LASER DIODE INITIATED DETONATORS FOR SPACE APPLICATIONS

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ABSTRACT

Ensign Bickford Aerospace Company (EBAC) has over ten years of experience in the design and development of laser ordnance systems. Recent efforts have focused on the development of laser diode ordnance systems for space applications. Because the laser initiated detonators contain only insensitive secondary explosives, a high degree of system safety is achieved. Typical performance characteristics of a laser diode initiated detonator are described in this paper, including all-fire level, no-fire level, function time, and output. A finite difference model used at EBAC to predict detonator performance, is described and calculated results are compared to experimental data. Finally, the use of statistically designed experiments to evalute performance of laser initiated detonators is discussed.

INTRODUCTION

Work on all-secondary explosive laser initiated detonators began at Ensign Bickford Aerospace Company (EBAC) in the early 1980's. Although initial efforts were based on solid state (Nd:YAG) laser initiation, the more recent emphasis has been in the area of laser diode initiated detonators. The feasibility of laser diode initiation is due largely to dramatic improvements in diode output power and, to a lesser extent, improvements in powder blending technology for laser grade explosives.

Because they have relatively low autoignition temperatures, secondary explosives such as RDX and HMX are excellent candidates for laser diode initiation. Since the optical absorption of these materials at typical laser diode wavelengths is relatively poor (Ref. 1) additives such as graphite, carbon black, and boron are used to enhance powder absorptivity and, therefore, lower detonator all-fire level.

PETN has been found to be susceptible to temperature cycling induced effects and should not be considered for laser diode initiation applications. The temperature cycling problems with PETN are not unique to laser initiation, but have also been reported with other forms of thermal ignition, such as hot bridgewire (HBW) and semiconductor bridge (SCB) initiation.

Initial detonator designs at EBAC were based on the concept of flying plate initiation (Ref. 2). In this approach, a confined donor explosive charge is ignited by the laser pulse and burns until sufficient pressure has been built up to rupture a confinement disc. The ruptured disc, or flying plate, is then propelled down a barrel by the high pressure gases produced by the donor charge at a velocity in excess of 1 km/sec. The velocity of the flying plate is sufficient to shock initiate a secondary explosive acceptor charge at the end of the barrel.

More recent efforts relative to laser initiated detonators have been based on the principle of deflagration-to-detonation transition (DDT). As with the flying plate detonator, a confined secondary explosive donor charge is ignited by the laser pulse, causing it to deflagrate and rupture the confining disc. In this type of device, however, the "barrel" contains a relatively long column of secondary explosive termed the "transition charge". As the high pressure gases and the ruptured disc drive into the transition charge, the reaction transitions into a high order detonation.

Confinement is an extremely important parameter in all-secondary explosive laser initiated detonators. As a general rule of thumb, the more insensitive the explosive, the higher the degree of confinement needed for reliable function.

Important design requirements for laser diode initiated detonators include all-fire and no-fire levels, output, function time, and environmental ruggedness. Typical environmental requirements include hot and cold temperature function, as well as temperature cycling, thermal shock, vibration, and pyrotechnic shock. For DDT detonators, run-to-detonation distance is also an important parameter, since it directly related to detonator size and weight, as well as margin.

Performance of laser diode initiated DDT detonators can be predicted and optimized using tools such as computer modeling as advanced experimental design techniques. At EBAC, finite difference modeling has been used to predict ignition-related aspects of detonator performance, including all-fire and no-fire levels, and effects of temperature and laser diode pulse width. Advanced experimental design techniques have been used to optimize detonator design parameters, such as powder density, particle size, and column diameter.

PERFORMANCE CHARACTERISTICS

Important performance characteristics of laser diode ignited detonators include all-fire level, no-fire level, function time, and output. All-fire and no-fire levels are determined by performing sensitivity tests, such as Bruceton, Langlie, or Neyer (Ref. 3) and are conducted at a fixed laser diode pulse width. The data reported in this paper are based on a pulse width of 20 ms. Detonator all-fire and no-fire tests are normally conducted at "worst case" temperature levels, which are typically -54°C and 74°C, respectively.

Twenty (20) each all-secondary explosive laser diode initiated detonators were used to determine all-fire and no-fire levels. As was noted above, the laser diode pulse width was 20 ms. The detonators were coupled to the laser diodes via a 200 μm diameter optical fiber. The .999/95% all-fire level was found to be 478 mW at -54°C. The .001/95% no-fire level, at 74°C, was 116 mW. It should be noted that these tests were performed with a single SMA type fiber optic connector between the laser diode and detonator. The all-fire and no-fire level, therefore, are actually for the detonator plus one connector.

For electro-explosive devices (EED's) no-fire testing is normally conducted using a 5 minute duration constant current pulse as a worse case scenario rather than the actual firing pulse, which may be only tens of milliseconds in duration. This requirement stems from concerns relative to potential sources of RF energy in proximity to EED's, where the firing circuit can act as an antennae and induce an electrical current in the bridgewire. In general, a 5 minute no-fire requirement may not be applicable to laser initiated detonators, however, it certainly represents a conservative approach to no-fire testing.

Twenty additional laser diode initiated detonators were assembled and utilized in a 5 minute laser diode no-fire test. The laser diode was operated continuously (CW) for 5 minutes while performing this test. As before, a 200 μm diameter optical fiber was used to couple the laser diode to the detonator and the detonators were conditioned to 74°C. Data analysis yielded a .001/95% no-fire level of 98 mW. Again, this value includes one connector between the diode and detonator. Note that there is only a 15% decrease in the no-fire level between pulse widths of 20 ms and 5 minutes. This is attributable to the small spot size achieved by coupling the fiber directly to the powder, which minimizes the effective thermal mass.

As with all thermally ignited devices, function time of a laser diode initiated detonator varies inversely with the applied power. Twenty additional detonators were fabricated to assess the effect of laser diode power on detonator function time. Two detonators each were fired at levels from 300 mW to 1.2 watts, in increments of 100 mW. The tests were conducted at ambient temperature using a 20 ms laser diode pulse and a 200 μm diameter optical fiber. A graph of function time versus diode power is shown in Figure 1. The line drawn through the data points in Figure 1 is a least squares fit of the form $y=a+b/x^2$. As before, note that the data is based on a single SMA connector between the laser diode and detonator.

The final performance characteristic of laser diode initited detonators to be discussed is output. Standard EBAC test detonators include a one grain HNS-IA output charge housed in a .005 inch thick stainless steel cup and pressed at 32,000 psi. In tests at ambient temperature with steel witness blocks, the average dent produced by the laser initiated detonators was .012 inches.

FINITE DIFFERENCE MODELING

Because of their axial symmetry, typical laser diode initiated detonators are excellent candidates for finite difference modeling techniques. In reference 4, the author presented a laser diode ignition model based on a one-dimensional finite difference solution of the governing time-dependent heat conduction equation. An improved two-dimensional model has since been developed and used to predict the performance of EBAC laser diode initiated detonators. The general heat conduction equation is shown in equation (1) below. Note that a cylindrical coordinate system has been chosen and that a heat generation term has been included.

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{a}\frac{\partial T}{\partial t} \tag{1}$$

where: T = temperature
t = time
z = axial coordinate
r = radial coordinate
ϕ = angular coordinate
q = heat generation rate
k = thermal conductivity
a = thermal diffusivity

For an axially symmetric system, as is the case with typical laser diode initiated detonators, equation (1) reduces to:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{a}\frac{\partial T}{\partial t} \tag{2}$$

Optical absorption of the incident laser radiation by the donor charge is handled by the heat generation term, which may be written as follows:

$$q = \alpha \cdot p \tag{3}$$

where: α = absorptivity of first fire mix
p = incident power density

As first order approximations, it may be assumed that thermal conductivity and heat capacity are constant and do not vary with temperature. Also, as a first order approximation, the model does not include a self-heating term for decomposition of the explosive material, but instead assumes a constant autoignition temperature.

Equation (2) may be solved using conventional finite difference techniques. Due to the large number of nodes needed to reasonably model a laser initiated detonator, a computer is needed to carry out the detailed calculations.

The finite difference model has been used to model the laser diode ignition characteristics of a fine particle HMX/Carbon Black blend. Figure 2 shows the predicted function time as a function of laser diode power assuming a 100 μm diameter spot size. Calculated results are shown for the two-dimensional model described by equation (2) and also for a one-dimensional (axial only) model. Also noted in Figure 2 for reference, are a pair of experimental data points for fine particle HMX/carbon black (Ref. 1).

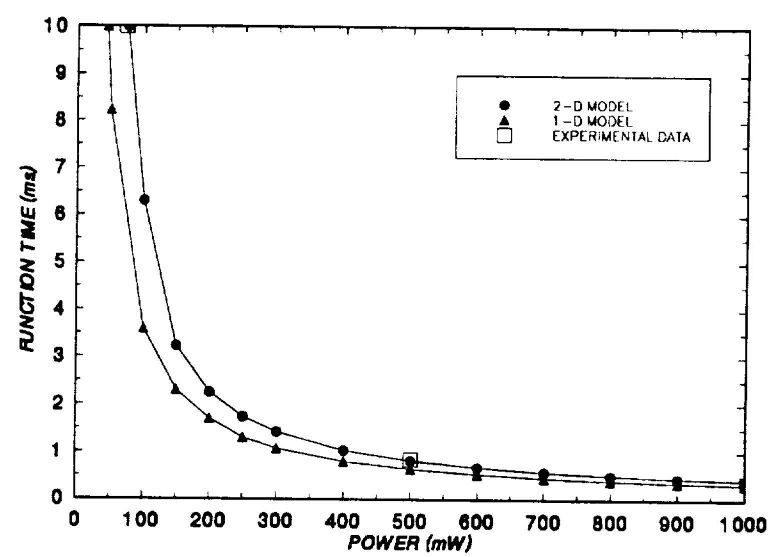

Figure 2
Comparison of 1-D and 2-D Finite Difference Calculations

Note that the two-dimensional model predictions are in excellent agreement with the experimental data points. In addition, note that the function times predicted by the one-dimensional and two-dimensional models converge as the diode power increases. At relatively high power levels, the one-dimensional results are also in reasonably good agreement with the experimental data, however, at lower power levels the one-dimensional model underestimates the diode power required for ignition because radial heat losses are not accounted for.

Another obvious limitation of the one-dimensional model is its inability to accurately predict spot size effects. The laser diode ignition threshold for HMX/carbon black has been found to scale as the diameter raised to the 1.4 power (Ref. 5). A one-dimensional model, however, inherently assumes that initiation is a function of power density. In other words, the one-dimensional model will predict that the ignition threshold varies as the diameter squared. The two-dimensional model is in much closer agreement with experimental data, predicting that ignition threshold scales with the diameter raised to the 1.6 power. The effect of varying the laser diode pulse duration has also been studied using the finite difference model. Figure 3 shows the predicted ignition threshold as a function of spot size for laser diode pulse widths of 10 and 20 ms.

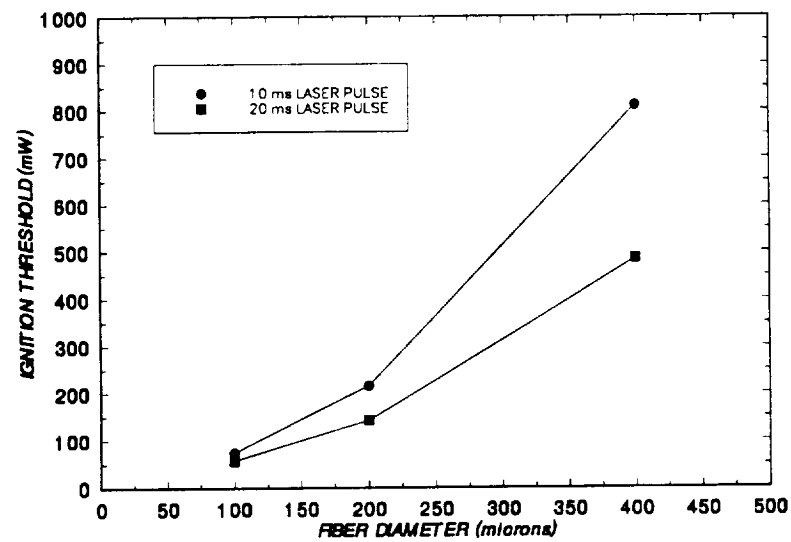

Figure 3
Effect of Laser Diode Pulse Width on Ignition Threshold

Due to the larger thermal mass associated with a larger spot size, the penalty of a higher ignition threshold is reduced by using a longer pulse duration.

Finally, the finite difference model has been used to predict the effect of temperature on ignition threshold. Figure 4 shows the predicted ignition threshold as a function of spot size for temperatures of -54°C, 22°C, and 74°C. A 20 ms laser diode pulse was used as the basis for these calculations.

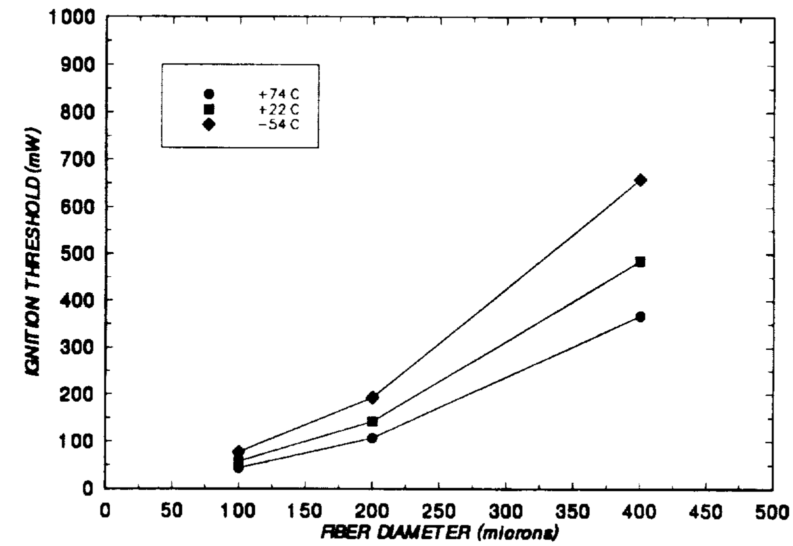

Figure 4
Effect of Temperature on Ignition Threshold

EXPERIMENTAL DESIGN TECHNIQUES

The finite difference modeling discussed above addressed only the ignition characteristics of laser diode initiated detonators. Design parameters affecting the ignition characteristics can be optimized with the aid of the heat transfer model, however, testing is obviously required in order to verify the model predictions.

In addition, the design of laser diode initiated deflagration-to-detonation transition (DDT) detonators also requires optimization of those parameters affecting the transition from burning to high order detonation.

At EBAC, advanced experimental design techniques have been used to investigate the effects of parameters such as transition charge diameter, loading density, specific surface area, and confinement disc thickness on the run distance to detonation and function time of laser initiated detonators. Although the tests were conducted using a pulsed Nd:YAG laser source, the run distance to detonation data is applicable to laser diode initiated detonators, as well. Although

EBAC considers the specific parameter values and test results to be company confidential information, a summary of the results is presented here.

For the transition charge designed experiment, a total of twenty-three tests were conducted. Three levels were considered for each of the four parameters studies, except confinement disc thickness, for which there were only two levels. From the results, an optimized design configuration was established via statistical analysis. In addition, a trend analyses was performed to evaluate the effect of each parameter on the run distance to detonation. Figure 5 shows the combined effect of charge density and specific surface area on run distance to detonation.

REFERENCES

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MARGIN
THICKNESS = 1.4, DIAMETER = .67

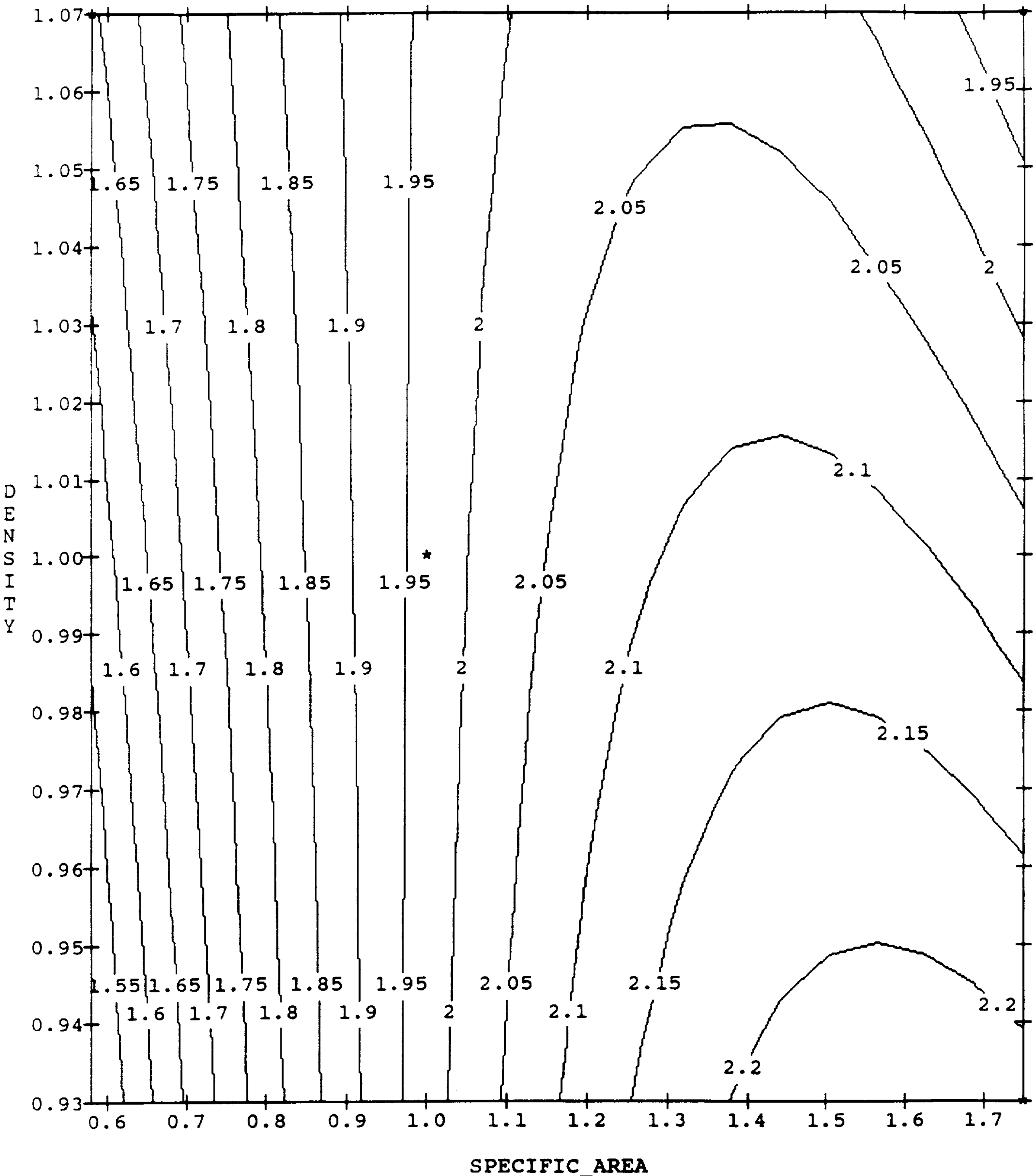

Figure 5
Combined Effect of Density and Specific Surface Area