SAND2005-2460C

Light Initiated High Explosive Impulse Load Calibration

75th SAVIAC Shock and Vibration Symposium

W. Gary Rivera
Sandia National Laboratories[†]
PO Box 5800
Albuquerque, NM 87185-1454
(505) 844-5672

The Sandia National Laboratories Light Initiated High Explosives (LIHE) Facility, in Albuquerque, New Mexico, has recently undergone a resurrection from mothball status. This new LIHE facility will provide a simulated environment representative of a cold x-ray blowoff impulse generated by an exo-atmospheric hostile nuclear encounter. This above ground simulation generates the proper impulse by initiating a thin layer of a light sensitive primary explosive, spray deposited on the test object.

While in operation prior to 1992, an explosive calibration curve had been developed to accurately predict the impulse load delivered by the spray deposited silver acetylide – silver nitrate explosive. To understand any differences between the past and current process, an explosive calibration test series has been completed using explosive formulated by today's chemical constituents, processes and procedures, and personnel.

INTRODUCTION

The Sandia National Laboratories Light Initiated High Explosives (LIHE) Facility, in Albuquerque, New Mexico, has recently undergone a reconstruction and resurrection from mothball status. This new LIHE facility will provide a simulated environment representative of a cold x-ray blowoff impulse generated by an exo-atmospheric hostile nuclear encounter. This above ground simulation generates the proper impulse by initiating a thin layer of a light sensitive primary explosive, that has been spray deposited on the test object. In the past, this facility has conducted numerous full system and component impulse tests for validation and acceptance purposes. The facility is currently being reconstituted to conduct full systems impulse tests for both weapon systems qualifications and computer code validation.

While in operation prior to 1992, an explosive calibration curve had been developed to accurately predict the impulse load delivered by the spray deposited silver acetylide – silver nitrate (SASN) explosive. While procedures for formulation of the SASN explosive remain nearly the same as those in the past, it is desired to understand whether the current explosive product is similar to or the same as that produced circa 1992. To achieve this understanding, an explosive calibration test series has been completed using explosive formulated by today's chemical constituents, processes and procedures, and personnel.

[†] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

LIGHT INITIATED HIGH EXPLSOIVE

The LIHE facility utilizes a process where explosive is formulated, sprayed painted onto a surface, and detonated using a high energy light source. The direct spray LIHE technique has been reported is several Shock and Vibration Symposia, and is briefly described here. [1, 2, 3, 4, 5] It should be noted that the SASN explosive, though relatively low in explosive output, is a highly sensitive primary explosive, and special facilities and procedures are required to safely work with this material.

Because the silver acetelyide – silver nitrate explosive is not commonly used and is difficult to transport, it is formulated on site. [6] The process for making the explosive starts with silver nitrate crystals, acetonitrile, and acetylene. A precipitation process is employed in which acetylene gas is dispersed through the solution of silver nitrate in acetonitrile. The silver nitrate reacts with the acetylene gas as follows:

$$3AgNO_3 + C_2H_2 \rightarrow Ag_2C_2 \cdot AgNO_3 + 2HNO_3$$

The SASN ($Ag_2C_2 \cdot AgNO_3$) settles out as a white precipitate, seen in Figure 1, where the nitric acid (HNO_3) remains mixed with the acetonitrile, which does not participate in the reaction. The explosive solution is washed with acetone, reducing the nitric acid content by approximately 98.8%, resulting in an explosive product ready to spray.

The explosive is pumped as a suspension in acetone to a spray gun for application to the test item. The spray gun atomizes the explosive/acetone mixture, resulting in a deposition of SASN on the test item with the excess acetone evaporating during the spray process.

A computer controlled robotic arm is used to precisely position the spray gun over the test item surface. [7] Typically, tens to hundreds of spray passes over the test item are required to achieve a designed explosive deposition. The measure of explosive deposition on a sprayed surface is areal density, defined as the mass of explosive divided by the area on which it is deposited. Areal density is given in units of mass per area (i.e. mg/cm^2), and denoted ρ_A. Deposition is measured using small covar coupons, typically 1.905 cm (0.75”) diameter, magnetically attached to the sprayed surface. After a number of sprays have been completed, coupons are remotely removed from the test item and weighed to determine explosive weight per given area. The spraying of explosive on covar coupons , magnetically attached to a flat backboard, in a horizontal trajectory is shown in Figure 2.

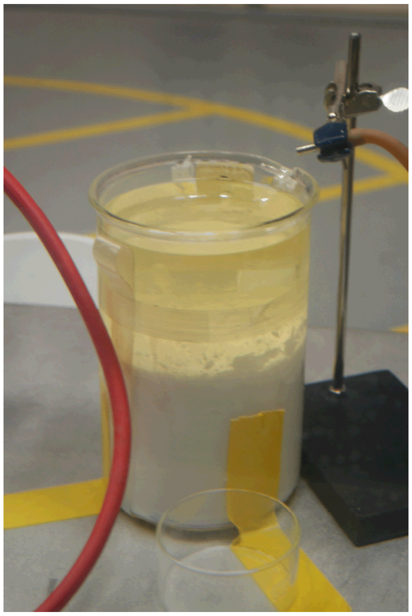

Figure 1. SASN Explosive in Acetone

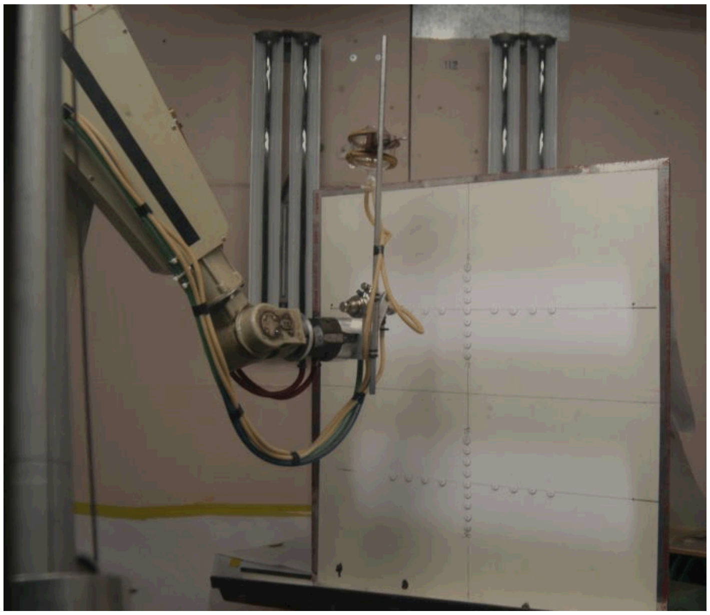

Figure 2. SASN Application to Covar Coupons

After spray, the explosive is exposed to ultraviolet light for 3 to 5 minutes, causing the surface of the explosive to darken from a white color to a burnt cream color. This effect greatly enhances the number of detonation points on the surface of the test item when exposed to the energized light array, resulting in greater detonation simultaneity.

The light source to detonate the explosive consists of an array of tungsten wires enclosed in quartz tubs and energized by the discharge of a capacitor bank. [4, 5] When the capacitor bank is discharged through the tungsten the wires vaporize leaving an electrical arc in the quartz tube. This arc becomes the light/heat source for SASN explosive, transferring energy through the quartz tube to explosive surface. For this explosive calibration a small light array, shown in Figure 3, powered by a 10kV-300J capacitor bank, is used to detonate the explosive on the coupon, shown in Figure 4.

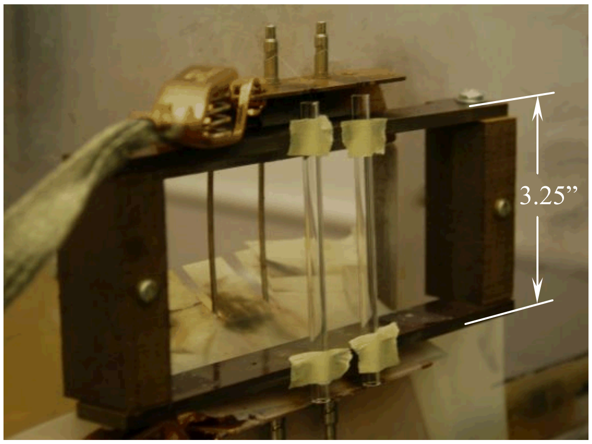

Figure 3. Small Light Array

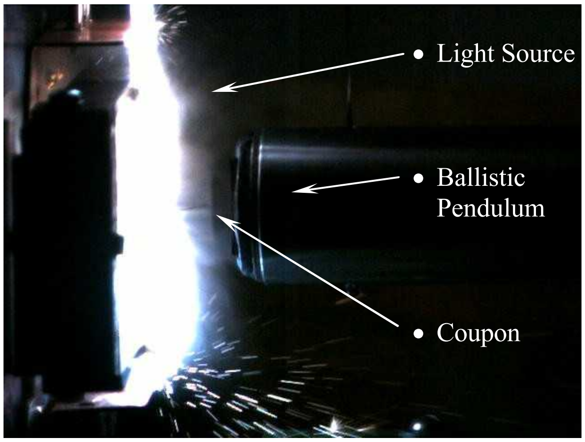

Figure 4. Light Array and Explosive Detonation

Prior to the facility being mothballed in 1992, an explosive calibration curve was established. This curve correlated explosive performance to the SASN areal density deposited on the sprayed surface by relating the specific impulse, I_{sp}, to areal density, ρ_A, in a two part curve. It is believed that the explosive calibration curve changes from quadratic to linear at a point of 22.5 mg/cm^2. This is most likely due to the physical/chemical properties of the explosive, such as critical diameter, and volumetric density. For areal densities less than 22.5 mg/cm^2 a quadratic function was defined:

$$I_{sp} = 0.86 \cdot \rho_A^2 + 37.95 \cdot \rho_A \tag{1}$$

And for areal densities greater than 22.5 mg/cm^2 a linear function was defined:

$$I_{sp} = 76.26 \cdot \rho_A - 427.06 \tag{2}$$

TEST METHOD

In order to determine the impulse to areal density relationship for the current formulation of the SASN explosive an extensive calibration series has been undertaken. While the performance characteristics of the SASN have been reported in the past [7], and the process to formulate the explosive has been kept as constant as possible, it is understood that minor differences in process and constituents, as well as unexpected issues, may produce a difference in the formulation. Therefore, a keen understanding of the function between specific impulse and areal density for the present day formulation is required. The calibration process involves spraying explosive on coupons to the designed deposition, determining the precise explosive deposition per coupon, conditioning the explosive, and individually firing each coupon while recording explosive output.

Deposition of the SASN explosive onto each coupon is accomplished in a batch process. Multiple covar coupons, 1.905 cm (0.75") in diameter, are magnetically attached to a flat backboard oriented vertically within reach of the spray gun attached to the robot arm. Explosive is formulated by the established technique for each spray operation. [6] The backboard and coupons are then sprayed with explosive in horizontal passes. After a number of sprays have been completed a coupon can be remotely removed from the backboard and weighed on a digital scale to determine explosive deposition. This deposition weight is converted to areal density by dividing by the area of each coupon, which for this testing has been a constant 2.85 cm^2.

In order to evaluate the explosive performance at multiple areal density levels, coupons were removed from the backboard after a specified number of spray passes. In the case where a lower than expected areal density is encountered during a weigh, the coupon could be returned to the sprayed surface for additional explosive deposition and future measurements. After spray operations have concluded, each coupon is weighed to determine the pre-conditioned explosive areal density. Remote coupon handling, conducted with master/slave manipulator arms through an eleven inch thick protective window, is shown in Figure 5.

With the desired areal densities being achieved, each coupon is environmentally conditioned in the spray booth overnight to assure that all of the acetone carrier has evaporated and only SASN explosive remains. The overnight conditioning requires that the coupons remain at a nominal 26.7ºC (80ºF), and 20%-35% relative humidity. This overnight "drying" is an established process for conditioning the explosive before an explosive test. Next, the coupons are removed from the spray booth and taken to the location of the Small Bank light array for "sun-tanning" and testing as shown in Figure 6.

Figure 5. Remote Coupon Handling

Figure 6. SASN Sun-Tanning on Coupons

Once conditioned, a ballistic pendulum assembly, shown in Figure 7, is used to measure the explosive output from each coupon. The pendulum mass is positioned in front of the small bank light array allowing for a 2.54 cm (1.0") spacing between the coupon, magnetically held to the pendulum, and the light source. A non-contact eddy current displacement gage measures the movement of the pendulum mass, with a 0.0025 cm (0.001") resolution, which is converted to impulse though a data reduction routine described below.

The ballistic pendulum's displacement takes the form of a slightly damped sine wave. The eddy current displacement gage has an effective measurement range of 2.54 cm (1.0"), and is positioned to record both directions of pendulum travel, effectively allowing a maximum positive displacement of 1.27 cm (0.50"). So that the delivered impulse does not drive the mass beyond the gage's range, it is necessary to match the expected impulse with one of two pendulum masses, 353.8 g (0.779 lbm) for areal densities less than 18.5 mg/cm^2, and 1713.6 g (3.774 lbm) for areal densities greater than 18.5 mg/cm^2. A typical pendulum displacement trace is given in Figure 8.

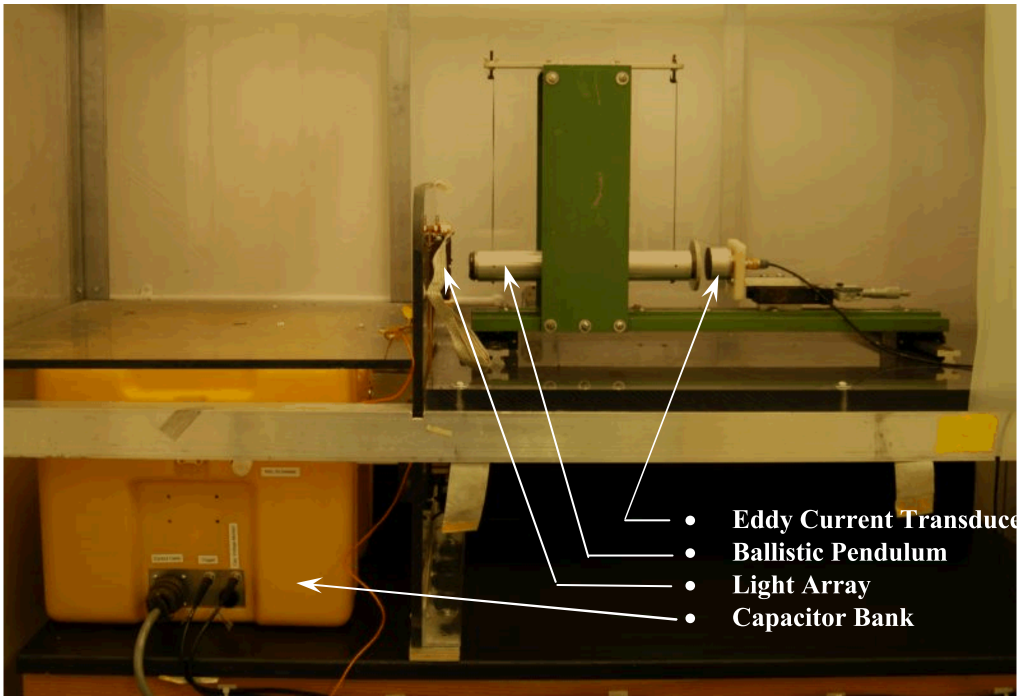

Figure 7. Small Bank Ballistic Pendulum Assembly

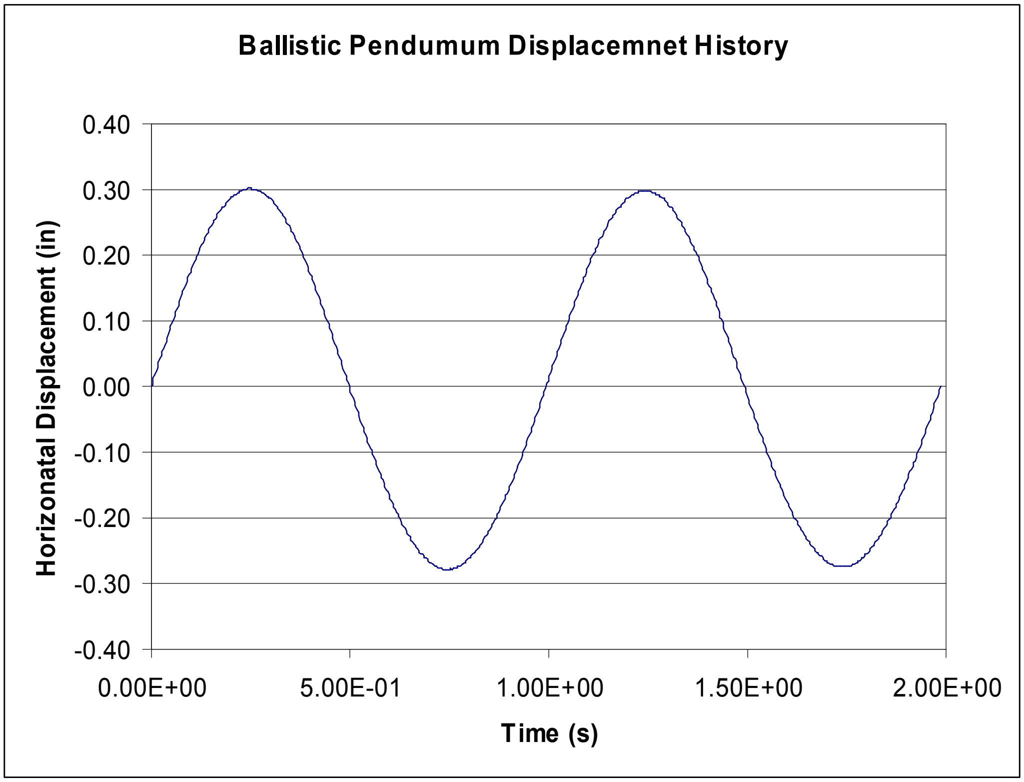

Figure 8. Typical Pendulum Mass Displacement

The impulse delivered by the areal density for each coupon is determined by calculating the pendulum's initial velocity, v_0 from the sinusoidal displacement.

It is assumed that the damped motion of the pendulum follows the simple pendulum equation:

$$X = A \cdot e^{-\alpha \cdot t} \cdot \sin(\omega \cdot t) \tag{3}$$

where X is the horizontal displacement of the mass, A is the un-damped amplitude, α is the logarithmic decay rate, ω the pendulum frequency, and t is time. By measuring two peaks (time and amplitude) of the sinusoidal motion of the pendulum, the decay rate, and frequency of the pendulum, can be found using equations (4) and (5) respectively.

$$\alpha = \ln\left[\frac{P_1}{-P_2}\right] \cdot \frac{1}{t_2 - t_1} \tag{4}$$

$$\omega = \frac{\pi}{t_2 - t_1} \tag{5}$$

P_1 and P_2 are absolute values of the amplitude of peaks, corresponding to the times t_1 and t_2 respectively. It is understood that the pendulum motion is not ideal. In an attempt to account for this source of error three values of un-damped pendulum amplitude, A, are calculated using equation (6). Using index notation, were i=1 to 3,

$$A_i = \frac{P_i}{e^{-\alpha t_i} \cdot \sin(\omega \cdot t_i)} \tag{6}$$

An average un-damped amplitude is then used to calculate the initial velocity of the pendulum.

$$v_0 = \frac{\sum_1^3 A_i}{3} \cdot \omega \tag{7}$$

Total impulse delivered to the ballistic pendulum, or the product of specific impulse and area, is defined as its change in momentum. Because the pendulum is at rest prior to the explosive detonation, the relation becomes

$$I_{sp} \cdot A_{coupon} = M_p \cdot v_0 \tag{8}$$

again, where I_{sp} is the specific impulse, M_p is the mass of the pendulum v_0 is the initial velocity, and A_{coupon} is the area of the coupon. Solving equation (8) for specific impulse,

$$I_{sp} = \frac{M_p \cdot v_0}{A_{coupon}} \tag{9}$$

Now with initial velocity of the pendulum, calculated using equation (7), the specific impulse delivered to the pendulum from the explosive deposited on the coupon is calculated using equation (9).

Another method for determining v_0 is to calculate the initial slope of the displacement of the pendulum. This calculation is simply the ratio of the change in displacement over the change in time:

$$v_0 = \frac{\Delta X}{\Delta t} \tag{10}$$

Because a finite mass cannot instantaneously accelerate from standstill to a finite velocity, care is taken to determine v_0 after a short (~5 millisecond) acceleration phase. Unfortunately, due to the very short times and distances used for this calculation, it is prone to relatively large round-off error, and has been used as a magnitude check of the initial velocity calculated using equation (7).

There are three sources of measurement error in the calibration process: Weighing of the coupon, measurement of the pendulum displacement, and variances in the blast wave interaction with the pendulum face. [reference] Each coupon is weighed several times with a scale accuracy of ±0.2 mg. The displacement of the pendulum mass involves knowing the weight of the pendulum mass to ±0.2 mg and the displacement to within ±2%. The variances in the blast wave interaction result in an extraneous variance of ±30 taps, and is constant over the impulse range. Putting all of these errors together gives a maximum and minimum error for a given areal density. This range is a complicated function of areal density, explosive weight, coupon area, error to data reduction methods, displacement gage non-linearity, and blast variance. The specifics and derivation are reported in detail in Reference 6, though the error bars are shown in Figures 9 and 10.

EXPERIMENTAL RESULTS

Multiple formulation and spray activities were completed for the calibration resulting in coupons with areal densities ranging between 1.9 and 45.6 mg/cm^2. A total of 131 coupons were tested on the small bank pendulum covering ten spray operations and nine months of testing.

Each spray operation involved formulating one or two 275 gram batches of explosive using chemical constituents currently available. Standard covar coupons were arranged on a flat backboard in various configurations, depending on the objectives of the spray. The first of these tests exercised a spray pattern consisting of two non-overlapping horizontal spray passes with coupons arranged in horizontal rows. After achieving successes in these early tests, spray operations progressed to flat horizontal trajectories with multiple overlapping spray passes. While the explosive deposition rate changed, the designed areal density was achieved. Final areal density is considered to be equivalent regardless of the deposition rate in which it was achieved. Each test is plotted against the previous facility calibration curve in Figure 9.

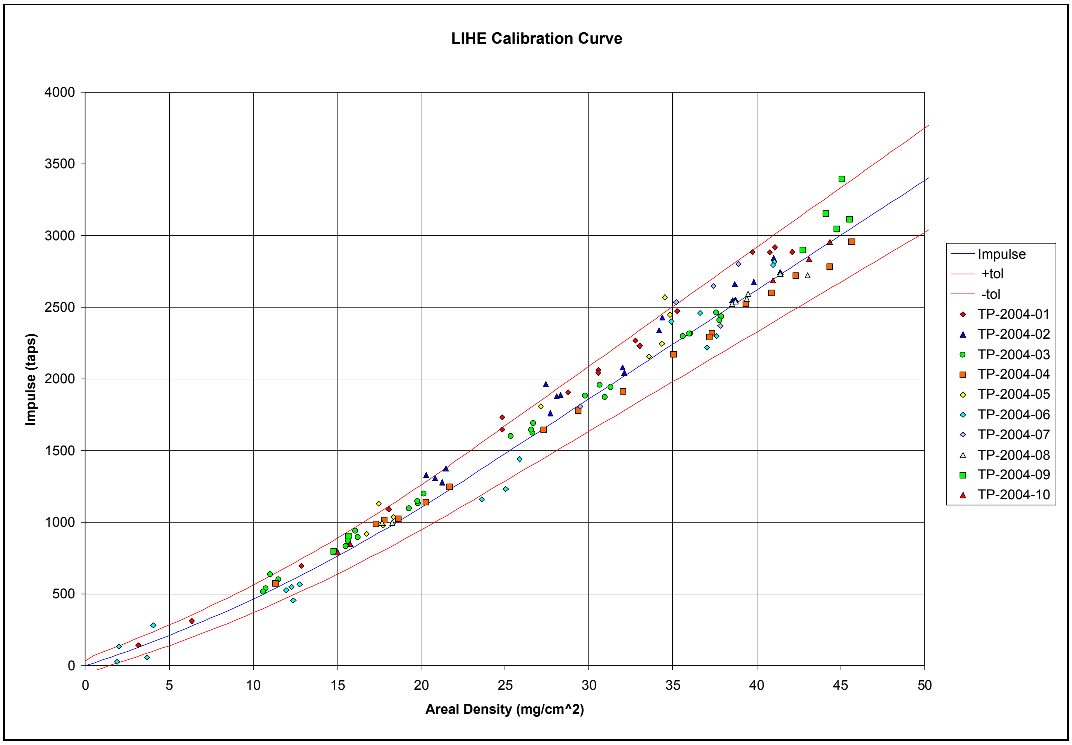

Figure 9. Specific Impulse versus Areal Density for Sprayed SASN

While 56 tests were conducted below the 22.5 mg/cm^2 point, only six tests were conducted below 10.0 mg/cm^2, due to other test constraints. In addition, the ballistic pendulum displacement data collected at these levels, with the existing 354 gram pendulum mass, is very low in amplitude making initial velocity difficult to calculate, and prone to error. For these reasons, determination of the quadratic portion of the calibration curve below 22.5 mg/cm^2 is not attempted at this time. However, the calculated impulse delivered in this area did seem to conform to the old calibration.

A linear regression was performed on the remaining 75 tests conducted at areal densities between 22.5 and 45.6 mg/cm^2. The resulting specific impulse as a function of areal density for this range is found to be

$$I_{sp} = 74.23 \cdot \rho_A - 328.9 \tag{11}$$

Immediately a difference of 2.7% in slope and 23% in intercept is observed. But plotting both curves on the same scale (Figure 10) shows that the difference is actually quite small compared to the measurement error bounds.

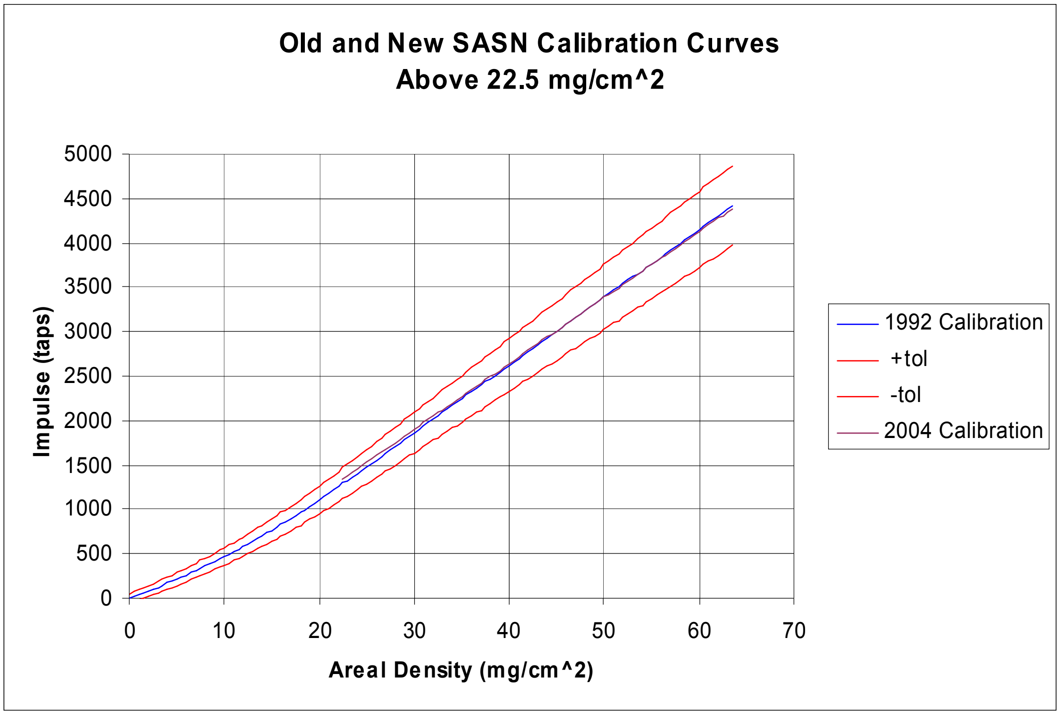

Figure 10. Comparison of 1992 and 2004 SASN Calibration Curves

DISCUSSION

A comparison of the old facility calibration curve and the current calibration curve clearly shows a small numerical difference between the two calibrations, but this difference is small compared to the potential measurement error in the system.

To further emphasize the importance of this calibration activity, several explosive formulations during this series resulted in an explosive product that did not conform to the expected characteristics of the normal SASN explosive, though the exact formulation steps were followed. The normal SASN explosive product is white in color, and when dry, has the consistency of extra fine powder. This unusual product was brown in color and appeared to have a crystalline consistency, much like a fine sand. It is believed that it could not have been spray deposited with our current techniques because of the difference in consistency, and thus was properly disposed. An investigation into the cause of the anomaly showed that the acetylene used in the formulation was manufactured in a different process than the lot previously used for successful formulations. This new process introduced contaminates into the formulation, changing its color, structure, and possibly explosive output. Unfortunately, the supplier of the acetylene did not note the change in process because it was transparent to the "standard" acetylene user. In this case, it was fortuitous that unusual product was obviously different in color, and was immediately ruled suspect in quality. The LIHE facility has since changed its processes to identify differences in chemical manufacturing processes to assure that only the proper chemical constituents are used to formulate the SASN explosive.

CONCLUSION

A successful explosive calibration series has been conducted with 130 explosive tests and over 10 explosive formulations being completed. This investigation has conclusively shown that the processes, procedures, and constituents of the formulation and spray processes used today results in an explosive performance that is nearly identical to that used prior to 1992 for areal densities above 22.5 mg/cm^2. Because the data below 22.5 mg/cm^2 also seems to conform to the 1992 curve, it is assumed, for now, that the 1992 calibration in this range is also valid. For these reasons, the LIHE facility will continue to use the 1992 calibration for current and near future design and analysis activities.

While this investigation has been successful in verifying explosive performance at areal densities above 22.5 mg/cm^2, there still exists work to characterize and verify the performance at low impulse levels. This will likely involve multiple tests, several spray operations, and additional ballistic pendulum hardware to adequately characterize the performance.

REFERENCES

1. R.A. Benham, F.H. Mathews, "X-Ray Simulation with Light-Initiated Explosive," The Shock and Vibration Bulletin, Bulletin 45, June 1975, pp 87-91.

2. R.A. Benham, F.H. Mathews, P.B. Higgins, "Application of Light Initiated Explosive for Simulating X-Ray Blowoff Impulse Effects on a Full Scale Reentry Vehicle", The Shock and Vibration Bulletin, Bulletin 47, September 1977, pp 9-16.

3. F. H. Mathews, "A Theory for the Calculation of Explosive Deposition Profiles from the Spray Painting of Light Initiated Explosive", The Shock and Vibration Bulletin, Bulletin 51, May 1981, pp 189-204.

4. P.B. Higgins, "An Arc Source for Initiating Light-Sensitive Explosives," The Shock and Vibration Bulletin, Bulletin 46, June 1976, pp 191-195.

5. F. H. Mathews, "A Computational Model Describing the Initiation of Silver Acetylide-Silver Nitrate Explosive by and Intense Light Source", The Shock and Vibration Bulletin, Bulletin 49, September 1979, pp 177-191.

6. R. A. Benham, "Light Initiated Explosive Formulation and Impulse Calibration Procedures", Memorandum of Record, Sandia National Laboratories, April 7, 1977.

7. K.L. Pendleton, "Robotic Application of Light-Initiated Explosive to Conical Reentry Vehicles", SAND87-1900, Sandia National Laboratories, Albuquerque, NM, December 1987.