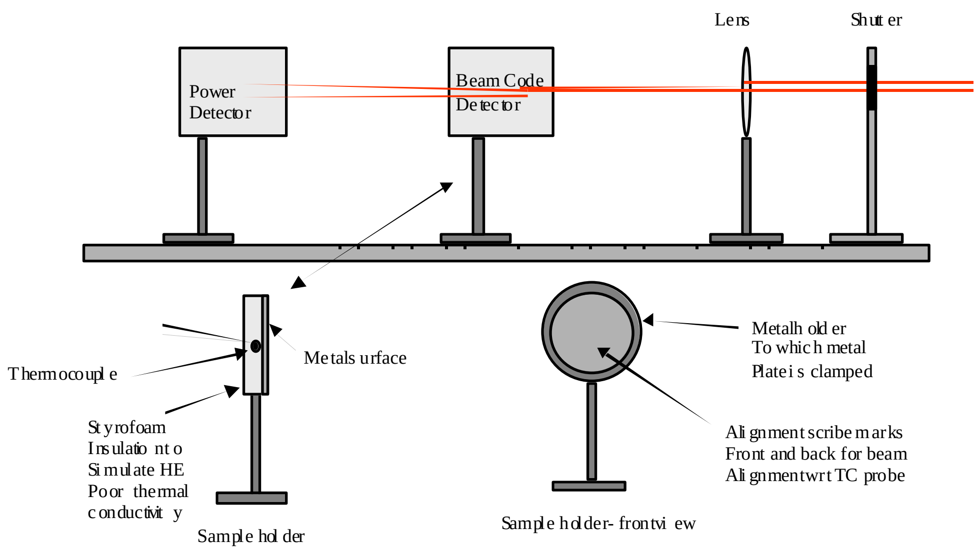

Figure 1

Experimental arrangement for measuring laser-induced temperature changes in metal plates.

ANALYSIS – High power laser on encased high explosives

This analysis considers the simplest simulation that accurately matches the experimental results requiring a numerical solution to the two-dimensional heat-flow problem through a thin metal plate.

It is assumed that the metal is a thin plate of uniform thickness, clamped as a circular disk at the periphery, and illuminated on one side, at the center, by a laser beam with a flat top circular illumination profile. For these calculations, it is assumed that there is no heat flow from the surface of the plate (except for the heat flow into the plate from the laser beam). The temperature is assumed to be fixed at the radius of the circular clamp into an infinite heat sink.

The heat flow equation may be obtained from:

$$H = -k\nabla T \qquad (1)$$

where H is the heat flow, k is the thermal conductivity, and T is the temperature. The conservation of energy implies $\nabla \bullet H = du/dt$ where u is the specific internal energy. Further, du/dt = CdT/dt where C is the specific heat of the material at temperature T. The result of these equations with Eq. 1 is

$$\nabla^2 T = \frac{C}{k}\frac{\partial T}{\partial t} \qquad (2)$$

When thermal equilibrium is reached, T obeys Laplace's equation: $\nabla^2 T = 0$.

In order to allow a single numerical simulation to represent a large number of physical cases, the equations to be simulated should be expressed in terms of dimensionless variables. We choose the thickness of the plate, taken to be w, as the unit of length. The normalized coordinate perpendicular to the flat surface of the plate will be z, which is actual length divided by w. The normalized radial coordinate is r, so that $0 \le r \le R/w$, where R is the radius at which the plate is clamped with the circular clamp. Then Eq. 2 becomes

$$\left(\frac{1}{r}\right)\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2}=0, \qquad (3)$$

where symmetry in the rotation about z and thermal equilibrium are assumed.

If the laser beam has a total power P and effective radius r_l, the power density in the beam is $P/\pi r_l^2$. At constant power density, Eqn. 1 shows the normal derivative (on the z=0 side of the disk with respect to the dimensionless coordinate z) at the place of laser incidence is

$$\frac{\partial T}{\partial z}=(1-\rho)\left(\frac{P_W}{\pi r_1^2 k}\right) \qquad (4)$$

where ρ is the reflection coefficient for the laser beam at the metal surface. To allow a simple value of one for the normal derivative boundary condition for numerical simulation we replace the actual temperature T by F' with

$$T=(1-\rho)\left(\frac{P_W}{\pi r_1^2 k}\right)F' \qquad (5)$$

Now the fully normalized equation is Eq. 3 with T replaced by F' and with boundary conditions $\frac{\partial F}{\partial r}=-1$ on z = 0, $0 \le r \le r_l/w$.

Numerical simulation shows that the radial flow of heat becomes uniform throughout the radial cross section of the metal disk before r = 10 for cases having $r_l/w < 8$. Thus it is sufficient, for disks having R/w > 10 to carry out numerical simulation only to r = 10 and use an analytic solution for r > 10. For r > 10 one has no variation in z so the problem becomes one-dimensional with analytic solution

$$F'=-k\ln\left(\frac{r_w}{R}\right)+F0', \qquad (6)$$

where F0' is the normalized ambient temperature at the clamped radius R of the plate. This results in boundary condition for the simulation of

$$F'=-k\ln\left(\frac{10}{R}\right)+F0' \quad \text{at } r = 10.$$

Next, note that conservation of energy in the steady state heat flow requires that the total heat flux in equals total heat flux out. Thus since normalized heat flux density out can be expressed at r = 10 as $-\partial F'/\partial r = k/r = k/10$ and normalized heat flux density in has been taken as one, the requirement becomes $2\pi 10k/10 = \pi(r_l/w)^2$ or $k = (1/2)(r_l/w)^2$.

Finally, we replace F' by $F = F' - F'|_{r=10}$ so that the equation to be solved numerically and its boundary conditions are

$$\left(\frac{1}{r}\right)\frac{\partial}{\partial r}\left(r\frac{\partial F}{\partial r}\right)+\frac{\partial^2 F}{\partial z^2}=0 \qquad (7)$$

$$\frac{\partial F}{\partial r}=-1, z=0, \quad 0\le r\le \frac{r_1}{w}$$

$$F=0, \quad 0\le z\le 1, \quad r=10$$

$$and \quad \frac{\partial F}{\partial n}=0 \quad \text{for all other surfaces.}$$

Thus the problem has been reduced to a two-dimensional, one parameter (r_l/w) study (as long as the parameter R/w is sufficiently large).

The relationship of normalized to unnormalized values is

$$T=(1-\rho)\left[\frac{P_w}{(\pi r_1^2 k)}\right]\left\{F+\frac{1}{2}\left(\frac{r_1}{w}\right)^2\ln\left(\frac{R}{10w}\right)\right\}+T_0 \qquad (8)$$

SIMULATION RESULTS AND COMPARISON WITH EXPERIMENT

Numerical simulations were run for r_l/w values 0.05, 0.1, 0.2, 1, 2, and 4. Calculations were carried out using *Student's QuickField*[1]. Calculations for F vs. r for the values of r_1/w are shown in Fig. 2 for temperatures on the face of the plate opposite the point of the incident laser beam (the side that would contact the HE).

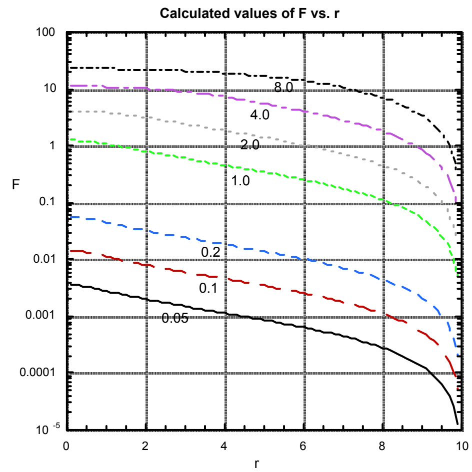

Figure 2
Calculated values of F vs. r for various values of r_l/w.

To check how well these predictions agree with experiment, we first take the case of 0.254 mm thick Cu and a laser beam radius of 0.25 mm with powers ranging from 1 to 8 W. We assume that the thermocouple probe measures the average temperature under the area of contact with the metal. From Fig. 3 we can get an average value of F to use in this calculation. Using this value of F and Eq. 8 with a value of .46 for the reflectivity of Cu, we get the results shown in Fig. 4.

We note that there is reasonably good agreement but the data and experiment do differ by about 10%. In fact, if we used a 10% change in the value of reflectivity, 0.51 instead of 0.46, then the data would agree very well.

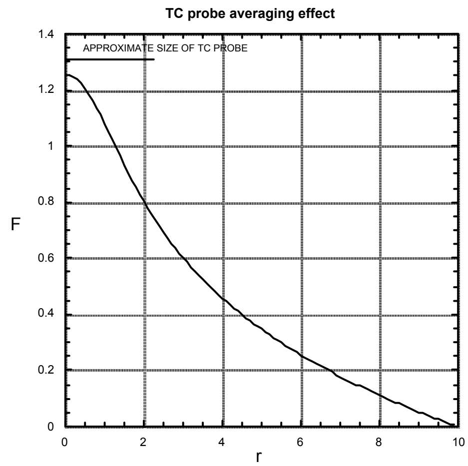

Figure 3

Relative size of the TC probe in relation to the temperature drop off for $r_l = 1$.

We suspect this is the explanation for the disagreement since the reflectivity of Cu changes very rapidly in spectral region.

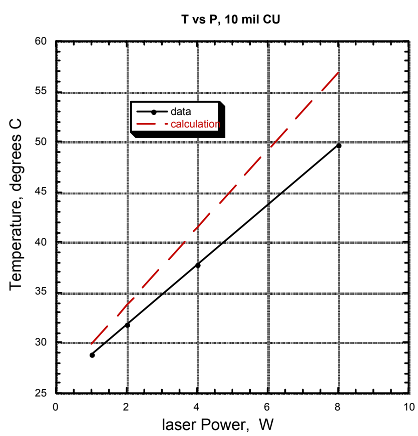

Figure 4

Calculated and experimental curves for the temperature of a .254 mm thick Cu sample irradiated with a .25 mm radius beam.

Likewise, the calculated value of temperature vs. power is plotted along with the data of stainless steel we get reasonable, but not exact agreement (Fig. 5). Again an adjustment in the value of the reflectivity from .56 to .52 would make both the data and calculations agree.

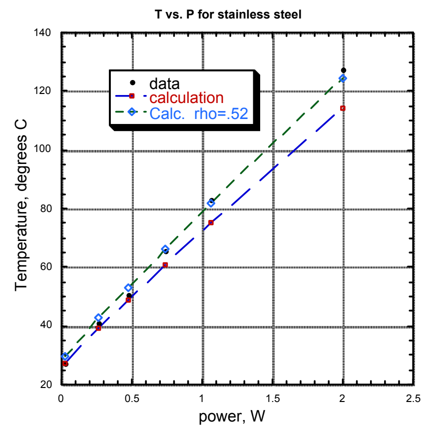

Figure 5

T vs. P for stainless steel compared with the calculated values using two different values of the reflectivity.

It should be noted that at higher power levels than 2 W with stainless steel that other mechanisms of heat removal start to become significant and the calculations are no longer valid. Radiation and convection will both play a part by cooling the front surface of the sample. Figure 6 shows a calculation of the front and back surfaces of a metal and one can see that the temperature on the front side is about a factor of 4 greater than the backside. This temperature difference varies with spot size but for the cases we tested the variation was no greater than a factor of 4. Since radiation goes as σT^4 where σ is the Stefan-Boltzmann constant, the front side of the plate will radiate at a rate of approximately 256 times that of the back. This effect lowers the temperature measured on the backside with respect to the simulated value. For the purpose of this study; however, such high powers are only of academic interest since one would almost never expect to see CW alignment powers at this level.

The variation of the temperature on the backside of the metal with respect to the laser spot size is also of interest from a safety standpoint. To investigate this, stainless steel was once again used since the temperature rise is greatest, and thus easier to measure. Holding the power constant, the spot size was varied from .1 mm diameter to .822 mm diameter. This is a power density variation from 188 W/cm^2 to 12,700 W/cm^2.

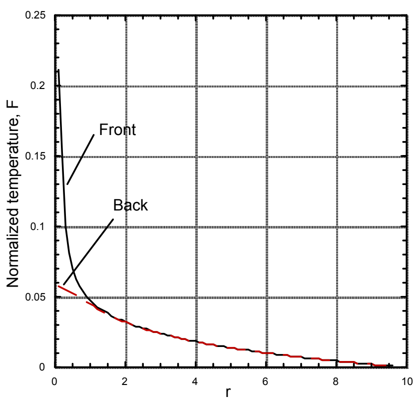

Figure 6

Calculation of the front side and backside temperature vs. r for r_l/w = 0. 2.

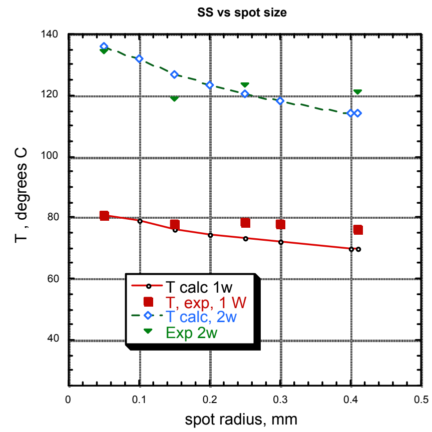

Figure 7

Temperature vs. spot diameter on the backside of a .254 mm thick stainless steel plate. Solid lines are the calculated values.

Figure 7 shows the experimental results compared with calculation. The peak temperature on the back side of the plate opposite the point of incidence of the laser beam decreases as the beam radius increases while the total power in the beam remains constant. This dependence is somewhat weak and, for sufficiently small beam radii, the temperature levels off and does not increase further.

Another parameter of importance is the thickness of the metal. Experimentally we chose Al for this study because of the availability of thin, uniform samples of material. Figure 8 shows a plot of the temperature on the backside of the Al vs. the thickness of the Al for both experimental data and the numerical simulation.

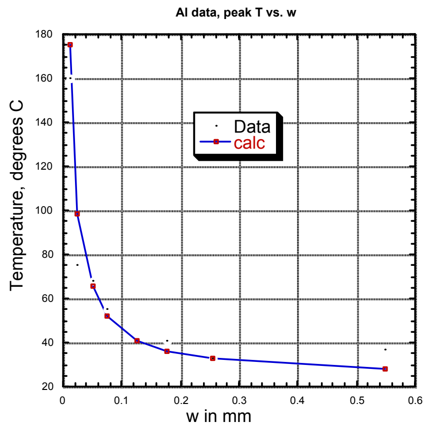

Figure 8

The temperature on the backside of Al as a function of the Al thickness.

The data were taken with a constant laser power of 4 W and a spot size of .1 mm diameter.

The agreement is rather good with the greatest departures occurring with the thin samples. The lower measured values of the two thinnest samples may arise because of the experimental arrangement.

In order to support such thin films of Al in the experimental configuration it was necessary to put a thin glass slide (.15mm thick) over the "laser entrance" side of the Al. Although the glass slide has poor thermal conductivity compared to the Al, it is six to twelve times as thick and, therefore, can cause a non-trivial effect in the temperature measurement.

DISCUSSION – High power laser on encased explosives

The numerical solution for temperature in a thin plate heated by a laser beam shows no surprises. The temperature rise on the side opposite the laser beam incidence only varies weakly with the size of the input laser beam. The dependence of the temperature on input laser power varies linearly and agrees well with the data. The temperature rise is fairly sensitive to values used for the reflectivity of the metal. Experiment and simulations also agree well for the temperature rise on the opposite side of the plate to laser incidence as a function of the metal thickness.

We have chosen a conservative approach for the amount of laser light permitted on explosive assemblies during manned operations. The data for encased explosives allow us to set some limits based upon safety margins deemed acceptable. For a 50˚ C maximum temperature allowed for the explosive during laser irradiation (~30˚ C above ambient), and for a .25 mm thick sample of the metals the following input laser power levels can be determined:

Cu	**4.0 W**
Al	**5.0 W**
Ta	**0.7 W**
SS	**0.23 W**

Table 1

Note that these levels have an additional factor-of-two safety margin to account for the temperature distribution within the thermocouple junction area. The 50˚ C limit is a temperature rise factor of about 4 below the temperature at which PETN, the most thermally sensitive of the common explosives we used, shows some sign of reaction.

As a further safety margin, let's assume that we have a blackened area of the metal that will cause a total absorption of the laser energy.

Using the values of the reflectivity in Fig. 9[2,3,4] we can adjust the safety margins downward for a totally absorbing material:

Cu	**1.32 W**
Al	**0.35 W**
Ta	**0.34 W**
SS	**0.10 W**

Table 2

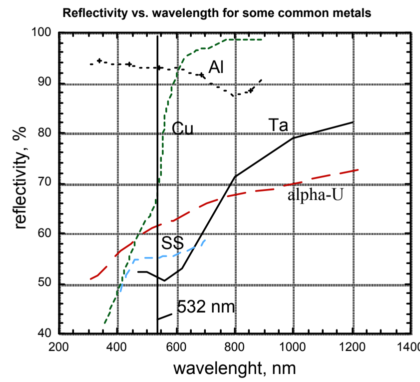

Figure 9.
Reflectivity of some common metals[2,3,4].

Most alignment intensities at LLNL are no more than 5 mW. There is occasion, however, when we desire to put multiple alignment beams on the explosive assembly. Assume we have 20 beams, each with a power of 5 mW, all concentrated onto a .2 mm diameter footprint. This worse case scenario then would have a total power of .1 W on the metal. This is the value for stainless steel that would cause a 50° C temperature on the metal in the case of a totally absorbing area. Even though this scenario is unlikely, we have determined that this is an unacceptable safety margin. If we limited the number of simultaneous beams to 5 this would buy us another factor of 4 in safety. Combined with the fact that the original temperature rise is a factor of 4 or more below the most thermally sensitive explosive we deal with, we now in reality have a factor of 16 safety margin for a worse case scenario.

Even though the majority of the data taken are at 532 nm, Fig. 9 shows that in the case of the four metals considered, the curves are relatively flat or improve toward longer wavelengths in the range of 500 to 800 nm. This information, combined with the fact we have already taken a worst-case scenario where all of the laser energy is absorbed, there is no reason that any laser in this range could not safely be used under the above restrictions.

EXPERIMENT #2 – High power laser on bare high explosives.

In order to establish safe operating limits for experiments which involve manned operation (usually meaning alignment) of CW laser light on HE, we performed a series of tests on 8 common types of HEs. With the exception of the pure HMX sample that was irradiated at 514 nm, all samples were irradiated with the 532 nm, Spectra Physics Millennia X laser. Spot size diameters used in the experiment were measured with a Coherent BeamCode analyzer and for most experiments were 1 mm. The diameters given are for full width, 10% maximum.

The HE sample was placed in a 2 gm HE containment chamber and the power level inside was measured before each experiment by a Coherent 210 power meter.

In all experiments, the sample was inspected under a microscope both before and after irradiation. The criteria for damage / no damage was this visual inspection. The samples were held in a plastic sleeve that was inserted in a Delrin holder. The Delrin holder was placed in a stainless steel holder inside the chamber. Heat flow had to go through several millimeters of plastic/Delrin to reach the metal heat sink, so the HE was fairly well thermally isolated. The sample size was .25 inches in diameter by 2 mm thick with the exception of the PETN, which was .3 inches in diameter by .3 inches thick. The PETN was also measured in an aluminum holder.

Table 3 below summarizes the power levels where damage, if any, was observed for the various samples. All samples were irradiated for 20 minutes with one exception we will discuss later.

Several comments are in order. The "pure white" samples were very difficult to damage. We believe this is due to the very high albedo (~80%) and the high transmission and scattering of the laser light inside the sample. A dramatic example of this is in the LX-14 sample (94.5% HMX + 4.5% Estane binder). When we irradiated the white area of the sample we observed no damage at 800 mW. However, when the laser light was focused onto the blue prill dye areas that same amount of incident power burned a hole completely through the sample! Laser power had to be dropped to 340 mW on the dyed areas before the damage threshold was reached.

HIGH EXPLOSIVE	DAMAGE POWER	SPOT SIZE	COMMENT
PETN	No damage at 800 mW	1 mm, 0.5 mm	Density = 1.55 gm/cc
HMX	No damage at 654 mW	0.3 mm	514 mW laser
LX-16	800mW	1 mm, 0.5 mm	1 mm no damage, 0.5 mm showed damage
LX-14	340 mW (+0, -50 mW)	1 mm	Damage level for blue prill dye region
TNT	340 mW (+0, -50 mW)	1 mm	
LX-17	230 mW (+0, -50 mW)	1 mm	
LX-15	110 mW (+0, -30 mW)	1 mm	
PBX-9407	70 mW (+0, -25 mW)	1 mm	

Table 3

Laser power levels that caused damage to high explosive samples

In the LX-16 sample (PETN + 4% FPC 461 binder) no damage was observed at 800 mW with a 1 mm spot size but at 0.5 mm spot size, a small area on the surface looked "glassy" with tiny fracture lines radiating outward. We believe the surface was melted and upon removing the beam, the area under went rapid cooling and thus stress fractures were formed. It is interesting that pure PETN did not show damage at these levels whereas the LX-16 did.

Our guess is that this must be due to the binder in the LX-16. Also note that 800 mW at a 1 mm spot size corresponds to 100 W/cm^2 and 400 W/cm^2 for the .5 mm spot size.

The LX-17 sample, (92.5% TATB + 7.5% Kel-F binder), in Figure 10 below and LX-15 sample (95% HNS + 5% Kel-F binder) show the formation of crystals around the damage sites. This suggests that vaporization occurred at the damage sites and the crystals then re-condensed.

Figure 10
Laser irradiation of LX-17, 800 mW, 1 mm spot size for 20 minutes.

This also suggests that it is very difficult to initiate these materials with laser light. To emphasize this point we took a LX-15 sample and put approximately 1.05 W on a 0.172 mm spot on the sample. This is 5 kW/cm^2. We were attempting to initiate the sample in this experiment.

After nine minutes, the LX-15 sample showed a large, cone shaped crater with a 1 cm column of ash snaking from the surface. It did not detonate. If the sample had been confined, however, detonation might have occurred.

DISCUSSION -- High power laser on bare high explosives

We believe the data here shows that for the samples measured and the wavelengths of laser light used, that a level of 7 mW focused in a 1 mm spot size would be a safe limit to place on manned operation. The worst case measured was PBX-9407 (94% RDX + 6% Exon 461 binder), which showed no damage at all at 40 mW and only very slight damage at 75 mW. The 7 mW level would be a factor of 7 to 10 below these numbers.

EXPERIMENT #3 – Low power laser on bare high explosives.

At LLNL, low power alignment lasers are used to align higher power femtosecond laser beams onto exposed HE samples. The low power alignment beams are themselves tightly focused onto the HE samples, due to the optical system the beams pass through. This can result in small spot sizes and extremely high laser power densities.

EXPLOSIVE NAME	HE BASE COMPOSITION	COMMENT
Ultrafine TATB	TATB	No observable damage
Single crystal HMX	HMX (pure)	No observable damage
LX-04	HMX	No observable damage
LX-14	HMX	No observable damage
LX-15	HNS	No observable damage
LX-16	PETN	No observable damage
LX-17	TATB	No observable damage
Comp-B	RDX/TNT	No observable damage
TNT	TNT	No observable damage
PETN	PETN	No observable damage
LX-20	HMX	No observable damage
PBX-9407	RDX	No observable damage
PBX-9501	HMX	No observable damage

Table 3

2.4 mW laser power and 19kW/cm^2 laser fluence damage effects on 13 HE samples.

Furthermore, HE samples are routinely inspected with a non contact laser profilometer, which focuses a low power laser beam to extremely small spot sizes (2 to 10 microns).

In order to establish safe operating limits for experiments that involve manned operation while aligning low power laser light on bare HE, we performed a series of tests on 13 common high explosives used in the HEAF at LLNL. All samples were irradiated with a 670 nm, 2.4 milliwatt fiber-coupled diode laser. The focal spot size imaged upon the HE surface was measured afterwards using a standard knife-edge technique. Beam diameter of the focal spot was determined to be 4 microns - for total knife translation from full power to zero power. Laser power was measured using the Coherent LabMaster Ultra optical power meter. Samples were enclosed in a 2-gram capacity HE containment tank prior to exposure to laser light. A remote translator positioned the exposed HE surface at the focal point determined using a small imaging camera to view the retro-reflected speckle pattern.

A 4 micron diameter spot was focused upon the surface of the HE samples using the 670 nm diode laser and a 4.5 mm aspheric lens,. The average power density was calculated to be about 19 kW/cm^2 at the focal waist of the beam. Each individual HE sample was exposed to this power density (fluence) for a 5-minute duration. Following exposure, each sample was inspected using a 27x stereo microscope. Microscopy images (before and after exposure) were recorded and compared. No damage or visible effects were observed on the sample surfaces after laser exposure.

An average laser power density of 19 $kWatts/cm^2$ with total power of 2.4 mW caused no damage, discoloration, or any other discernable changes to the surface of the high explosives listed in the above table. This demonstrates that Class I or Class II laser beams (630-670 nm) can safely be focused on the listed high explosives above if the power density is below 19 $kWatts/cm^2$ and the total power is less than 2.4 mW. It is reasonable to conclude that for alignment laser beams in the 670 nm wavelength region, 2 kW/cm^2 would provide a safety margin of 10 times below the fluence level tested above and could be considered to be a safe level for laser illumination on bare HE.

A non-contact laser profilometer, a laser confocal displacement meter made by Optimet Corp. is used at LLNL to measure HE sample surfaces. This device uses a 1 mW CW diode laser at 670 nm and creates a spot size diameter of 8 microns, providing a power density of about 2 $kWatts/cm^2$. The power density of the optical profilometer is an order of magnitude less than was generated in this last direct HE exposure experiment.

These experiments suggest that the main source of laser heating of explosives is total laser power; with spot size a second-order effect.

SAFETY GUIDELINES –-

1) High power laser beams on metals in contact with HE.

The idea here is to prevent an excessive temperature rise on the surface in contact with the HE in order to avoid a reaction. The simulations in Experiment #1 give good agreement and an understanding of what is going on, but should only be used as a rough guide in determining safety issues. One should not attempt to use these simulations outside of the limits of the assumption set forth in the definitions of the terms. If simulations are to be used to predict a new material behavior, the reflectivity and thermal conductivity of the material must be well defined or the results may vary considerably. **In the interest of safety, it should always be assumed that all of the laser light is absorbed when making calculations to get an upper limit of temperature rise.**

2) High power laser beams on exposed HE.

In Experiment #2 it has been shown that with 514 nm and 532 nm lasers, the threshold of damage begins around 70 mW with 1 mm and 0.5 mm spot sizes. However, some of these explosives, especially those with dyed prills or dark colored binders show strong absorption in the darker areas of the sample. Irradiation of LX-14 showed a dramatic difference in sensitivity at 532 nm between the white and dyed areas, presumably due to the difference in absorption at that wavelength. Absorption measurements with 1064 nm laser light, however, shows very little difference between the white and dyed prill areas[6]. If data had been taken at 1064 nm we would have no knowledge whether the dyed areas are more sensitive than the white areas of the sample. The data summarized in Table 1 sets the safety limits for illuminating HE samples with 532 nm and 514 nm beams.

When setting up experiments, one must do careful planning so that these optical power limits, even in the worst-case, are never exceeded. It is also very important to specify the wavelength when using these limits.

3) Low power laser beams on bare HE.

Since no damage was observed at 19 kW/cm^2, with 2.4 mW total power, **we conclude it is safe to use a 1 mW laser focused to an 8 micron beam diameter or larger** (2 kW/cm^2 is a factor of about 10 times lower than our test value of 19 kW/cm).

Laser Parameter	Spec	Units
Laser Power	2.4	milliwatts
Spot Size Diameter	4	microns
Fluence	19	kW/cm^2
Exposure time	5	minutes
Laser wavelength	670	nm

Table 5

Laser illumination parameters that caused no reaction to all HE samples in Experiment 3.

Standard HE safety practice dictates that alignment lasers should be set to the lowest power necessary to do the job. Neutral density filters should be permanently affixed to alignment lasers to reduce laser beam power to well below the guideline levels for additional safety.

We hope this information will be of use in updating existing documents which address the safe levels of laser light allowed on bare HE and HE components. Again, always specify the wavelength.

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