SAND91/0711C

Invited Paper Submitted to the 18th International Symposium on Shock Waves

Institute of Fluid Science, Tohoku University, Sendai

July 21-26, 1991

SAND--91-0711C

DE91 015564

**THE USE OF HIGH VELOCITY LAUNCHERS
FOR SCIENTIFIC AND ENGINEERING STUDIES**

*J. R. Asay, L. C. Chhabildas, and M. D. Furnish
Sandia National Laboratories
Albuquerque, New Mexico 87185*

Abstract

Shockwave techniques have been used for decades to study the dynamic states of matter in temperature and pressure regimes inaccessible by other methods. These techniques have been employed in a wide variety of scientific, military, and commercial applications. A principal scientific objective has been to determine high-pressure equations of state (EOS) to ultra-high pressures; pressures of tens of Mbar have been reported for several materials. Most recently, these methods have been used for studies of thermophysical properties under shock compression, including phase transition kinetics, and mechanical properties, such as the high-pressure yield strength. In this paper, a brief discussion of recent developments in high velocity launchers is given. Advances in techniques for subjecting materials to a wide range of loading conditions is presented, including selected illustrations of shockwave measurements to Mbar pressures.

I. Introduction

The development of high-velocity guns has played a central role in understanding material processes at temperature and pressure extremes inaccessible by other means (Davison and Graham, 1979). A principal application of these launchers is the study of the high-pressure equations of state and material properties. The earliest shock compression measurements were determined through use of explosive loading method (Chhabildas and Graham, 1989). These methods were useful in determining EOS properties that could not be studied by other methods. However, their main limitation is that the initial loading conditions are extremely limited, so that their principal use has been confined to measurements of shock Hugonot states.

In recent years, high-velocity guns have replaced explosive loading for shock wave measurements in most laboratories. Gun methods provide well controlled and precise loading for producing and

MASTER *ab*
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

probing the shocked state. Since, these methods allow a broad variety of loading conditions, they can be used to determine-physically based material properties, such as high-pressure compressive strength.

In this paper, we present a brief discussion of developments in launcher techniques and include several specific examples. One example is the measurement of strength properties in tungsten to 2 Mbar for both shock loading and shockless (continuous) loading (Chhabildas et al., 1987, 1990, 1991). Shockless loading is a recent innovation in impact loading (Barker, 1984), which allows determination of quasi-isentropic material properties under dynamic compression. Measurements of unloading from the shocked state are also discussed. Future directions for gun launchers and shockwave applications are also discussed in the paper.

II. Launcher Capabilities

A large range of launchers has been developed for material property studies (Chhabildas and Graham, 1989). The simplest systems are gas-driven guns, 50-100 mm in diameter, which have a maximum velocity of about 1.4 km/s and can produce impact pressures of about 0.3 Mbar in high density materials. High -pressure helium gas is normally used to launch projectile masses of a few kilograms in these guns. The next level of capability includes propellant-driven guns which can launch kilogram-projectiles to velocities of about 2.3 km/s. Impact pressures to about 1 Mbar can be produced in high-impedance materials such as tungsten with these launchers. Two-stage light-gas guns increase achievable projectile velocities in the laboratory (for a few tens of grams) to 8 km/s for practical applications (Charters, 1986). These launchers allow impact pressures of several Mbar in the laboratory. Figure 1 summarizes the states that can be obtained with these different launcher systems.

Asay and Graham (1978), Charters (1986), and Chhabildas and Graham (1989) summarize the capabilities of the different guns developed for EOS and dynamic material property studies. Other recent advances include a modified two-stage gun, which extends projectile velocities to over 12 km/s for gram-sized projectiles (Chhabildas et al. 1991). This technique uses the two-stage light gas gun to launch a third-stage projectile with shockless loading methods. Velocities up to 10.4 km/s have been reported for 0.8-g flyer plates using this technique; velocities as high as 14 km/s are feasible (Chhabildas, et al., 1991).

For material property studies, it is essential that the impact condition be precisely controlled. Figure 2 illustrates the typical configuration used for planar shock studies. The misalignment (tilt) of the impactor with the specimen must typically be less than 1 mrad at the lower impact velocities, although misalignment of a few mrad are tolerable at impact velocities exceeding 5 km/s. Since the initial state is determined from the impact condition, the velocity of the projectile must be accurately known (typically to better than 0.5%). When these conditions are met, very accurate EOS data can be determined from shockwave measurements using high-velocity guns.

A unique capability of gun launchers is that a variety of loading conditions can be achieved and

precisely controlled. Figure 3 illustrates the various loading conditions that can be achieved with high-velocity gun launchers. The basic experiment consists of a simple impact condition, which produces a single step loading that is maintained for a long time duration compared to shockwave transit in the sample. This method is useful for generating very accurate EOS (shock Hugoniot) data on materials. Nellis and coworkers (1982) report Hugoniot data with accuracies of 1% using this approach.

Another variation in launcher technology involves the impact of a thin flyer, which produces a short pulse duration in the specimen and can be used to generate the release adiabat of specimen. Use of a time-resolved gauge on the specimen allows determination of the stress-strain unloading curve from the shocked state (Asay et al., 1986). If the back surface of the specimen is a free surface, this technique can also be used to determine dynamic tensile strengths (spall strength). Another recent method for determining release adiabats employs the use of direct impact of a specimen with a time-resolved gauge.

A recent innovation involves the uses of graded density impactors to produce shockless loading (Barker, 1986). In this technique, an impactor is used which has a variable shock impedance throughout its thickness. The impact surface of the graded density impactor (referred to as a "pillow") has a low shock impedance, typically a low density plastic, followed by a gradual increase in impedance, to a final value equivalent to that of copper at the back surface. Impact of the pillow produces a low initial shock, followed by shockless loading to the final state. This method allows control of the temperature state, since shockless loading is nearly isentropic. Since shock-induced melting can be circumvented with this approach, material properties in the solid phase can be studied to extremely high pressures.

A final technique discussed here concerns the direct measurement of shear properties under shock loading (Abou-Sayed, Chhabildas, Gupta et al., 1980). This method uses an oblique impactor shown in Figure 3 to impact a specimen at similar inclined angle. Impact produces both a normal component of motion and a transverse component. The normal component provides EOS or dynamic material property data as in normal impact. The transverse component results in a direct determination of shear-dependent properties. This technique, referred to as the "pressure-shear" or "compression-shear" technique, has been valuable for determining shear-dependent properties of metals and composites under shock loading.

The other aspect of shock wave developments which has been crucial to the use of high-velocity launchers concerns development of time-resolved diagnostics for measuring the structure of shock waves. Several diagnostic techniques have been developed which are discussed in detail by Graham and Asay (1978), Chhabildas (1986) and Chhabildas and Graham (1989), so that only a brief survey is given here. A variety of pin and optical diagnostics have been developed to measure shock velocity, which is basic to EOS measurements. Piezoelectric, piezoresistive, electromagnetic and interferometric methods have been used for wave structure measurements (Chhabildas and Graham, 1989). Recent advances in shockwave diagnostics, which include time-resolved measurement of shock-induced temperature and wave structure. The combination of

these methods has been used to determine high-pressure material strength, spallation strength, phase transition kinetics and unloading adiabats for materials (Asay and Kerley, 1986). In addition to compression properties, Curran and coworkers (1987) have written a recent review of techniques for determining dynamic failure properties of solids.

III Examples of Shock Wave Studies

Several examples of the capabilities of shock compression methods are provided in the review articles by Duvall and Graham (1977), Davison and Graham (1979), Asay and Kerley (1986) and Curran and coworkers (1987). Here we will present only a few examples to illustrate recent results.

High-pressure EOS (Mbar Hugoniot in Cu, 4000 Mbar Al data by Soviets)

A gun experiment may achieve pressures up to approximately 5 MBar (0.5 TPa). Such stress states are sufficient to achieve melting in many materials. Gun techniques, however, do not allow the direct observation of vaporization or other very-high-pressure dynamic phenomena except for such low-melting materials as cadmium or lead or for porous materials (eg. Wise *et al.*, in press).

Higher-pressure shock states may be achieved using underground nuclear explosions as drivers. In these states, shock heating may be so strong that the ion-thermal and electronic components of the pressure are comparable to the compression component (Mitchell *et al.*, 1991). Pressures to approximately 4 GBar (400 TPa) have been reached by this technique in aluminum (Vladimirov *et al.*, 1984), and to somewhat lower pressures in copper (Al'tschuler, *et. al.*, 1962). At such pressure levels, temperatures are above the Fermi level (reached at about 76 MBar in aluminum) and core ionization may become important. Electron-ion coupling may give negative Hugoniot slopes over certain pressure ranges. This has been observed in Soviet experimental results (Vladimirov *et al.*, 1984), and has been modeled by Livermore scientists (Young *et al.*, 1985), although Livermore gun experiments to somewhat lower pressures have not found evidence for the expected break in the Hugoniot slope (Nellis *et al.*, 1988).

Spallation Results

Shock wave techniques are also useful in determining the fracture strength of materials. For a variety of engineering applications, such as weapon design, explosive welding, and recovery fixtures for material synthesis, it is essential that the final product survive the high strain-rate loading process. From the standpoint of scientific studies, shock wave methods allow a means of determining nucleation and growth processes (Curran, *et. al.* 1981, Grady, 1988) resulting from defect

generation and propagation. A basic understanding of these processes is necessary for developing fracture-resistant materials which approach theoretical strength. The mechanism for material fracture includes the nucleation of defects (voids or cracks), the growth, propagation, and eventually the coalescence of these defects to form a rupture surface within the material. It is therefore meaningful to discuss the entire fragmentation process in terms of the energy expended in creating the fracture process (Grady, 1988). The energy consumed in the fracture process can be further related to material properties such as the dynamic yield strength or the fracture toughness by estimating the energy required for void growth or in creating a fracture surface. It is therefore not surprising that there a correlation is observed between normalized spall strength (i.e., the ratio of the material spall strength to its density) and fracture toughness for a variety of materials (Chhabildas, 1990). The concepts of fracture and fragmentation have been verified in a series of well-controlled high-pressure gas-driven plate-drive experiments (Barker et. al., 1990, Chhabildas, et. al., 1990), in which the mean fragment size resulting from plate failure during acceleration is related to normalized spall strength. Considerations of the physical processes associated with fracture and fragmentation were important in recognizing fracture toughness or normalized spall strength as a measure of a material's ability to resist fragmentation, and led to an engineering success, namely the ability to launch plates to high velocities using gas-driven systems (Chhabildas, et al., 1990).

Material Strength Studies Under Shockless Loading

It is well known from quasi-static experiments that the yield, or ultimate tensile strength, of materials depends on stress, temperature, and loading rate. With the development of *dynamic* time-dependent loading techniques, referred to as quasi-isentropic loading (Barker, 1984, Chhabildas, 1988), one can now determine the temperature, pressure, and loading rate effects on the dynamic yield strength, and the spall strength of materials to stresses approaching 3 Mbar (Chhabildas et al., 1990c, 1990d). Under shock loading to a stress of interest, the strain rates induced in the shock front are controlled primarily by material viscosity, whereas under plane quasi-isentropic loading, the rates can be controlled. For shock loading, the internal energy change of the material corresponds to the area under the Rayleigh line in the pressure-volume plane, whereas under plane quasi-isentropic loading the internal energy change is given by the area under the isentropic loading curve. Thus, for large compressions, the internal energy change under quasi-isentropic compression will be substantially less than that for shock loading to the same stress, resulting in lower energy (temperature) states. A comparison of shock loading and quasi-isentropic loading experiments to the same stress will, therefore, allow determination of pressure, temperature, and rate-dependent material properties.

A determination of the dynamic yield strength of tungsten under shock and quasi isentropic loading (Chhabildas et al., 1990c, 1991) up to 250 GPa, suggests an increase in yield strength with increasing final stress as shown in Figure 4. However, the dynamic yield strength of tungsten under the slower rates of quasi-isentropic loading is a factor of three larger than that obtained for shock loading to stresses approaching 250 GPa. The temperature of tungsten shocked to 250 GPa is estimated to be 5000 K, whereas under quasi-isentropic compression to 250 GPa it is less than 1000 K. In quasi-loading experiments, the temperature of the material is much lower than that

under shock loading.

Likewise, a determination of the spall strength of tantalum precompressed to 19 GPa and 60 GPa under shock and quasi-isentropic loading, respectively, indicates an increase in spall strength under quasi-isentropic loading. A spall strength measurement of 8.1 GPa under quasi-isentropic compression is an increase of 27% when compared to a value of ~ 6.2 GPa after shock compression to 19 GPa. This increase may be a result of slightly lower temperatures induced as a consequence of quasi-isentropic loading. A lesser concentration of defects (and therefore a lower concentration of nucleation centers for spall initiation) created as a result of slower rates of loading under quasi-isentropic precompression may also have contributed to increase of spall strength.

From an engineering standpoint, understanding of physically based processes affecting the microstructure under quasi-isentropic loading responsible for increasing yield strength and spall strength can lead to the synthesis of high strength materials.

Pressure-Shear Loading

In the last decade, experimental techniques have also been developed to generate dynamic pressure-shear loading conditions with launcher techniques (Abou-Sayed, et al., 1979; Gupta et al., 1980; Chhabildas and Swegle, 1980;). This is an important development, since material properties can be studied under more general loading conditions with these methods. The technique is versatile enough to probe material response over a wide range of pressure-shear states. However, slippage or strength of bonded interfaces can be a controlling factor in estimating the shear stress states introduced in the material. Nevertheless, stress-dependent shear modulus (in the shocked state) can be determined directly from these experiments through a direct measurement of shear wave speed in a pressure-shear experiment (Chhabildas, 1988, Gupta et al., 198x). These measurements, when combined with elastic release wave speed values obtained from traditional shock loading experiments, yield estimates for stress or volume-dependent bulk moduli.

A novel technique which allows determination of dynamic coefficient of friction between two sliding bodies (Chhabildas, 1989), has been developed using the techniques developed for pressure-shear loading. In this technique, a solid cone is made to slide into a mating hollow cone at ordnance velocities of 1 km/s. The ratio of the normal stress to the magnitude of transmitted shear stress, which is limited by friction, is a direct measure of the dynamic coefficient of friction, assuming that a Coulomb law for friction is applicable. In particular, it has been determined that for smooth machined surfaces of 4340 steel at sliding velocities of ~ 1 km/s, the dynamic coefficient of friction is ~ 0.05 and is an order of magnitude lower than that obtained statically. This is a novel concept, which paves the way for determination of dynamic coefficients of friction for a variety of geological and engineering materials.

Shock Induced Melting in Materials

With increasing shock amplitude, sufficient internal energy is deposited in the shocked material to

induce melting. However, the volume change in the shocked material associated with melting is extremely small. Therefore, it cannot be easily observed, either in the shock velocity-particle velocity plane, i.e., on the shock Hugoniot. As the shocked material approaches the melt boundary, both the shear stress and the shear modulus (Asay et al., 1975) vanish. This causes the sound speed behind the shocked front to transform from elastic to bulk wave speeds. This principle has been used to accurately determine melting phase changes in the shocked state (Chhabildas, 1986). Since the early measurements for determining elastic release wave speeds (Al'tschuler, et al., 1971), this technique has been used to detect melting under shock compression in porous aluminum (Asay et al. 1975), bismuth (Asay 1977), aluminum (McQueen et al., 1984, Asay et al., 1986), tantalum (Brown et al., 1984), iron (Brown, et al., 1980) and quartz (Lyzenga, et al., 1983, Chhabildas, 1986). Shock induced melting studies contribute toward validation of the equations of state, with particular emphasis on various melting laws such as Lindemanns melting law. In case of geological materials, such as iron and quartz, these measurements are also useful to infer the composition of the earth's inner and outer cores or the mantle (Ahrens, 1986). Asay and Kerley (1986) discuss additional shock wave determinations of dynamic phase changes.

Mass-Mixing and Chemical Reactions under Shock Loading

A variety of solid and solid-liquid mixtures have been observed to undergo chemical reactions under dynamic loading. This is especially interesting because it implies that mass mixing may occur on a microsecond time scale in these systems. These reactions have been inferred primarily on the basis of EOS or by analysis of recovered samples, although reactions may also affect shock evolution or heating to an observable degree.

A few examples follow. Porous limestone saturated with water compresses under 5 - 12 GPa shocks to a density consistent with ikaite (calcium carbonate hexahydrate), about 20% denser than the unreacted mixture (Furnish, 1990). Ceramic compacts of TiB_2 , B_4C , SiC of 96 - 98% theoretical density have been produced by shock-compacting powders of Ti, B and C; these are extremely difficult to produce directly by sintering techniques (Persson *et al.*, 1990). Similarly, a powder mixture of Y_2O_3 , BaO, BaO_2 and CuO may be shocked to give a superconducting compact (Miller, 1990). Diamond powder mixed with Si and C and shocked yields diamond + SiC in a form with more than twice the hardness achievable through non-shock production (Sawaoka and Akahashi, 1987). In the last three cases, chemical reactions have occurred in shocked powders to produce a commercially useful product. Finally, Horie and Kipp (1990) have modeled the known exothermic shock-induced reaction of aluminum with nickel, which yields bimetallics and alloys, but the necessary shock-decay or pyrometry experiments to test their model have not been performed.

Impact Studies of Cryogenic Liquids to Constrain Giant Planet Models

Gun impact studies have been performed on liquified hydrogen, helium, methane, carbon dioxide and a mixture referred to as "synthetic Uranus" (see, eg. Hamilton *et al.*, 1988), largely for the

purpose of constraining models of the giant planets (Jupiter, Saturn, Uranus and Neptune). By a fortunate coincidence, the Hugoniot of these materials traverse regions of pressure/temperature space not altogether different from those of interest for planetary studies. Experiments have been conducted to measure the EOS of these materials, and their electrical conductivity and temperature under shock-loaded conditions. Electrical conductivity measurements on compressed hydrogen conducted by Mitchell *et al.* (in press) may help explain the shallow centering point and large amplitude of the magnetic field of Uranus (0.3 radii from the planet's center). Further work may be required in assessing the role which water, with a potentially high protonic conductivity, may play in creating a magnetic field. Hydrogen metallization is still an open question. Equation-of-state studies conducted on synthetic Uranus (a mixture of water, ammonia and isopropanol) show some consistencies with the calculated mass distribution of Uranus (Mitchell *et al.*, 1990).

Pyrometry experiments on shocked liquid nitrogen show the interesting phenomenon of "shock cooling" (Radousky, 1988). Nitrogen is interpreted as passing through an endothermic dissociation under shock at about 30 GPa (density of 2 gm/cm³ and temperature of 7000K). A reshock passing through nitrogen under these conditions may cool the material by up to 1000K. The dissociation has not been observed in static (diamond-anvil cell) experiments, and apparently requires the higher temperature of the dynamic experiments to proceed.

IV Recent Advances in Launcher Technology

Substantial effort has been directed to the development of launcher systems that can achieve even higher projectile velocities. Examples include electromagnetic techniques such as railgun launchers (Asay *et al.*, 1990) which can accelerate projectiles to velocities inaccessible with mechanical systems and electrostatic techniques employed in Van der Graaff accelerators (Keaton *et al.*, 1990) to accelerate small particles to very high velocities. Laboratory railguns have achieved projectile velocities of 7.5 km/s to date, although much higher velocities are, in principle, possible. Van der Graaff accelerators have achieved velocities of over 100 km/s for picogram-sized particles. Other inductive launchers, including the reconnection gun and the coilgun (Kay *et al.*, 1990), are being developed to use electromagnetic concepts for accelerating projectiles, although these guns have yet not achieved the high velocities reported for railguns. In addition to electromagnetically driven guns, other electric techniques are being explored for mass acceleration. One example is the electric gun (Osher *et al.*, 1990), which generates plasmas through capacitor discharge to accelerate thin plastic flyers to peak velocities in the range of 20 km/s.

A recent advance by Chhabildas and coworkers (1991) allows the use of two-stage light gas guns to achieve ultra-high velocities in a stage approach. In this method, the momentum of the projectile is transferred to a thin flyer which is mounted in an barrel extension at the muzzle of the gun. Precautions are taken to ensure that nearly shockless loading of the flyer is achieved by using a graded density impactor on the projectile and to minimize radial gradients in the flyer through the use of guard-ring approaches. This technique has been used to launch 0.8-gm aluminum flyers to velocities over 12 km/s.

V. Other Uses Of High Velocity Launchers

In addition to material property studies, high-velocity launchers are fundamental to a variety of other applications. These include guns designed specifically to study materials subjected to ballistic loading, such as projectile or meteorite impact. Dynamic phenomena of importance in these studies concerns the failure response of target and projectile materials and the effects of debris in the form of finely dispersed fragments or vapor produced during failure of these components. Analysis of this debris and the interaction of the debris with other components is fundamentally important in several applications, including the design of better armors for weapon systems and the design of debris shields for spacecraft (Chhabildas et. al.).

REFERENCES

Abou-Sayed, A. S., R. J. Clifton, and L. Herman (1976). *Exp. Mech.*, 16, 127--132.

Ahrens, T. J. , (1986), Application of Shock Wave Data to Earth and Planetary Science, In Y. M. Gupta (ed.), *Shock Waves in Condensed Matter*, Plenum Publishing, 601--605.

Al'tshuler, L. V. , A. A. Bakanova and R. F. Trunin, *Ah. Eksp. Teor. Fiz.*, 42,91 (1962) [*Sov. Phys. JETP*, 15, 65, 1962].

Al'tshuler, L. V., M. I. Brazhnick, and G. S. Telegin (1971). *J. Appl. Mech. Tech. Phys.*, 12, 921-926.

Asay, J. R. and D. B. Hayes (1975). *J. Appl. Phys.*, 46, 4789-4800.

Asay, J. R. and G. I. Kerley (1987). The Response of Materials to Dynamic Loading. *Int'l. J. of Impact Engr.*, 5, 69-99.

Asay, J. R., L. C. Chhabildas, T. G. Trucano, and G. I. Kerley (1986). High Pressure Strength of Shocked Aluminum. In Y. M. Gupta (ed.), *Shock Waves in Condensed Matter*, Plenum Publishing, 145--149.

Asay, J. R., T. G. Trucano, and R. S. Hawke, (1990). The use of Hypervelocity Launchers to Explore Previously Inaccessible State of Matter, *J. Impact Engng.*, V 10, 51-66.

Barker, L. M. (1984). High-Pressure Quasi-Isentropic Experiments. In J. R. Asay, R. A. Graham, and G. K. Straub(eds.) *Shock Waves In Condensed Matter--1983*, Elsevier Science Publ., B.V.,

217-224.

Barker, L. M., L. C. Chhabildas, J. R. Asay, and T. G. Trucano (1990), "High Gas Pressure Acceleration of Flier Plates: Experimental Technique," *Int. J. Impact Engng*, V10, 67.

Brown, J. M., and R. G. McQueen (1980). *Geophys. Res. letters.*, 7, 533--536.

Brown, J. M. and J. W. Shaner (1984). Rarefaction Velocities in Shocked Tantalum. In J. R. Asay, R. A. Graham, and G. K. Straub (eds.), *Shock Waves in Condensed Matter--1983*, Elsevier Science Publ., B.V., 91--94.

Charters, A. C. (1986), Development of the High-velocity Gas-Dynamics Gun, in *Int'l J. of Impact Engr.*, 5, 181-203.

Chhabildas, L. C. and J. W. Swegle (1980). *J. Appl. Phys.*, 51, 4799-4807.

Chhabildas, L. C. (1986). Shock Loading and Release Behavior of X-Cut Quartz. In Y. M. Gupta (ed.), *Shock Waves in Condensed Matter*, Plenum Publishing, 601-605.

Chhabildas, L. C. (1986). Survey of Diagnostic Tools Used in Hypervelocity Impact Studies, in *Int'l J. of Impact Engr.*, 5, 205-220.

Chhabildas, L. C., (1988). "Pressure-Shear Loading of Materials, in *Shock Waves in Condensed Matter - 1987* , S. C. Schmidt, N. C. Holmes (editors), Elsevier Science Publishers B. V. , (1988) 579.

Chhabildas, L. C. and L. M. Barker, (1988). "Dynamic Quasi-Isentropic Compression of Tungsten," in *Shock Waves in Condensed Matter - 1987* , S. C. Schmidt, N. C. Holmes (editors), Elsevier Science Publishers B. V. , (1988) 111.

Chhabildas, L. C., and R. A. Graham (1989). Developments in Measurement Techniques for Shock-loaded Solids, in *Techniques and Theory of Stress Measurements for Shock Applications-AMD Vol83*, R. B. Stout, F. R. Norwood, and M. E. Fourney, eds., Amer. Soc. Mech. Engr., N.Y.

Chhabildas, L. C., L. M. Barker, J. R. Asay, and T. G. Trucano (1990a). " Spall Strength Measurements on Shock Loaded Refractory Metals," in *Shock Compression of Condensed Matter - 1989*, S. C. Schmidt, J. N. Johnson, L. W. Davison (editors), Elsevier Science Publishers B. V. , 429.

Chhabildas, L. C., L. M. Barker, J. R. Asay, and T. G. Trucano (1990b). "Relationship of Fragment Size to Normalized Spall Strength for Materials," *Int. J. Impact Engng*, V10, 107.

Chhabildas, L. C., J. R. Asay, and L. M. Barker (1990c). "Dynamic Quasi-Isentropic Loading of Tungsten," in *High Pressure Research*, 1990, V5, 842.

Chhabildas, L. C. and J. R. Asay (1991). "Quasi-Isentropic Compression Techniques for Material Property Studies" in *EXPLOMET, Shock Waves and High-Strain-Rate Phenomena in Metals*, edited by M. A. Meyers, L. E. Murr, and K. P. Staudhammer.

Chhabildas, L. C., L. M. Barker, J. R. Asay (1991). T. G. Trucano, G. I. Kerley, Sandia's New Hypervelocity Launcher - HVL, Sandia National Laboratories Report SAND91-0657,

Chhabildas, L. C. , L. M. Barker, J. R. Asay, T. G. Trucano, G. I. Kerley, J. E. Dunn (1991). Launch Capabilities to Over 10 km/s, in *Shock Waves in Condensed Matter - 1991* , S. C. Schmidt, R. Dick, J. W. Forbes, (editors), Elsevier Science Publishers B. V. , in preparation.

Curran, D. R., L. Seaman, and D. A. Shockey (1981). In *Shock Waves and High-Strain-Rate Phenomena in Metals*, edited by M. A. Meyers, and L. E. Murr, Plenum Publishers, 129.

Curran, D. R., L. Seaman, and D. A. Shockey (1987). *Dynamic Failure of Solids*, Physics Reports, 147, 253-388.

Davison, L. W. and R. A. Graham (1979). *Shock Compression of Solids* Phys. Rep., 55, 257-379.

Duvall, G. E. and R. A. Graham (1977). *Rev. Modern Phys.*, 49, 523-579.

Furnish, M. D. (1989). S. C. Schmitt, J. N. Johnson and L. W. Davison (eds), Elsevier (1990). *Dynamic Compression and Release Experiments on Indiana Limestone*, pp. 625-628 in *Shock Compression of Condensed Matter*.

Grady, D. E. (1988). "The Spall Strength of Condensed Matter," *J. Mech. Phys. Solids*, 36 (1988) 353.

Graham, R. A. and J. R. Asay (1978). *Measurements of Wave Profiles in Shock Loaded Solids, High Temperatures--High Pressures*, 10, 355-390.

Gupta, Y. M., D. D. Keough, D. F. Walter, K. C. Dao, D. Henley, and A. Urweider (1980). *Rev. Sci. Instrum.*, 51, 183-194.

Hamilton, D. C., W. J. Nellis, N. C. Homes, H. B. Radousky, F. H. Ree and M. Nicol (1987). *Elec-*

trical Conductivity and Equation of State Measurements on Planetary Fluids at High Pressures and Temperatures, pp. 99-101 in Shock Waves in Condensed Matter. S. C. Schmidt and N. C. Holmes (eds), Elsevier (1988).

Horie, Y., and M. E. Kipp, Modeling of Chemical Reactions in the Mixture of Al-Ni Powders Under Shock-Wave Compression, pp. 387-390 in Shock Compression of Condensed Matter - 1989, S. C. Schmitt, J. N. Johnson and L. W. Davison (eds), Elsevier (1990).

Kaye, R. J., E. L. Brawley, B. W. Duggin, E. C. Chare, D. C. Rovang, and M. M. Widner (1990). Design and performance of a Multi-Stage Cylindrical Reconnection Launcher, 5th Symposium of Electromagnetic Launch Technology, Destin, Florida, April 2-5 1990.

Keaton, P. W. G. C. Idzork, L. J. Rowton, J. D. Seagrave, G. L. Stradling, S. D. Bergeson, M. T. Collopy, H. L. Curling, D. B. McColl, and J. D. Smith (1990) J. Impact Engng., V 10, 295-308.

Lyzenga, G. A., T. J. Ahrens, and A. C. Mitchell (1983). J. Geophys. Res., 88, 2431--2444.

McQueen, R. G., J. N. Fritz, and C. E. Morris (1984). The Velocity of Sound Behind Strong Shock Waves in 2024 Al. In Shock Waves in Condensed Matter-1983, J. R. Asay, R. A. Graham, and G. K. Straub (eds.), Elsevier Science Publ., B.V., 95-98.

Miller, A. R., Explosive Synthesis of a Y-Ba-Cu-O Superconductor, pp. 603-606 in Shock Compression of Condensed Matter - 1989, S. C. Schmitt, J. N. Johnson and L. W. Davison (eds), Elsevier, (1990).

Mitchell, A. C., W. J. Nellis, D. J. Erskine and P. C. McCandless, Electrical Conductivity of Shock-Compressed Liquid Hydrogen, in Shock Waves in Condensed Matter, S. C. Schmidt, R. D. Dick, J. W. Forbes and D. G. Tasker, eds., Elsevier, in press.

Mitchell, A. C., W. J. Nellis, N. C. Holmes, D. J. Erskine, P. C. McCandless, D. L. Raviza and L. D. Cassidy, Equation of State Data of Shock Compressed Liquid CO₂ and Synthetic Uranus, p. 95 in Shock Compression of Condensed Matter - 1989, S. C. Schmitt, J. N. Johnson and L. W. Davison (eds), Elsevier (1990).

Mitchell, A. C., W. J. Nellis, J. A. Moriarty, R. A. Heinle, N. C. Holmes, R. E. Tipton and G. W. Repp, Equation of State of Al, Cu, Mo and Pb at Shock Pressures up to 2.4 TPa (24 MBar), J. Appl. Phys., 69, 2981-2986 (1991).

Nellis, W. J. (1982). Properties of Condensed Matter to Ultrahigh Dynamic Pressures, High Pressure Measurement Techniques, ed. by G. N. Peggs, Appl. Sci. Publ, London.

Nellis, W. J., J. A. Moriarty, A. C. Mitchell, M. Ross, R. G. Dandrea, N. W. Ashcroft, N. C. Holmes and G. R. Gathers, Metal Physics at Ultrahigh Pressure: Aluminum, Copper and Lead as Prototypes, Phys. Rev. Lett, 60, 1414-1417 (1988).

Osher, J. E. , H. H. Chau, G. R. Gathers, R. S. Lee, and R. C. Weingart (1990). Hypervelocity Acceleration and Impact Experiments with the LLNL Electric Gun, Int. J. Impact Engg., V 10, 439-452.

Persson, P. A., R. Ward and N. N. Thadhani, Shock-Induced Reaction Synthesis (SRS) Assisted Compaction of Ceramics, pp. 539-542 in Shock Compression of Condensed Matter - 1989, S. C. Schmitt, J. N. Johnson and L. W. Davison (eds), Elsevier (1990).

Radousky, H. B. (1988). Shock-Induced Cooling in Dense Fluids, pp. 89-94 in Shock Waves in Condensed Matter 1987, S. C. Schmidt and N. C. Holmes (eds), Elsevier.

Sawaoka, A., and T. Akahashi, U. S. Patent 4,655,830 and 4,695,321 (1987).

Steinberg, D. J. (1986). Constitutive Model Used in Computer Simulation of Time-Resolved Shock Wave Data, Int. J. Impact Engg., V 5 , 603-612.

Vladimirov, A. S., N. P. Voloshin, V. N. Nogin, A. V. Petrovtsev and V. A. Simonenko, Pis'ma Zh. Eksp. Teor. Fiz. 39, 69 (1984) [JETP Lett., 39, 82 (1984)].

Wise, J. L., G. I. Kerley and T. G. Trucano, Shock Vaporization Studies on Zinc and Porous Carbon, in Shock Waves in Condensed Matter, S. C. Schmidt, R. D. Dick, J. W. Forbes and D. G. Tasker, eds., Elsevier, in press.

Young, D. A., J. K. Wolford, F. J. Rogers and K. S. Holian, Theory of the Aluminum Shock Equation of State to 10^4 MBar, Phys. Lett. A, 108, 157-160 (1985).

The Use Of High Velocity Launchers for Scientific And Engineering Studies

J. R. Asay

L. C. Chhabildas

M. D. Furnish

18th Shock Wave Symposium

Sendai, Japan

Sandia National Laboratories

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Need For High Velocity Launchers Is Motivated By Scientific and Engineering Applications

- EOS - Static methods for determining EOS are limited

Shock wave techniques extend accessible pressure and temperature regimes

- Drilling - requires knowledge of dynamic properties of metals and geological materials
- Shock Synthesis - New materials are required with improved strength and toughness

This Presentation Will Briefly Summarize

- **Launcher Techniques**
- **Diagnostic Methods**
- **Applications**
- **New Directions**

Of Shock Wave Techniques

Shock Compression Studies Are A Principal Application Of High-Velocity Launcher Technologies

- **Forty Year History**
- **Substantial, Continuous Evolution of Launcher Technologies and Shock-Wave Tools**
- **Wide Variety of Sensors**
- **Substantially Improved Capabilities**
- **Development Currently Active, Vital**
- **Five to Ten Year Development Period**
- **Credibility Rests on Challenging Technique, Establishing Limitations**

LOADING TECHNIQUES

- **EXPLOSIVE LOADING**

PLANE-WAVE LENS
EXPLOSIVELY-DRIVEN FLYER PLATES

- **SMOOTH-BORE GUNS**

SINGLE-STAGE COMPRESSED GAS GUNS
PROPELLANT GUNS
TWO-STAGE LIGHT GAS GUNS
RAIL GUNS (Three-Stage Light Gas Guns)

- **RADIATION**

LASER BEAMS
ELECTRON BEAMS
NUCLEAR EXPLOSIONS

Summary Of Launch Capabilities

Launcher Technology	Total Mass Package (gm)	Particle Mass (gm)	Velocity (km / s)	Bore Size
Light-Gas Gun	30	-	7.3	28 mm
	20	-	8.0	20 mm
	10	1	7.5	28 mm
	0.225	0.012	9.6	8.5 mm
	0.025	0.001	10.2	4.8 mm
Electric Gun		0.043	18	1-cm ²
Plasma Gun		10 ⁻⁷	15	100 μm
Van de Graff		10 ⁻¹³	10	1 μm
		10 ⁻¹⁵	50	1 μm
Rail Gun	3	-	7.5	13 mm
Shaped Charge Jet		1	11.4	varies
Fast Shock Tube		1	9	9 mm
HVL		2.6	8.1	19 mm
		1.3	9.5	19 mm
		0.75	10.4	19 mm

Single-Stage Light-Gas Gun Technology

Typical Operating Conditions

- Helium Gas
- 100 mm Bore
- 1-2 kg Projectiles

Impact Conditions

- Peak Projectile Velocity
~1.2 km/s
- Impact Pressures
~0.3 Mbar in Tungsten

P91E1000.37

Propellant Gun Technology

Typical Operating Conditions

- Propellant Loads to 9 kg
- 89 mm Bore
- 1.5 kg Projectiles

Impact Conditions

- Peak Projectile Velocity
~2.3 km/s
- Impact Pressures
~1 Mbar in Tungsten

Two-Stage Light-Gas Gun Technology

Typical Operating Conditions

- Helium or Hydrogen Gas
- 20 mm - 63 mm Bore
- 10 gm - 50 gm Projectiles

Impact Conditions

- Peak Velocity ~ 8 km/s
- Impact Pressures
 ~ 7 Mbar in Tungsten

P91E1000.35

Launcher Capabilities

HELEOS LAUNCHER

Hypervelocity Launcher has been Developed to Access New Regimes of Material Response

Two-Stage Light-Gas Gun

- Modified Two-Stage Light-Gas Gun
- Use of Graded-Density Impactor Provide Shockless Launching
- Aluminum Flyer-Plates Launched to Velocities Exceeding 10 km/s

L. C. CHHABILDAS, 1534
MAY 1990

P90E1000.19

Sandia's Three-Stage Rail Gun

Injection velocity = 6-8 km/s

Max. proj. vel. = 15 km/s

Proj. mass = 3g

Proj. diameter = 12.7mm

D. B. HAYES, 1530
MARCH 1989

P89G1000.12

Lead-In Header Shock Wave Techniques Significantly Extend Pressures Accessible In The Laboratory

91F1000.09

Impact Studies Require Combined Experimental And Computational Studies

- Thermomechanical Properties
Equation of State Studies
- Debris Characterization
- 3D - Computational Capability
- Hypervelocity Impact Testing

High-Velocity Impact Phenomena Encompass A Broad Range Of Material Effects

STRESS WAVES AND HYDRODYNAMIC FLOW

- EOS
- PLASTIC FLOW
- FAILURE

MIXED PHASE FLOW

- MULTIPHASE FLOW
- MIXTURE INTERACTIONS
- ABLATION

EXPANDED STATES, SPALL AND FRAGMENTATION

- FRAGMENTATION
- VAPORIZATION

LETHALITY CHARACTERIZATION

- DEBRIS / TARGET INTERACTION
- THRESHOLD EFFECTS CRITERIA

$$T_1 < T_2 < T_3 < T_4$$

The Advent Of Time-Resolved Shock Wave Techniques Significantly Expands Accessibility To Thermophysical Property Data

Traditional Technique

- One Data Point / Experiment
- EOS Data Only

Time-Resolved Technique (Continuous Loading / Unloading Data)

- Mechanical Properties
- Kinetic Properties

GUN APPLICATIONS

NORMAL IMPACT

OBLIQUE IMPACT

The Development Of Shockless Loading Techniques Significantly Expands The Accessible States Of Matter

EVOLUTION OF TECHNIQUES

EVOLUTION OF TECHNIQUES

Rarefaction Shock In Calcite

EQUATIONS OF MOTION

SHOCK

$$\begin{aligned} VU &= V_0(U - u) \\ P - P_0 &= Uu/V \\ E - E_0 &= 1/2(P + P_0)(V_0 - V) \end{aligned}$$

CONTINUOUS

$$\begin{aligned} dV &= -V_0 du/c \\ dp &= cdu/V_0 \\ dE &= -1/2PdV/V \end{aligned}$$

Shock-Wave Profile

A Broad Variety Of Thermophysical And Mechanical Property Data Can Be Measured With Shock Wave Techniques

- **Hugoniot Pressure - Volume**
- **Isentropic Pressure - Volume**
- **Pressure - Temperature - Dependent Sound Speeds**
- **High-Pressure Shear and Bulk Moduli**
- **Phase Transition Boundaries and Kinetics**
- **Ambient and High-Pressure Compressive Shear Strength**
- **Dynamic Tensile Strength**
- **Fracture and Fragmentation Processes**

Hydrocode

A ROBUST 3-D EULERIAN HYDROCODE (CTH) HAS BEEN USED FOR SIMULATIONS

J.R. ASAY
March 1991

26
will explain
91B1000.26

TYPES OF PHASE CHANGES

MELTING (NaCl)

POLYMORPHIC (IRON)

BARKER (1972)

KORMER, ET. AL. (1965)

VAPORIZATION (LEAD)

AL'TSCHULER, ET. AL. (1980)

Multiple Shock Wave Techniques Determine Deformation Mechanisms and the Kinetics of Dynamic Phase Transitions

Transformation Rate Mechanisms

- Dynamic yielding produces localized heating
- Thermal activation produces heterogeneous transformation
- Shock-Recovered glass lamellae indicate local heating

SHOCK-INDUCED VAPORIZATION

Shock Wave Techniques Identify Thermophysical States At Ultra High Pressures

91F1000.02

Velocity vs. Pressure for Shocked Iron.

Phase-Diagram for Iron

New Capabilities

THE HVL EXTENDS EOS AND LETHALITY TESTING TO STATES OF FULL VAPORIZATION

Shock Vaporization

- Code Validation for full vaporization
- Study of Engineering Materials

91B1000.15

Lethality

- Database for Code Validation
- Application to Multiple-Shell Rvs

J.R. ASAY
MARCH 1991

CHEMICAL REACTIONS IN SHOCKED MATERIALS

86TW1000.42

Chemical Reactions Occur On Shock Wave Timescales

- Mass mixing and chemical or alloying reactions occur on μsec timescale
- Systems may be evaluated by recovery of samples or by EOS
- Exothermic reactions may give observable shock evolution or temperature signatures

Examples:

- Water + Porous CaCO_3 (Limestone)

(Ikaite)

Diagnostic: EOS

Mixture scale 10 nm

- Fe_3O_4 (magnetite) Fe_2O_3 (Hematite)

- Combinations of Ti, B, C, Al_2O_3 powders $\rightarrow \text{TiB}_2$, B_4C , SiC , etc.
(Compacts 96-98% theoretical, difficult to directly manufacture)

- $\text{Y}_2\text{O}_3 + \text{BaO} + \text{BaO}_2 + \text{CuO} \rightarrow$ Superconducting compacts

- Diamond + Si + C $\rightarrow$ Diamond + SiC
(Hardness more than doubled over non-shock production)

- Al + Ni Al/Ni alloys + intermetallics Ni_3Al (exothermic)

Diagnostics:

- Tests on recovered materials
- EOS of time materials

Impact Studies Of Cryogenic Liquids

(CN_2 , H_2 , CH_4 , "Synthetic Uranus")

- Shock wave studies sample correct P/T regimes for giant planets
 - Electrical conductivity measurements on H_2
 - Interpret Uranus' magnetic field (Large entered at $0.3 R_U$ from center)
 - Do we need to check H_2O also (High protonic conductivity)
 - EOS - Constrain planetary compositions
 - Metallization - Still an open question
- Shock cooling - exhibited by N_2
 - Undergoes dissociation at $7000\gamma_1$, $30 \sigma P \lambda$, 2 gm/cm^3
 - Dissociation is endsthermic
 - Reshock actually cools material

Temperature (K)

↑ FACE SUPERIEURE ↑ THIS SIDE UP ↑

STRENGTH IN THE SHOCKED STATE

NORMALIZED YIELD STRENGTH, γ/γ_0

$u, \text{mm}/\mu\text{s}$

05V1000.52

DYNAMIC COMPRESSIVE STRENGTH

PLATE IMPACT EXPERIMENTS

SUMMARY

Wave structure measurements determine shock and shockless response of candidate plate materials to high pressure

Unique measurements of compressive strength can be made to Mbar pressures

Specific results for dynamic strength are material dependent

L. C. CHHABILDAS, 1543
MARCH 1991

89G1000.06

Propellant Gun Techniques Are Useful For Determining High-Pressure Material Properties Of Ceramics

91F1000.05

Fracture and Fragmentation

Fragmentation characteristics and particle size depends on impact conditions and the thermophysical state of the material.

APPLICATIONS IN DYNAMIC FRAGMENTATION

DEFENSE

• SD

• Communication Systems

SAFEGUARDS

• Nuclear Reactor
Accidents

• Reactor Safety

ENERGY

• Oil Shale Rubblizing

• Enhanced Oil Gas Recovery

Theories Have Been Developed To Predict Fragment Distributions For Generalized Failures

LEAD IMPACT EXPERIMENT

P91F1000.08

Carbon-Silver
(70 MEV/nucleon
impact energy)

NUCLEAR FRAGMENTATION following a heavy-ion collision is recorded in a photographic emulsion (*above*), which acts as target and detector. A carbon nucleus accelerated to 70 MeV per nucleon has struck a silver nucleus in the emulsion. At this moderate energy some 16 fragments of nuclear matter (*labeled in the diagram at left*) radiate from the site of the collision. They are nuclei of deuterium, helium, lithium and beryllium, with from two to nine nucleons. The event was recorded by Bo Jakobsson and his colleagues from the University of Lund.

High Velocity Launchers Can Be Used To Determine Dynamic Friction Coefficients

Launcher and Shock Compression Technologies are Playing an Important Role in Several New Developments

- **Debris Shield Development for Space Assets**
- **Earth-to-Orbit Launcher Developments**
- **Fuel Injection for Fusion Reactors**
- **Synthesis of New Materials**

THE PRINCIPAL THREAT TO SPACE SYSTEMS IN LOW-EARTH ORBIT ARISES FROM ENGAGEMENT WITH ORBITAL DEBRIS

Debris Planes, April 1988

91A1000.17

- Low-earth orbital debris results from destruction of third-stage rockets and interorbit collisions
- The median mass and velocity of orbital debris is 1 gm and 10.3 km/s
- Protection systems must cover a broad range of engagement conditions

Orbital Debris Study

The Un-normalized Velocity Distribution Relative to Spacecraft
With an Orbital Inclination of 30°

Chhabildas, 1543
June, 1991
91E1000.15

Lethality Tests

EXPERIMENTAL SIMULATION OF ORBITAL DEBRIS IMPACT ON WHIPPLE BUMPER SHIELD

J.R. ASAY
March 1991

91B1000.14

WHIPPLE BUMPER SHIELD TEST AT 10 km/s

SPACE-STATION HULL STRUCTURE IS PUNCTURED

Shock Wave Technology and Advanced Launchers will Continue to Play a Vital Role in Scientific and Technological Programs

- **Testing Base for Evaluating Material Response in Regimes Inaccessible by other Methods**
- **EOS Validation for Increased Emphasis on the use of Numerical Simulation to Replace Testing**
- **Development of New Materials for Specialized Applications**
- **Expansion to Broader Issues of Complete System Response**
- **Replacement of other Technologies (e.g., Rockets) to Decrease Costs**