SAND99-0450C

# Equation-of-state measurements with Z-pinch sources

J. R. Asay, C. Hall, J. E. Bailey, M. D. Knudson, K. G. Holland, D. L. Hanson, R. Johnston, M. A. Bernard,
W. M. Trott, R.E. Spielman, W.A. Stygar, D.H. McDaniel
*Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*



The Z Accelerator is a fast pulse power facility that is capable of producing controlled high-pressure conditions for studying the dynamic response of materials under loading conditions unachievable with other methods. In the z-pinch mode, the accelerator can produce up to 2 MJ of blackbody x-radiation over time scales of 5-10 ns for studying the ablatively-driven shock response of materials. In the direct current mode, currents up to 20 MA can be produced over time scales of 100 ns. Recent experiments in this configuration have demonstrated the feasibility of obtaining isentropic loading conditions with a magnetic pressure drive.
[Z accelerator, shock physics, isentropic compression, equation of state (EOS) phase transitions]

## Introduction

Validation of material models in a variety of scientific and technological applications requires accurate data regarding the high-pressure thermodynamic and mechanical properties. Traditional laboratory techniques for making these measurements involve light gas guns to generate the required thermodynamic states, and the use of high-resolution time-resolved diagnostics to measure the desired material properties. EOS and constitutive material properties of importance to modeling needs include high-pressure Hugoniot curves and off-Hugoniot properties, such as material strength and isentropic compression and decompression [1].

Conventional light gas guns are limited to impact pressures of about 7 Mbar in high-impedance materials. Pulsed radiation sources, such as high-intensity lasers, and pulsed power techniques significantly extend the accessible pressures and are becoming accepted methods for meeting the needs of material models in regimes inaccessible by gas guns. A present limitation of these new approaches is that samples must necessarily be small, typically a few tens of microns in thickness, which severely limits the accuracy of EOS measurements that can be made and also the ability to perform a variety of off-Hugoniot measurements. However, recent advances in z-pinch techniques for high-pressure material response studies provide potential opportunities for achieving accuracies comparable with gas guns because of the significantly larger samples that can be studied. Sample thicknesses approaching 1 mm may be possible with advances presently being made. These sample dimensions are comparable with gas gun sample dimensions so that accuracies should be comparable.

The Sandia Z accelerator [2] is a recently developed facility that generates x-ray energies of about 2 MJ over time scales of 5-10 ns with resulting temperatures of 100-150 eV in containment fixtures, referred to as hohlraums, that are a few cubic centimeters in volume. This intense radiation source can be used to ablatively drive shock waves to about pressures of about 10 Mbar in a variety of materials. Because of the large hohlraum sizes, larger sample sizes are possible with this source.

In this paper, we discuss recent developments in the use of the Sandia Z accelerator for Hugoniot and off-Hugoniot measurements. Preliminary data on high-pressure dynamic response include Hugoniot EOS data on aluminum to about 5 Mbar using the z-pinch technique and isentropic compression data on iron and copper to about 300 and 130 kbar, respectively, using the direct current mode on Z. The isentropic compression experiments are performed on sample thicknesses to 0.8 mm and allow determination of the $\alpha-\varepsilon$ phase transition and the kinetic properties of this transition. Specifically, isentropic compression data on iron have been analyzed with a two-phase rate dependent model of the bcc-hcp phase transition, which shows that the relatively slow rates of pressure application achieved with this technique result in observable kinetic effects that can be easily analyzed. Other work in progress with the Z Accelerator includes EOS studies of liquid deuterium and the development of uniform, constant pressure drives that will provide higher accuracy in EOS measurements.

## Z Accelerator

The Z accelerator is a fast pulsed power facility that stores 11.6 MJ of electrical energy capacitively and uses fast switches and transmission lines to deliver up to 20 MA of current to a low inductance load over time scales of 100 ns. In the z-pinch mode, this current is delivered to a cylindrical array of wires, typically about 300 individual tungsten wires with individual diameters of about 10 μm arranged in a cylindrical array with a diameter of about 1 cm. A photograph of a tungsten wire array is illustrated in Fig. 1. Application of the current creates a conducting plasma sheath from the expanded wires with a self-generated magnetic field that causes the plasma sheath to implode at high velocities on the central axis of the array. The resulting stagnated plasma produces extreme high temperatures over time intervals of 5-10 ns and creates a burst of intense x-rays. In a typical shock wave experiment, this radiation is contained within a metal container called a hohlraum, as

# DISCLAIMER

illustrated in Fig. 1, and used to ablatively produce shock waves in samples attached to the hohlraum.

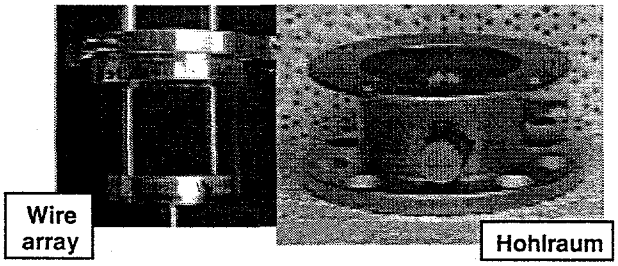



Fig. 1. Z-pinch technique for producing ablatively driven shock waves.

A standard hohlraum configuration for shock physics experiments is illustrated in Fig. 2. In this case, three separate secondary hohlraums are attached to a single primary hohlraum containing a z-pinch source. Various interferometer and optical breakout diagnostics are used to detect and measure shock wave properties on samples located on the end of the secondary hohlraums. The FOSBO technique is a fiber optic shock breakout technique, which is a primary diagnostic for measuring shock velocities. Typically, the arrival of the shock wave can be determined to a time resolution of less than 1 ns with optical streak recording. OBSBO refers to an open beam shock breakout technique [3], which is an alternate technique for measuring shock arrival at the rear surface of the sample.

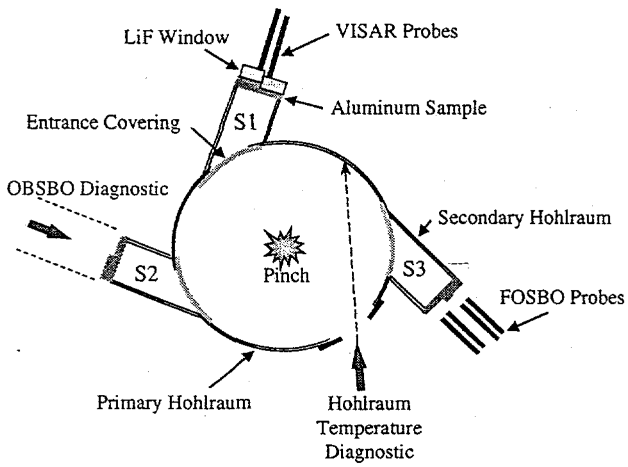



Fig. 2. Top view schematic of hohlraum geometry for producing planar shock waves.

The accelerator can also be used to produce high currents in a direct current mode, in which the anode and cathode of the machine are directly connected, as illustrated in Fig. 3. In this case, the high currents produced in the anode and cathodes during operation create an intense magnetic field in the evacuated region between the two that can produce pressure on the boundary of a specimen located in either conductor. The pressure is applied during development of current, with a

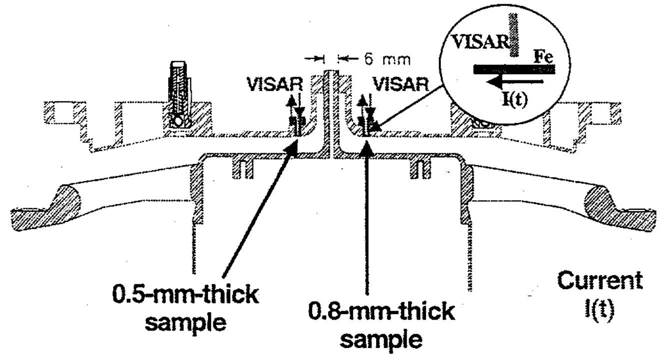



Fig. 3. Configuration for magnetically loading specimens using the direct current mode on Z.

resulting time scale of about 100 ns, so that a shock wave is not immediately formed in the specimen. Instead, a continuous compression wave referred to as an Ice wave (for Isentropic Compression Experiment) with a risetime correspond to the input risetime of the current is initially produced. The resulting thermodynamic process produced in the specimen is adiabatic and essentially isentropic [4].

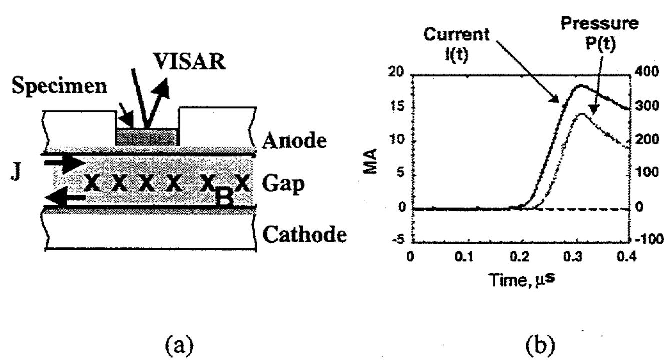



Fig. 4. (a) Technique for specimens exposed to magnetic pressures. (b) Calculated current and pressure profiles.

**Source Development for EOS Studies**

A major objective is to demonstrate the capability for performing accurate EOS measurements with the Z accelerator. To perform this evaluation, experiments are planned to cover the pressure range from about 1.5 Mbar to over 5 Mbar in order to overlap with existing gas gun

Hugoniot data and therefore establish EOS accuracy capabilities on Z. The results of five experiments are presented in Fig. 5. The first two experiments (Z259 and Z260) used hohlraum configurations as shown in Fig. 2 [3]. In these two experiments, three independent shock velocity and two independent particle velocity measurements were obtained; details of the experiments can be found in [3].

The second two aluminum experiments (Z270 and Z271) used a less conservative experimental approach where only two secondaries were used to measure the Hugoniot information,

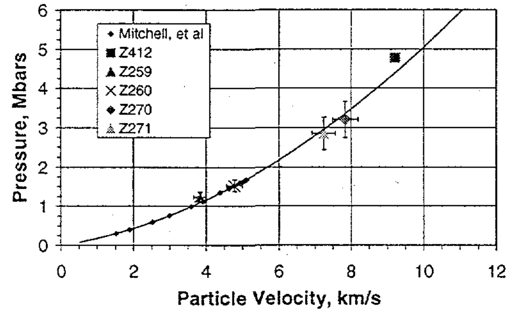



Fig. 5 Hugoniot data for aluminum obtained on Z.

which resulted in only one particle velocity and one shock velocity measurement. The specimen were 6 mm in diameter,

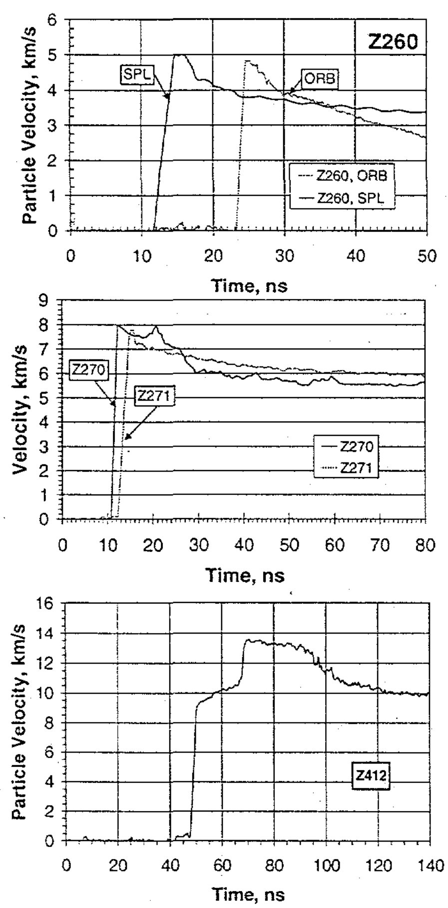



Figure 6. Measured VISAR wave profiles for (a) Z260, (b) Z270, Z271, and (c) Z412.

which maintained uniaxial strain for sample thicknesses of 100-200 μ during the time scale of the experiments.

The final data point (Z412) was obtained using foam filled secondaries to provide a constant pressure drive [to be published] during the time interval of interest for this measurement. The sample/LiF interface on Z412 was monitored by two VISARs, each having a different velocity per fringe sensitivity to eliminate ambiguity about the Hugoniot pressure state.

The value for particle velocity given is the peak of the wave when only velocity peaks when independent measurements were made at two different sample thicknesses to help account for the effects of attenuation. Shock velocity measurements are made with a streak camera by recording the change in surface reflectivity on each sample surface upon arrival of a strong shock. All aluminum samples were diamond turned from bar stock; the average density was 2.71 g/cc.

Velocity profiles as determined from the VISAR measurements are shown in Figure 6 for shots Z260 through Z412. The wave profiles are clearly attenuating in all cases except for Z412. The effect of shock attenuation on Hugoniot data accuracy was minimized by recording the velocity profiles on similar step thicknesses for both VISAR and SBO measurements and using the average $u_p$ between steps. An alternate method was to measure $u_p$ on a single step corresponding to an average thickness of the SBO plate heights (Z270, Z271, Z412). In this case, $u_p$ was obtained by taking an average particle velocity over the initial 10 ns of the shocked state. This portion of the wave correlates to the time required for the shock to propagate across the stepped plate that was used to measure shock velocity.

From the measured quantities for shock velocity ($U_s$) and particle velocity ($u_p$), Hugoniot pressure can be calculated using the simplified relation [3] $P=\rho_o U_s u_p$. Results are plotted in the pressure-particle velocity and the shock velocity- particle velocity planes in Figure 5. As can be seen, our results are in fair agreement with extrapolations of established Hugoniot results [4] from flat plate impact experiments.

Although the preliminary Hugoniot results obtained on aluminum with the z-pinch technique are encouraging, two critical issues need to be resolved before accurate EOS data can be obtained. One is the temporal nature of the ablation drive. The attenuating shock waves illustrated in Fig. 6 indicate a non-constant pressure drive. For good EOS accuracy, the input pressure should be constant to less than 1% for times of at least 20 ns. This would allow sample thicknesses approaching 1 mm and resulting transit times that should result in 1% accurate shock velocity data. The other issue is that the pressure should be constant to about 0.5% over a lateral dimension of about 2-3 mm on the driving surface of the sample. Work is in progress to achieve both of these objectives [3].

**Cryogenic Target Experiments**

We have developed a general-purpose cryogenic target system for radiation-driven EOS and shock physics experiments on Z. A cryogenic system is used to cool one of the secondary hohlraums shown in Fig. 2 to temperatures sufficient to liquefy hydrogen, while maintaining the rest of the primary hohlraum near room temperature. The details of this system are described by Hanson [6]. Cooling is provided by a static-fill liquid helium cryostat connected through a cold finger and flexible thermal link to the cryogenic sample holder or cryocell [6].

Survivability of high value cryogenic components is a major issue for cryogenic system design on Z. Following a Z wire array implosion, more than 1 MJ of energy is dissipated in the form of radiation, hot plasma, and molten metal expanding from the hohlraum region. The LHe cryostat is shock-mounted inside a robust stainless steel blast shield and the thermal link provides standoff of the cryostat from the sample holder. Our cryostats have survived multiple Z shots without significant damage in this arrangement.

Liquid deuterium for $D_2$ EOS experiments on Z is condensed in the cryocell (Fig. 7). To reduce the conduction heat load to an acceptable level, the cryocell is thermally isolated from the primary hohlraum, the gas line, and the array of fiber optic diagnostic probes. In several experiments, liquid deuterium samples were condensed by filling the cryocell cavity with high purity $D_2$ gas at 18 psi, cooling the cryocell to its equilibrium temperature of 16-18 K, and then warming the cell to 22.0 K with the temperature control system, which is stable to 0.1 K. This produces a quiescent liquid deuterium sample with a boiling point of about 25 K.

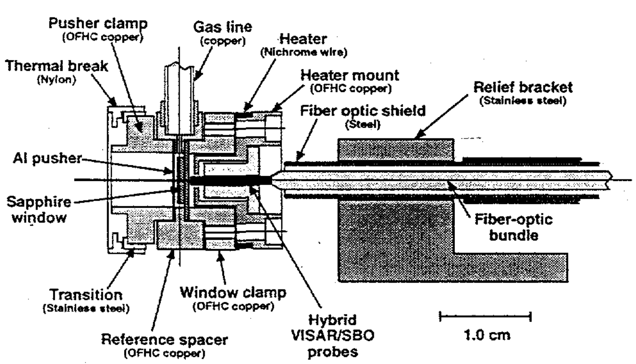
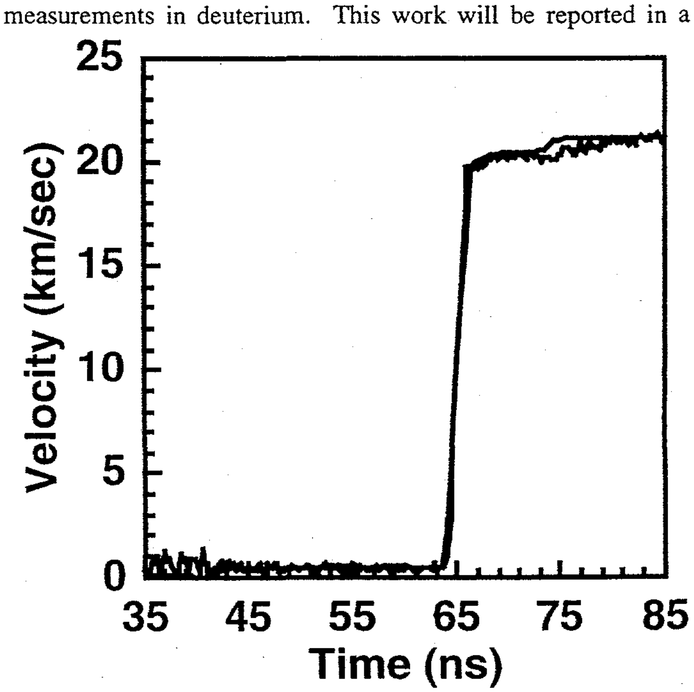



Fig. 7 Cryocell with front-stepped Al plate, liquid $D_2$ layer at 22.0 K and saphhire rear window for $D_2$ EOS measurements.

A number of diagnostics are used to simultaneously measure shock physics parameters in the Al pusher plate and liquid deuterium sample [3], including multiple VISAR interferometers, open beam and fiber optic shock breakout sensors, time-resolved optical spectroscopy probes to self-emission. The input laser light and output signals for these optical diagnostics are carried through fiber optic bundles to three hybrid fiber optic probes mounted in a thermal insulator directly behind the sapphire window. One problem seriously affecting diagnostic operation is Bremsstrahlung-darkening of the sapphire window near the time of peak radiation power. This problem is minimized through use of high purity optical components and by minimizing the amount of optical material located near the hohlraum. Several cryogenic experiments have been performed to demonstrate compatibility of all these diagnostics.

Initial experiments have produced pressures of about 400 Gpa in the Al pusher and 55 Gpa in liquid deuterium. In thew future these pressures will be increased through changes in hohlraum geometry and pusher plate material.

High quality VISAR data have been recorded in several experiments. Since the shock waves in deuterium should have very short rise times, the electronic resolution of the present system (~1-2 ns) is insufficient to track the number of corresponding fringes in the interferometer. Using VISARs with different fringe sensitivities eliminates the fringe ambiguity; this results in a uniquely measured particle velocity jump at the shock front. Previous shock experiments [7] suggests that shocked deuterium is conductive for pressures exceeding 300 kbar. In this case, the VISAR signals track the motion of a highly reflective metallized shock front in deuterium as it crosses the cell. A VISAR experiment is shown in Fig. 8, which illustrates the quality of signals that can be obtained in this experimental configuration. Experiments are in progress to refine the experimental configuration for EOS measurements in deuterium. This work will be reported in a



future publication.

Figure 8. VISAR records obtained in one experiment conducted with the cryogenic cell.

**Isentropic Compression Experiments**

ICE wave experiments were performed with the Z Accelerator to establish the feasibility of detecting polymorphic phase transitions. In this configuration, specimens were placed in the anode of the Sandia Z Accelerator as shown in Fig. 3. The center of each specimen was 1.385 cm from the centerline of the anode. In this arrangement, an increasing magnetic pressure is produced at the surface of the specimen described as follows,

$$P = B^2/2\mu_0 = 10^{-7} I^2/2\pi r^2 \text{ (in MKS units)}, \qquad (1)$$

where I is the time-dependent current and r is the distance from the axis of symmetry.

The iron samples were 3 mm in diameter and had nominal thicknesses of 0.5 mm and 0.8 mm [8]. In the experiments, the current applied to the front surface of both iron specimens increased to about 19.3 MA over a time interval of 100 ns. For this configuration, the pressure is not uniformly applied over the surface of the sample, but varies with radius as I/2. The non-planar pressure gradient was estimated to be about 8% from the center to a radius that could influence motion at the center. Although this variation is not acceptable for accurate EOS measurements, it was sufficient to demonstrate the sensitivity of the technique for detecting phase transitions and for evaluating kinetic effects in isentropic compression experiments. Although shock waves have been used to identify phase transitions, isentropic compression has not been previously used.

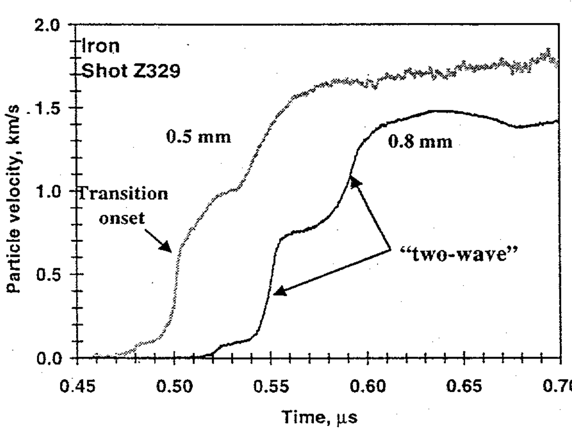



FIG. 9. VISAR profiles obtained on 0.5 and 0.8 mm thick iron samples.

Figure 9 shows the resulting free surface velocity profiles obtained on the two samples. The free surface velocity at 0.5 mm thickness shows an elastic precursor followed by the onset of the $\alpha$ - $\varepsilon$ phase transition at a velocity of about 0.6 km/s. A plateau is observed at a larger velocity signifying the onset of a two wave structure characteristic of shock-induced phase transformations. The profile for the thicker sample also shows the elastic wave, followed by a well defined two-wave structure.

The experimental results have been modeled with a rate-dependent model for the $\alpha$ - $\varepsilon$ phase transition [8]. These calculations indicate that the average transition rate is about 50 $\mu s^{-1}$, which is compatible with previously observed transition times under shock compression [9]. These results demonstrate the importance of phase transition kinetics in the $\alpha$ - $\varepsilon$ phase transition and the ability of ICE wave experiments to detect and quantify the transition rates.

To obtain approximate 1-D plane loading, another set of experiments was performed in which thin copper disks of 3 mm diameter and thicknesses of 0.6 and 0.9 mm were placed on the cylindrical feed of the anode, rather than the cathode as shown in Fig. 3. The configuration is nearly cylindrical, except for the interface of the flat specimens with the cylindrically symmetric anode. Specimens were located at a radius of 10 mm with respect to the center of the anode. The location of the flat specimen in a cylindrical anode introduces a small variation in pressure loading across the 3-mm diameter face of the sample on the order of 1%.

The wave profiles obtained in these experiments were analyzed using Lagrangian wave profile techniques to provide an estimate the loading path [4]. This approach does not account for the perturbation to the waves near the free surface and will lead to errors in the measured wave velocities at a give particle velocity. However, for the low peak pressures obtained in the present experiments, computer simulations showed that the error is less than 0.5% in pressure and less than 0.1% in

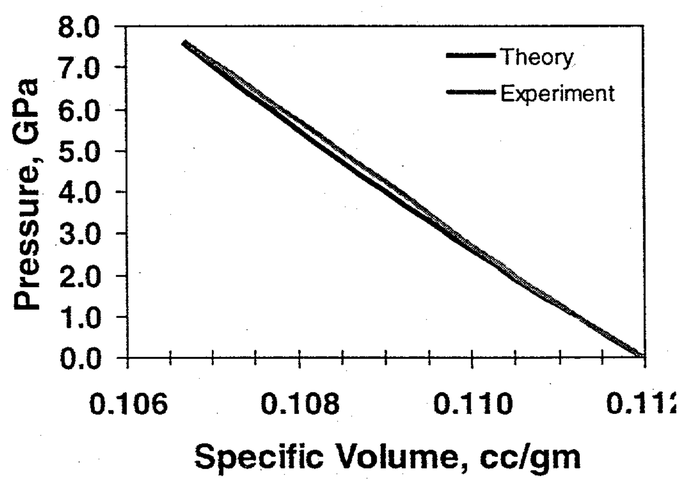


Fig. 10. Stress-volume curve in copper resulting from an ICE wave experiment.

specific volume. Using the approximations discussed above, it was possible to estimate the stress-volume loading path over the free surface velocity range to 0.4. The results are shown in Fig. 10. Also shown is an estimate of the isentrope in copper [4]. The figure illustrates that the experimental data are slightly higher than the theoretical predictions, by about 4% at 40 kbar. Part of this difference could be due to the known strong work hardening of copper under shock compression [4].

### Summary

This paper provides a brief review of research in progress to develop the capability for using the Z Accelerator to perform shock physics and EOS studies. Preliminary Hugoniot data has been obtained using a z-pinch ablation drive to determine the Hugoniot of aluminum to shock pressures of about 5 Mbar. These data are in reasonably agreement with published data obtained with gas guns, but work is in progress to improve the accuracy of these data through improved source conditions for the shock. Experiments are in progress to improve the accuracy of Hugoniot measurements on Z by developing a more spatially uniform, pressure drive lasting about 20 ns in shock EOS experiments. This work will be published in the future.

The EOS capability presently on Z also includes a cryogenic system, which is being developed to study the high pressure EOS of deuterium. A variety of advanced shock diagnostics, including multiple VISARs, shock breakout and time-resolved spectroscopy are being implemented for simultaneous measurements of the shocked state of deuterium. The system has been successfully operated at temperatures of 22 K and for shock pressures of about 500 kbar in deuterium. Work is in progress to acquire accurate Hugoniot data in deuterium over this pressure range and to extend the peak shock pressure to about 5 Mbar in deuterium.

The Z Accelerator has also been used to isentropically compress samples of iron and copper to pressures of 300 and 130 kbar, respectively. This is a new capability that shows considerable promise for studying the dynamic response of materials in thermodynamic regimes that have been previously inaccessible. Preliminary experiments have been performed on iron that illustrate a new capability for easily detecting phase transitions and for determining kinetic properties associated with the transition. These results indicate a transition time of about 40 ns for the $\alpha$–$\varepsilon$ phase transition in iron, which is in good agreement with previous data. Isentropic compression measurements made on copper indicate the ability to determine the P(V) loading curve of copper in one experiment. Experiments are in progress to perfect this technique for application to a large variety of conducting and non-conducting materials.

### Acknowledgments

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000. We are also indebted to the excellent technical assistance of Mike Bernard, Gary Anderson, Brian Clark, and Kevin Fleming.

### References

[1] J.R Asay, and G.I. Kerley, Int'l *J. Impact Eng'g*, **5** 69 (1987).
[2] M.K. Matzen, *Phys. Plasmas* **4** 1519 (1996).
[3] C.A. Hall et al., "Aluminum Hugoniot Measurements on the Sandia Z Accelerator", Proceedings of the APS Topical Group on Shock Compression of Condensed Matter, Snowbird, Utah, June 26-July 2 (1999).
[4] J.R. Asay, "Isentropic Compression Experiments on the Z Accelerator", ibid.
[5] A.C. Mitchell and W.J. Nellis, *J. Appl Phys* **52**, 1981,3363 (1981).
[6] D.L. Hanson et al., "Progress on Deuterium EOS Measurements on Z", Proceedings of the APS Topical Group on Shock Compression of Condensed Matter, Snowbird, Utah, June 26-July 2 (1999).
[7] G.W. Collins et al., Science **281**, 1178 (1998).
[8] J.R. Asay et al., "Isentropic Compression of Iron with the Z Accelerator", Proceedings of the APS Topical Group on Shock Compression of Condensed Matter, Snowbird, Utah, June 26-July 2 (1999).
[9] Andrews, D.J., *J. Comp. Phys.* **7**, 310 (1971).