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Adapting the STAR Facility Two Stage Light Gas-Gun with a Low-Pressure (Vacuum) Chamber for Hypervelocity Impact Diagnostics

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Abstract—Over the past few years, there has been an increasing interest in observing impact-flash phenomena from hypervelocity impacts using fast spectroscopy. The development of impact flash spectroscopy has produced results that can identify materials within complex impacts (multiple materials) and providing estimates of temperature from expansion products resulting from shocked materials. Questions have arisen regarding how the pressure in the impact chamber affects the fluorescence of excited molecules? Shock experiments are used to examine the dynamic response of materials under extreme temperatures and pressures. These conditions result in the excitation of the atoms and molecules involved in the experiment to a high energy level. Once excited, the atoms will eventually return to a lower energy level, releasing photons of specific energies, a process known as spontaneous emission. When collected and analyzed with spectroscopic techniques, the photons may be used to produce a spectrum relating the photons at various energy levels. These results can be further analyzed for properties of interest, such as material identification and temperature estimates. The most dramatic effect of pressure on spectroscopy is related to the collision rate of excited molecules with other molecules. Collisions shorten the lifetime of the excited state and reduce the intensity of radiation. The pressure, or commonly referred to as vacuum, within our chambers is typically 50 millitorr (~7 Pa) and is considered a *medium vacuum*. The vacuum we are attempting to achieve will be a high vacuum of 0.1 millitorr or lower. The intent of this paper is to discuss the challenges involved in the adaptation, the discussion of molecular collision rate resulting from the lower pressure, and the importance of minimizing the disturbance of the three-stage flyer plate during the transition from the medium-vacuum chamber to the high-vacuum chamber.

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INTRODUCTION

This paper will discuss the challenges and research involved for adapting an additional target chamber on Sandia National Laboratories three-stage light gas-gun for use in hypervelocity impact studies. Not only will this chamber be incorporated to adequately support all the diagnostics for our impact studies, but testing will be performed at a much lower pressure within the chamber.

Current Configuration

The Shock Thermodynamic Applied Research (STAR)[1] facility's two stage light gas gun has operated in many different modes over the last 20 years. The gun is a typical two-stage light gas gun by all standards, perhaps a little more robust in the breech area-a little less robust in the acceleration reservoir (AR) for guns of this size, but the operation is very similar to all two-stage guns. Figure 1 is a picture of the gun with a cartoon depicting the basic components.

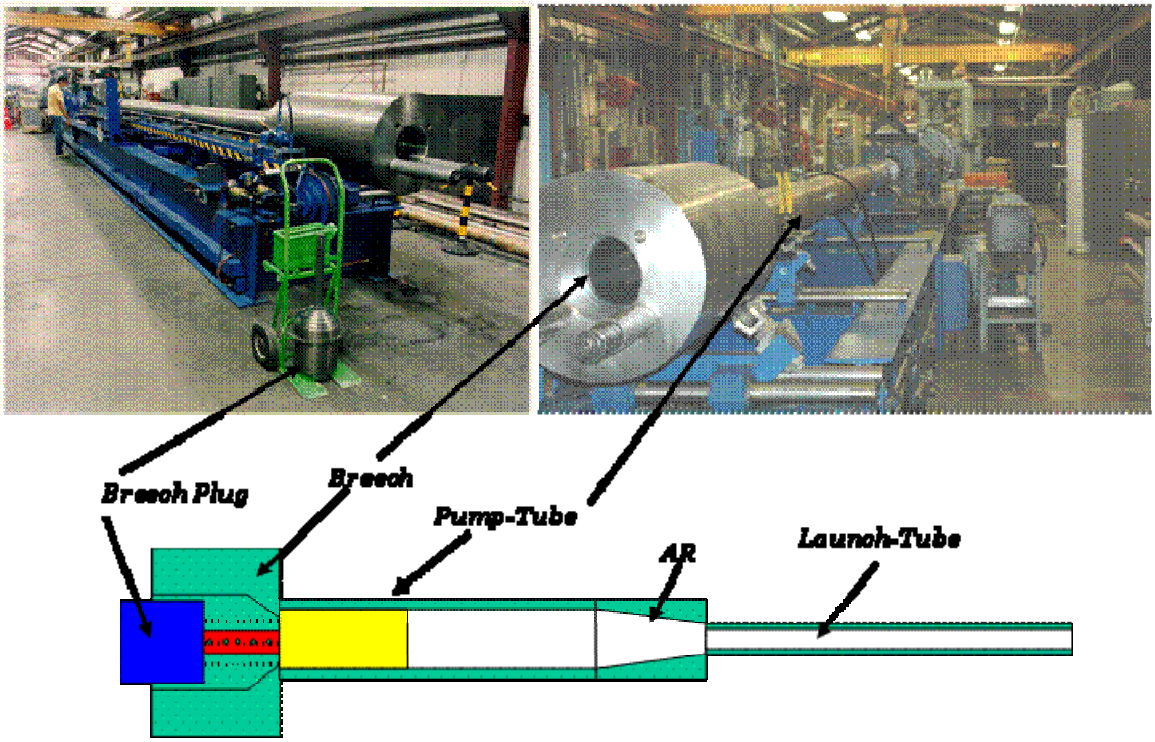

Figure 1. View of STAR two-stage light gas gun.

In fig. 2, the gun and target chamber are shown. In the left-most picture is the target chamber where the target assemblies reside. Primarily, the work on this gun is dynamic equation of state[2]. The two-stage gun is our most versatile at the STAR. Ballistic studies launching (1.35 – 6.0 km/s), projectiles faced with flat plates for material characterization (1.5 – 8.0 km/s) experiments, hypervelocity plate launch (5.0 – 12 km/s)[3], chunky projectiles (14.0 – 16.0 km/s)[4], and small particle launching[5] (> 19.0 km/s) are be performed on this system.

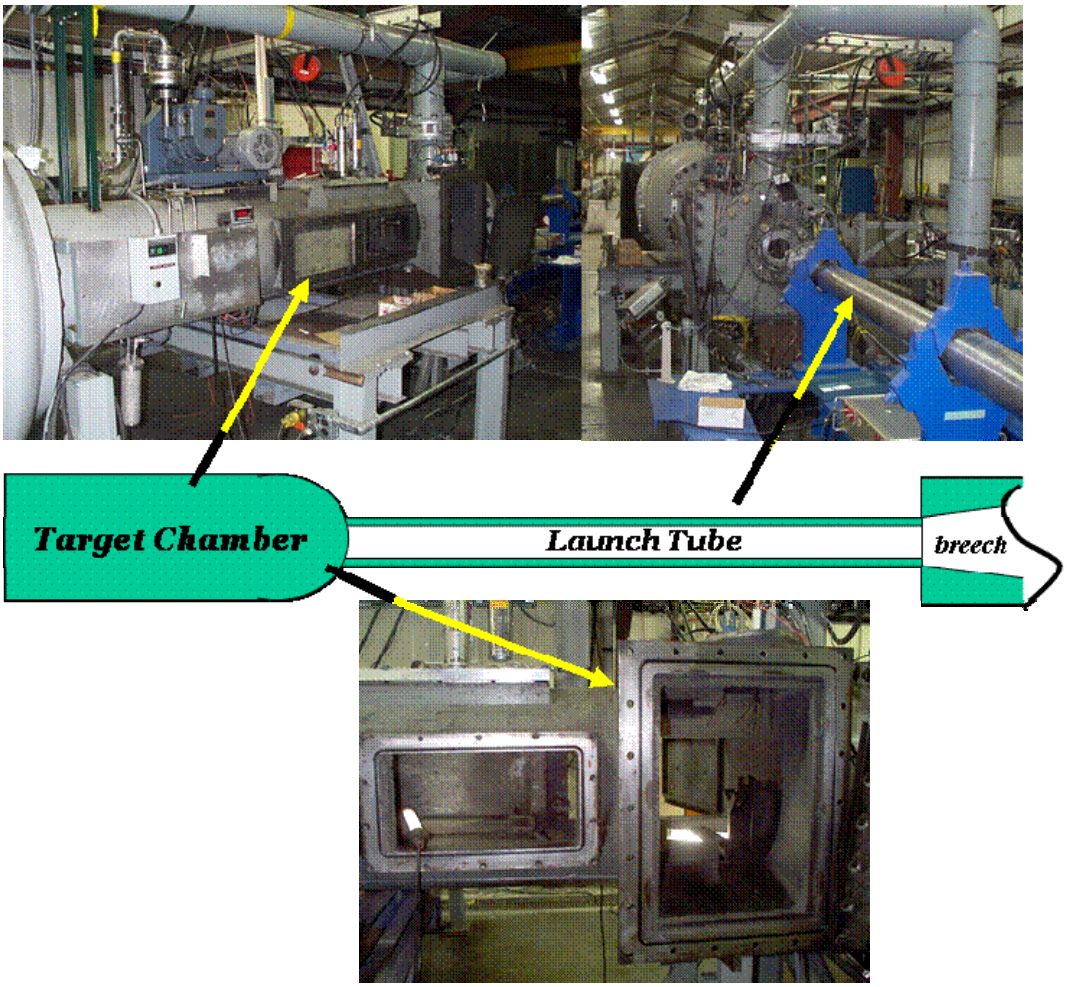

Figure 2. Pictures of impact chamber (left) and catcher/stopper chamber (right).

Figure 3 shows the catcher chamber and the new target chamber.

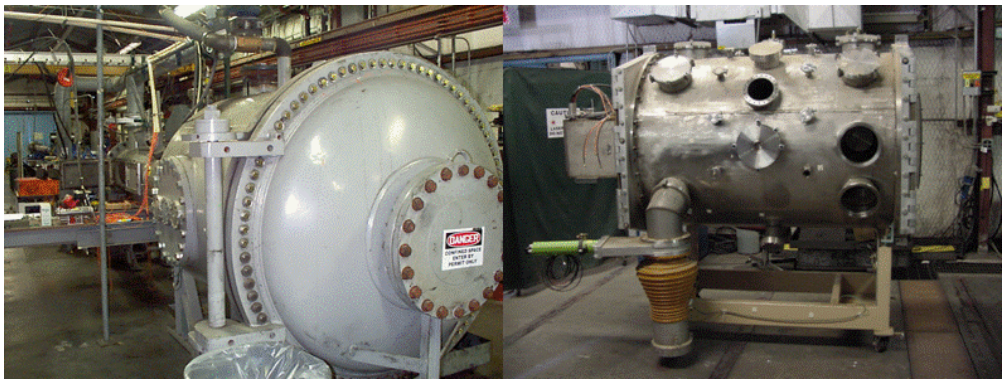

Figure 3. The left photo is the existing target chamber-which becomes part of the flight range. The right photo is the new target 'high-vacuum' chamber.

New high-vacuum Configuration

For our 'new' application of high-vacuum operations, the old target chamber now becomes part of the range and will be used as a gas-expansion chamber. The right photo in fig. 3 is the newly acquired target chamber. As one can see, the chamber is equipped with many ports to accommodate numerous diagnostics. The tank was obtained at Sandia National Laboratories when another department was discarding it after the completion of their program. We acquired it prior to their shipment to reclamation. The tank had previously been outfitted with two diffusion pumps, which we discarded and replaced it with a turbo-pump system.

Figure 4 provides a look on how we will connect the new tank with the older chamber. We will design a simple connecting tube that will work in the medium vacuum area. The connection of the two tanks will be an aluminum (or steel) flanged tube with vacuum seals, and a specially designed membrane to separate the two vacuums. Both chambers are initially evacuated with a roughing pump prior to turning on the turbo-pump. The thickness and material of the membrane are described in a subsequent section.

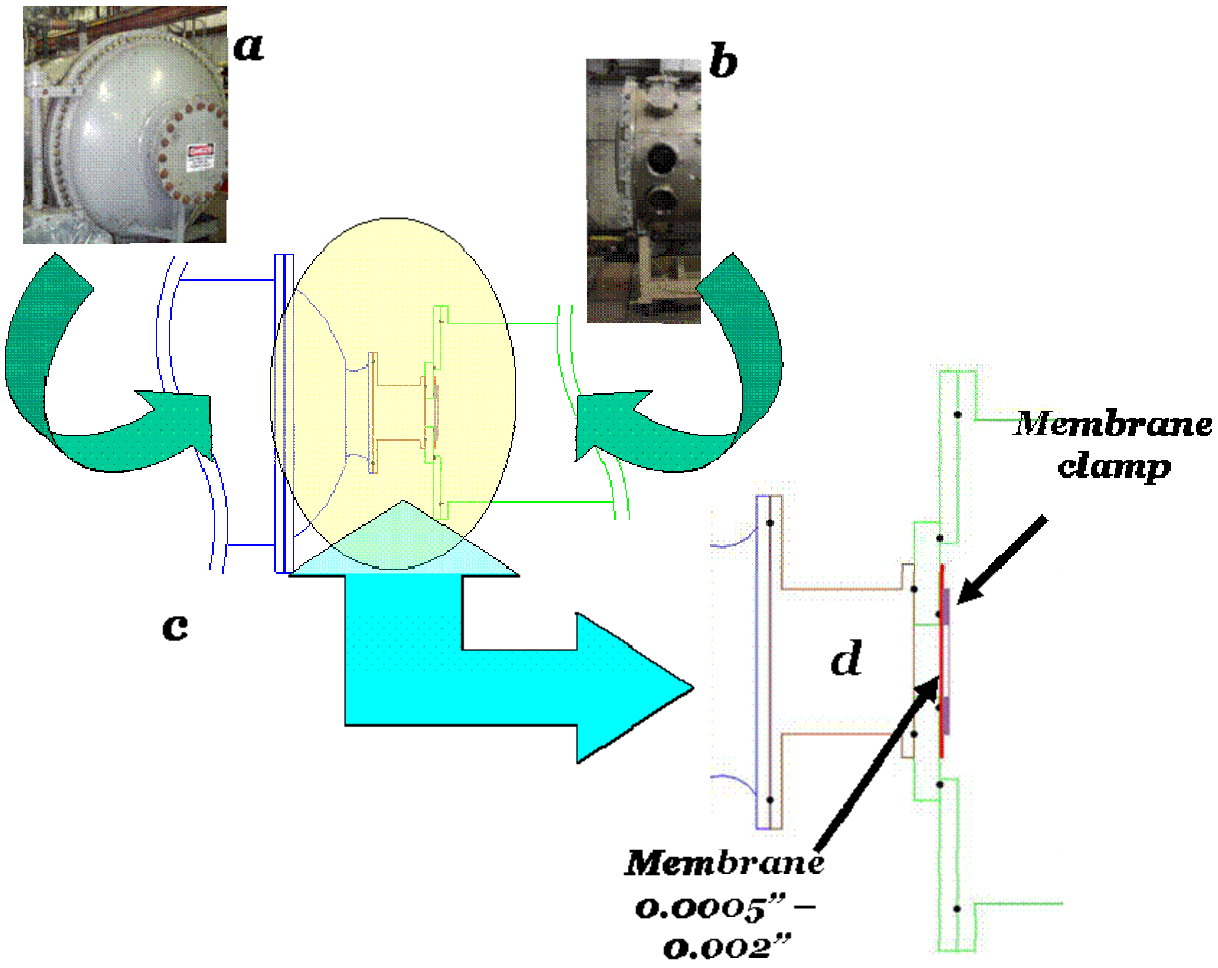

Figure 4. a) is the photo of the existing target chamber, b) will become the new high-vacuum chamber, c) is a drawing of how the two systems will be connected and d) is a zoomed view of the connecting assembly.

Membrane Design

The membrane that separates the two chambers must be designed in a manner that it is thick enough to form an adequate seal separating the two different pressure regimes, yet thin enough so that the flyer, which will penetrate the membrane during flight, is not affected or damaged from the encounter. We will be launching 1mm thick flyer plates (0.040") and hence 0.001" thick membrane would be 40 times thinner than the flyer plate. Upon impact a 100GPa-2ns pulse would be introduced into the flier plate. This pulse is anticipated to attenuate very rapidly before it exits the free surface. One needs to be sure that the peaks stress upon exit is much lower than the spall strength of the material – which is around 6 Gpa for the titanium plates that we are launching. Two-dimensional effects such as edge release will attenuate the stresses even faster than merely one-dimensional loading. A CTH computational analysis will be conducted prior to determining the optimum dimensions.

Why the need for lower pressure?

Shock experiments at extremely high velocities greater than 7 km/s are used to examine the dynamic response of materials at extreme temperatures and pressures[6]. Under these impact conditions targets are subject to melting and vaporization[7, 8]. These conditions result in the excitation of the atoms and molecules involved in the experiment. Once excited, the atoms will eventually return to a lower energy level, releasing photons of specific energies, a process known as spontaneous emission. When collected and analyzed with spectroscopic techniques, the photons may be used to produce a spectrum relating how many photons at various energy levels were collected. In other words, these photons will produce a spectrum and the "intensity" will depend on how many photons at various energy levels were collected. These photons, i.e., the emission spectrum can be diagnosed using spectroscopic techniques These results can be further analyzed for properties of interest, such as material identification[9] and temperature estimates[10, 11].

It is clear then, that recording as many of the atomic emissions as possible plays a key role in the diagnostics for these experiments, and the setup should be designed/optimized to minimize these losses. One factor that should not be overlooked is the effect of the target chamber pressure. A higher pressure results in a higher concentration of air atoms, meaning a higher probability of collisions with the excited materials of interest. Such a collision may result in a transfer of the excited material's energy to the air molecule via absorption, resulting in the loss of that particular photon emission. Thus, it is important to know how tank pressure contributes to the degree of quenching in these experiments resulting from collisions.

Molecular Collision Rate

A simple, qualitative approach to this problem comes in the form of the pressure dependence of the molecular collision rate for an ideal gas,

$$\frac{1}{\tau} = \sqrt{2} A u n,$$

where τ is the mean time between collisions, A is the molecular cross sectional area, *u* is the mean speed, and *n* is the number density. If the calculated mean time between collisions is very large compared to the average lifetime of the material's excited state, then collisional quenching will probably play a minor role in the experiments. Likewise, as this ratio approaches and exceeds unity, the effect becomes much more important. A quick analysis can be performed for tank pressures of interest, for the properties of air given in Table 1. At 298K and pressures of 0.1 mtorr and 50 mtorr, the mean time between collisions times, t , are calculated to be 8 μs and 16 ns, respectively.

Table 1. Properties of Air

A (m^2)	u (m/s)	n
0.3 e-18	1 e3	9.6e24*P(torr)/T

The intrinsic lifetime for an atom in the excited state is directly proportional to the inverse of its Einstein A coefficient,

$$\tau_{ba} = \frac{1}{A_{ba}}.$$

The NIST website[12] lists these coefficients for many well known atomic transitions, from which the excited lifetimes can be calculated, as shown in Table 2.

Table 2. Excited Lifetimes of Several Measured Transitions

Atom	Wavelength (nm)	Excited Lifetime (ns)
Al I	394.40	20.28
Al I	396.15	10.20
In I	410.18	17.86
In I	451.13	9.80
Ti II	430.79	217.4
Ti I	445.74	17.86
Ti I	453.32	11.33
Ti II	518.87	400.00
Na I	589.00	16.23
Na I	589.59	16.29
O II	520.67	30.0
O II	667.79	296.74
O III	1126.49	87.72
C III	620.56	9708.74
C I	667.41	3367.00
C I	769.25	847.46
C I	1126.07	5464.48
N I	621.44	3597.12
N I	666.70	5882.35
N I	770.35	1443.00
N I	1126.62	242.13

As indicated in Table 2, even the shortest excited lifetimes (~10 ns) on are the order of the mean time resulting from collisions for the 50 mtorr tank pressure (16 ns), and should be a cause for concern. On the other hand, it is only at the longest excited lifetimes that the mean collision time for the 0.1 mtorr tank pressure (8μs) becomes of the same order.

Stern-Volmer Collisional Quenching Model

The Stern-Volmer quenching model provides a more quantitative way to calculate the effect of the air molecules on the experimentally excited atoms. The equation is given by

$$\frac{F_0}{F} = 1 + K_{sv}[Q],$$

where F_0 and F is the fluorescence observed in the absence, and presence of the quencher, respectively, [Q] is the quencher concentration, and K_{sv} is the Stern-Volmer quenching constant:

$$K_{sv} = k_q \tau$$
$$k_q = \frac{8RT}{3\eta},$$

where k_q is the bimolecular quenching constant, τ is the excited state lifetime in the absence of the quencher, R is the ideal gas constant, T is the temperature, and η is the viscosity of the solution. Again, the quencher of interest here is air, and the material properties used are shown in Table 3.

Table 3. Stern-Volmer Calculation Constants for Air

R (J / K mol)	T (K)	η (N s / m^2)	R (J / kg K)	M (g/mol)
8.314	293	1.820e-5	287.05	28.77

With the constants shown in Table 3, k_q is calculated to be 3.569e8 m^3/ (mol s). The parameters, τ and tank pressure, can then be used to calculate Ksv and [Q], respectively. A parametric plot of F/F_0 versus τ for tank pressures of 0.1 and 50 mtorr is given below.

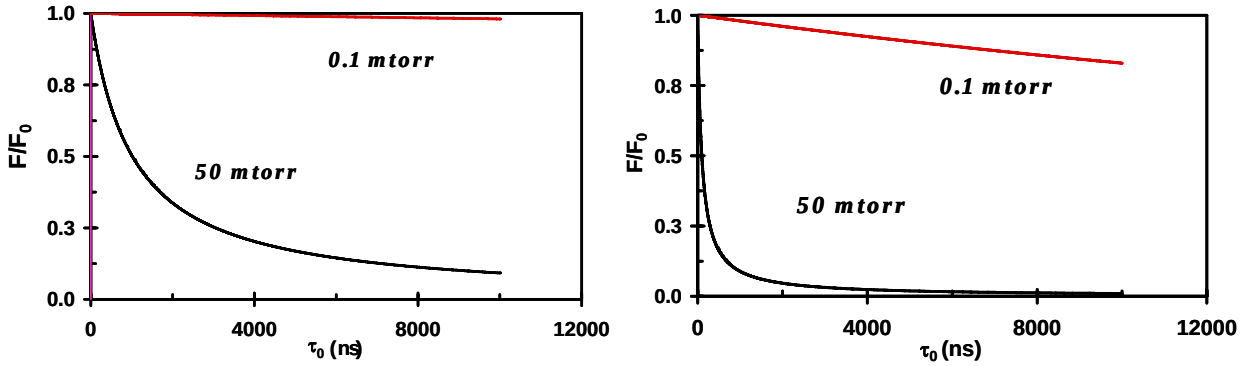

Figure 5. Plot showing effect of collisional quenching. The plot on the left indicates that in an 'air' environment, the quenching is negligible for the high vacuum where as in the low vacuum is significant. The right plot shows that in a nitrogen enriched environment the effects are significantly different

As shown in the plot above, and in agreement with the previous results, the effect of collisional quenching is negligible in the high vacuum tank up to excitation time's to10 μs (where a decrease of only 1.93% in the measured intensity due to quenching is calculated). The lower vacuum, however, results in possible problem with quenching. At excitation times of 1, 10, 100, 1000, and 10000 the measured intensities are anticipated to be 0.098%, 0.97%, 8.95%, 49.6%, and 90.8% less than what they would be without the quenching effect.

Discussion

Unfortunately, the collisional quenching is not simple and has to be measured for each pair of collision partners. The quenching is just a transfer of energy from the excited state of one atom/molecule to its collision partner. If the partner has energy levels that are close to the same value as the excited state, then transfer tends to be very efficient. If the partner has a large number of nearly equal energy levels, then quenching is achieved as the energy transfers and is dissipated in the collision partner. Efficiencies vary widely resulting in between one and hundreds of collisions to quench the emission. Water tends to be an efficient quencher and small atoms or molecules with only high-lying energy levels, such as hydrogen, helium, and to a certain extent, nitrogen are very inefficient.

It is not clear if the change in pressure have a dramatic (i.e. factor of 10) effect on the emission intensities as we approach a collision-free limit at the high pressure. The only certainty is that the lower pressure will provide an environment that allows the optimum emission conditions. It is difficult to estimate how much the higher pressure affects the results. The above mentioned calculations indicate that there could be some effect, but without a detailed model using collision de-activation rate constants, it is hard to quantify the results.

CONCLUSIONS

We have not performed a systematic study on this new system design, though the hardware is in hand and much of the pre-work analysis has been completed.

The *molecular collision rate study* and the *Stern-Volmer Collisional Quenching Model* seem to come to the agreement that the higher vacuum results in a significant decrease in the effect of collisional quenching for atoms with longer excitation lifetimes. Current experiments were all performed at tank pressures of about 50 mtorr. In these experiments lines such as Al, In, and Na were identified easily and consistently. The mean excited lifetime for these lines was, at the most, 20 ns. While this is on the order of the mean collision time for the air in the chamber, the Stern-Volmer analysis estimates that quenching is only a 2% effect.

Experiments on organic materials and Comp-B[10] did not produce the clean results seen in the verification studies. The composition, of these materials, however, consists largely of C, N, and O atoms, for which the excitation lifetime approaches 10 ns and there is a significant effect of quenching at 50 mtorr (91% of the expected photons are not seen). Switching to a higher vacuum, 0.1 mtorr, results in a significant decrease in the quenching effect (back to 2%), even for the longest excitation lifetimes. The move to a higher vacuum could result in much better results for these materials, but it is not significant for materials with short excitation lifetimes, such as Al, In, and Na.

REFERENCES

1. Asay, J.R., *The Sandia National Laboratories Shock Thermodynamics Applied Research (STAR) Facility*. 1981, Sandia National Laboratories: SAND81-1901: Albuquerque NM. p. 1-93.

2. Asay, J.R., L.C. Chhabildas, and L.M. Barker, *Projectile and impactor designs for plate-impact experiments*. 1985, Sandia National Laboratories: SAND85-2009.

3. Chhabildas, L.C., Dunn, J. E., Reinhart, W. D., Miller, J. M., *An impact technique to accelerate flier plates to velocities over 12 km/s.* Int. J. Impact Eng., 1993. **14**: p. 121-132.

4. Chhabildas, L.C., Kmetyk, L.N., Reinhart, W. D., Hall, C. A., *Enhanced hypervelocity launcher - capabilities to 16 km/s.* Int J Impact Eng, 1994. **17**: p. 183-194.

5. Thornhill, T.F., Chhabildas, L. C., Reinhart, W. D., Davidson, D. L., *Particle launch to 19 km/s for micro-meteoroid simulation using enchanced three-stage light gas gun hypervelocity launcher techniques.* Int J Impact Eng, 2006. **33**(1-12): p. 799-811.

6. Reinhart, W.D., Chhabildas, L. C., Carroll, D. E., Bergstresser, T. K., Thornhill, T. F., Winfree, N. A., *Equation of state measurments of materials using a three stage gun to impact velocities of 11 km/s.* Int J Impact Eng, 2000. **26**: p. 625-637.

7. Brannon, R.M., Chhabildas, L.C., *Experimental and numerical investigation of shock-induced full vaporization of zinc.* Int J Impact Eng., 1995. **17**: p. 109-120.

8. Chhabildas, L.C., Reinhart, W.D., Thornhill, T.F., Bessette, Saul, W.V., Lawrence, R.J., Kipp, M.E., *Debris Generation and Propagation Phenomenology from Hypervelocity Impacts on Aluminum from 6 to 11 k/ms.* Int J Impact Eng, 2003. **29**: p. 185-202.

9. Lawrence, R.J., Reinhart, W. D., Chhabildas, L. C., Thornhill, T. F., *Spectral measurements of hypervelocity impact flash.* Int J Impact Eng, 2006. **33**: p. 353-363.

10. Reinhart, W.D., Thornhill, T. F., Chhabildas, L. C., Breiland, W. G., Brown, J. L., *Temperature Measurements of Expansion Products from Shock Compressed Materials using High-Speed Spectroscopy*, in *to be published in: Int J Impact Eng*. 2007: Williamsburg, VA.

11. Thornhill, T.F., Reinhart, W. D., Chhabildas, L. C., Breiland, W. G., Alexander, C. S., Brown, J. L., *Characterization Of Prompt Flash Signatures Using High Speed Broadband Diode Detectors*, in *to be published in: Int J Impact Eng*. 2007: Williamsburg, VA.

12. *Atomic Spectra Database Lines Form*. National Institute Standards Technology 1901 [cited; Available from: http://physics.nist.gov/PhysRefData/ASD/lines_form.html.