Lawrence Livermore Laboratory

HIGH TEMPERATURE SCIENCE: FUTURE NEEDS AND ANTICIPATED
DEVELOPMENT IN HIGH-DENSITY SHOCK-WAVE RESEARCH

M. Ross
T. J. Ahrens
W. J. Nellis

March 7, 1979

Prepared for the National Research Council Committee on High Temperature
Science and Technology

MASTER

CONTENTS

Abstract	1
Introduction	2
Thermal Equations of State and the Grüneisen Parameter	3
Equations of State of Light Elements	5
Dense Plasma Research	5
Experimental Testing of Statistical Models and Electron-Band Theories of Matter	6
Some High-Temperature, High-Pressure Physical Phenomena Involving Electron Rearrangements	6
Ultrahigh-Pressure Shock-Wave Methods	7
High-Powered Lasers	9
Electrical Gun	10
Rail Gun	13
Nuclear Explosives	13
Space Shuttle-Based Compression Studies	15
Isentropic Compression	16
New Initiatives Using Current Driver Technology	17
Spectroscopic and Optical Properties	18
Expanded Metals Research	19
Flash X-Ray Diffraction	19

HIGH TEMPERATURE SCIENCE: FUTURE NEEDS AND ANTICIPATED
DEVELOPMENT IN HIGH-DENSITY SHOCK-WAVE RESEARCH*

ABSTRACT

Shock-wave experiments on condensed matter currently achieve pressures up to 5 Mbar, and temperatures over 20 000 K. In this report we survey a number of experimental methods that, in the next decade, may increase the conditions by an order of magnitude. These advanced experiments will allow us to investigate a new range of physics problems.

*Co-author T. J. Ahrens is with the Seismological Laboratory, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA.

INTRODUCTION

Of all the techniques currently available to carry out high-pressure experiments on condensed matter, the shock-wave method is capable of achieving the highest pressures. However, it is less commonly appreciated by the nonspecialist that, because of the irreversible nature of the shock process and the high energy densities needed to create a shock wave, extremely high temperature (up to several electron volts) are simultaneously generated. The combination of high temperatures and densities creates a unique capability for carrying out scientific research.

In most shock-compression experiments two kinematic variables, shock velocity and mass velocity, are measured. From these, and the initial density, the Hugoniot relations are directly used to compute the thermodynamic variables: pressure, density, and internal energy density. In the case of materials that are dielectrics in their unshocked state, shock temperatures can be measured by using high-speed radiative techniques, whereas in metallic materials, temperatures must be computed.

In this survey we will attempt to address the National Research Council (NRC) query: "Where may progress in high temperature, high density science be anticipated because of new techniques or new interests in shock wave research?" The survey is divided into three sections. In this introductory section we discuss some of the kinds of phenomena that appear in shock-wave data at high temperatures and densities, and we indicate how this data could be useful in advancing scientific understanding. We have emphasized, but not restricted ourselves to those aspects of shock-wave work that are likely to have a greater bearing on high-temperature research than on high-density studies. The section Ultrahigh-Pressure Shock-Wave Methods deals with some of the methods currently being considered for producing higher shock pressures than are currently attainable. A perpetual goal of high-pressure physics has been the attainment of yet higher pressures. However, a considerable amount of interesting science remains to be carried out, using present well-established driver systems, by adding new diagnostics and introducing new experimental goals. The subject of how current studies might be broadened, using the available shock-wave systems, is treated in the last section.

THERMAL EQUATIONS OF STATE AND THE GRÜNEISEN PARAMETER

The extremely high temperatures attained in a shock-wave experiment lead to unique advantages and serious difficulties for theoretical studies as well as difficulties for the potential use of this data for applications. Temperatures that may be as high as several electron volts, excite electrons, break chemical bonds, and act as probes of electronic structure under compression. The high temperatures allow atoms to penetrate their neighbor's repulsive cores and, in principle, permit a determination of the intermolecular forces at small internuclear separations. Thus shock-wave studies constitute a rich source of data, but one that has not been fully exploited. With a few exceptions, there appears to be a reluctance on the part of condensed-matter theoreticians to deal with high temperature and high densities simultaneously. The difficulties encountered in these problems are indeed formidable. In addition to having to predict the properties of electrons and the motion of ions, one must couple them and do the statistical mechanics properly. With an increasing data base, largely coming from shock-wave experiments and the use of computers to handle larger problems, many of these problems will become tractable within some satisfactory theoretical approximation.

Current electron-band theories compute electron properties of dense matter for static lattices and molecular dynamics can compute many-body motion of large numbers of ions with classical electrons. More effort needs to be expended to coupling the two. The electron-ion coupling will in turn be complicated by the loss of crystal symmetry when temperatures are above melting. For temperatures extending into the electron-volt range, attention must be paid to a treatment of electronic excitations. Additional theoretical work in this area is needed not only to understand the basic physics, but also to make shock-wave results more generally useful as thermodynamic data.

To extend this usefulness to the scientific and engineering community, the shock data must be readily reducible to isotherms. This reduction is currently subject to serious uncertainties in the theory and, for example, in the case of many geophysical materials at high pressure no adequate thermal equation-of-state theory exists. Many of the 0°K isotherms derived from shock data both

for geological and engineering materials are of questionable reliability. In the case of materials shocked to high pressure and high temperature, where partial ionization or disassociation occurs, an adequate theory for reducing shock data to isotherms must account for the properties of both the electronic and ionic degrees of freedom.

A parameter that has proven very useful in relating shock-wave data to isotherms is the Grüneisen parameter. It would be of great advantage to carry out experiments in which the Grüneisen parameter, γ , can be measured as a function of volume and temperature. This parameter is defined as

$$\gamma = V \left(\frac{\partial P}{\partial E} \right)_V, \quad (1)$$

where P , V , E are, respectively, pressure, volume, and energy. This equation relates the change in pressure to the change in energy at a constant volume and relates shock data directly to isotherms or isentropes. This parameter can be determined using reflected shock experiments or experiments in which the initial conditions are varied significantly by mechanical distention (porous or frothy initial states) or by *precompression* or *preheating*. Very little has been accomplished experimentally along the latter two lines to date. Also γ would be computable if our theoretical methods were sufficiently improved.

For the purpose of modeling the earth's interior, the relation of hydrostatic pressure (or depth) vs volume has been obtained from both seismological and shock-wave data. However, the reduction of shock-wave data to the adiabats needed for obtaining geophysical models requires a knowledge of γ ; unfortunately, credible predictive theories do not exist for dense silicates or oxides at high temperature. Consequently, measurements of γ will lead to an improvement in the reliability of the data available to planetary studies. As an illustration, the adiabatic gradient and hence temperature vs depth in a self-compressing single-component planetary interior can be obtained from

$$T = T_0 \exp \int_{V_0}^V \frac{\gamma}{V} dV, \quad (2)$$

where T_0 and V_0 are initial temperature and specific volume. The Gruneisen parameter is the key parameter required by the widely used Lindemann model to predict melting under compression. Therefore, accurate values of $\gamma(V, T)$ determined either experimentally or theoretically are required for improved descriptions of the thermal regimes of planetary interiors.

EQUATIONS OF STATE OF LIGHT ELEMENTS

Experimental equation-of-state data, for the light elements and their compounds under high pressures are scanty and of low precision. These data are needed to describe the interiors of the major planets; the data will play a central role in advancing the state of the art of theoretical studies of material properties.

Of primary importance with respect to the major planets is hydrogen for which shock-wave data are available to only 200 kbar ($\sim 4500^\circ$) and 900 kbar ($\sim 7500^\circ$) with uncertainties in density of 5 and 20% respectively. Also of interest are CH_4 , NH_3 , H_2O , He, and mixtures of these. Data on these systems up to 1 Mbar accurate to 1% should become available in the next few years.

DENSE PLASMA RESEARCH

In shock compression studies on condensed alkali metals, the noble gases, and compounds of the light elements, temperatures of the order of 2 eV ($\sim 23\,000\text{ K}$) are now commonly achieved. Using some of the anticipated future experimental technique (last section) temperatures, an order of magnitude greater will be attained. At these temperatures, hydrogen will be completely disassociated and turned into a dense plasma, and a number of the alkali metals, particularly cesium, rubidium, and potassium, as well as argon and xenon, will be converted to partially ionized plasmas. Experiments on the noble gases will grant us the opportunity to study for the first time plasmas at extreme densities, and to test present theories predicting their compressed

properties. Theories of dense plasmas are widely used for modeling of the stellar and Jovian interiors and are very important for predicting the plasma hydrodynamic flows that take place in inertial confinement fusion methods.

EXPERIMENTAL TESTING OF STATISTICAL MODELS AND ELECTRON-BAND THEORIES OF MATTER

A continued interest in theoretical physics has been the prediction of equations of state under pressure. The earliest descriptions were based on easily computable statistical atom approximations (Thomas-Fermi-like), but recently with the advent of large computers more exact quantum mechanical electron-band calculations have become more common. Statistical theories are unrealistic at normal densities but are more valid at extreme pressures and temperatures generally greater than about 10^2 Mbars and about 10^2 eV. Anticipated experiments in the multimegabar range will be useful to test the current generation of electron-band theories, and in delineating the pressure regime over which modifications of the statistical models are adequate.

SOME HIGH-TEMPERATURE, HIGH-PRESSURE PHYSICAL PHENOMENA INVOLVING ELECTRON REARRANGEMENTS

The earliest work in the electron-band theory of solids discussed the possibility that by decreasing the interatomic distance, broadening of electron bands will occur, with closure in the energy level gap between valence and conduction bands leading to semiconducting and metallic behavior. The measured shock-wave properties of a number of materials are profoundly influenced by the thermal excitation of electrons across an energy level gap that is narrowing. In effect these electrons anticipate the gap closure. These effects have already been seen and theoretically interpreted in shock-compressed Ar, Xe, and I_2 . Using the newer ultrahigh-pressure techniques, similar effects could be observable in helium and in the narrowing of the alkali metal, closed-core conduction band gap. Thus the high-temperature-generated, shock-compression experiments can act as probes of these energy level gaps at high density.

The breaking of chemical bonds under compression is another topic of long-standing interest. Recently, observation has been made in a number of shock experiments of what appears to be breaking of the diatomic bands in I_2 and

N₂. Study of O₂ is under way. Future work at higher pressures and temperatures could extend these studies to the remaining halogens and some small molecules. Of all the transitions of molecular substances to the metallic state, the transition of molecular to metallic hydrogen is by far the most significant phase transition in the solar system. The study of this transition represents one of the major goals of contemporary high-pressure physics.

Unfortunately, shock experiments are likely to be only of limited use for hydrogen because temperature increases rapidly with compression and the molecule will have become a plasma before reaching the metallization density. However, shock-compression results can be used to determine the intermolecular potentials by analyzing the data with statistical mechanical fluid theories. These potentials can be used to compute the molecular solid properties and predict a metallic transition. Isentropic compression experiments could be useful on these problems if the current state of the method were to be improved (see end of next section). This method could in principle achieve the necessary multimegabar pressures, with only modest temperature uses (1500°), to investigate the metallic hydrogen transition.

ULTRAHIGH-PRESSURE SHOCK-WAVE METHODS

The strongest shock waves routinely achievable in the United States for accurate material property measurements are approximately 5 Mbar using two-stage gas guns with accuracies within $\pm 1\%$ in pressure and density. Soviet scientists have utilized explosive systems that yield shock pressure to nearly twice this level, with almost comparable precision since the 1960's! Rather than using explosives, U.S. technology has relied on light-gas guns to accelerate projectiles to 7 km/s; shock pressure in a target sample is generated upon impact. In contrast, Soviet projectiles (iron) are explosively accelerated to approximately 14.7 km/s. The approximate pressures achievable in the elements with tantalum projectiles at 7 and 15 km/s are shown in Fig. 1. This figure shows that the achievable pressure is quite sensitive to atomic number. In the case of compressible materials or porous media, the pressure wave is accompanied by a large temperature rise. For example, temperatures of approximately 1 eV are obtained upon compression of 20% porous CaAl₂Si₂O₈ to

FIG. 1. Approximate shock pressures achieved in the elements by tantalum impactors at 7 and 15 km/s.

160 GPa (1.6 Mbar). In the case of argon, final pressures of approximately 100 GPa (1 Mbar) have been attained at three times liquid density and temperatures about 2 eV. Similar conditions can be achieved for the alkali metals.

Figure 1 also shows some approximate pressures that could be achieved if shock velocities could be raised to 15 km/s. Pressures of up to 20 Mbar could be achieved with concurrent order-of-magnitude increases in the final temperature.

Gas guns are presently operating at limits imposed by material properties and launch-tube frictions. Several techniques for generating and diagnosing ultrahigh-pressure shock waves, above approximately 5 Mbar, are currently under development. These are listed below. All are either in the stage of testing feasibility or in the design stage. All the techniques are dynamic and, except for isentropic compression, involve shock waves that produce high temperatures as well as high pressures. The techniques discussed in this section are as follows:

- High-powered lasers.
- Electrical gun.
- Rail gun.
- Nuclear explosives.
- Space shuttle-based compression studies.
- Isentropic compression.

HIGH-POWER LASERS

The capabilities of high-power lasers to generate ultrahigh-pressure shock waves has been long recognized. When an ultrashort light pulse is focused down to a small spot on a sample surface, a high-pressure shock wave is produced by ablation of the sample surface by the energy delivered to the target.

The pressure produced depends upon the pulse shape, peak power in the pulse, the radiative and thermodynamic properties of the target, and the irradiated spot size. The LLL Janus laser produces about 2×10^{11} W in each of two beams in a 300 ps pulse. Focused onto a 0.3-mm-diam spot, such a laser pulse produces about 20 Mbar in aluminum. More powerful lasers being developed for fusion research will be capable of producing more than 100 Mbar.

Detection of laser-driven shock waves presently depends upon detecting the strong heating (several eV) produced by the shock wave. Thus, a light flash is produced when the shock arrives at a free surface. By focusing this light onto the image plane of an ultrafast streak camera, the arrival times at planes a known distance apart can be measured and the shock velocity calculated (Fig. 2).

In practice, shock transit times of 0.3 to 1 ns, and shock propagation lengths of approximately 10 μm must be measured. Uniformity of laser pulse energy deposition, preparation and measurement of target dimensions, and shock propagation times all pose challenging technical problems that are currently being addressed. A long development period will be required to refine such diagnostics and tune the laser pulses. Also the effects of laser-beam inhomogeneity, radiative preheating from the shock front, sample grain size, surface roughness, and other phenomena affecting shock structure need to be investigated.

In addition, diagnostics for measuring a second shock parameter, like mass velocity or density for example, must be developed. Such a development will be more complicated than that for shock velocity because of 10- μm and approximately 1-ns size and time scales, respectively.

ELECTRICAL GUN

This device, which is currently under development, employs thin metal foils that are exploded by rapidly discharging a capacitor bank through them. The expanding metal shears off a projectile that is a plastic-metal laminate and accelerates the projectile through a barrel for a few millimeters long. In one operating version the plastic is about 300 μm thick and the metal foil a few tens of μm thick. The thin plastic-metal laminate experiences accelerations of a few tens of million times the acceleration of gravity (Fig. 3). To date although foils have been driven to 15 km/s, their constant planarity (required for one-dimensional flow) remains to be explored.

Shock velocity is measured by a streak camera as in the case of laser-driven experiments. The main advantage of the method is that the mass velocity behind the shock can be deduced from the impact velocity of the projectile. This velocity is measured with a Fabry-Perot interferometer.

FIG. 2. Illustration of laser light pulse incident on a stepped target. The shock transit time is measured by an ultrafast streak camera.

FIG. 3. Schematic of the electric gun showing the placement of the exploding foil, laminated flyer, barrel, target, and optical diagnostics. The metal flyer is typically a few tens of micrometres thick, and the target is approximately 2 to 3 times the thickness of the flyer.

In the tens of Mbar regime, this method has time and distance scales similar to the laser-driven experiments, namely approximately 1 ns and 10 μ m.

RAIL GUN

The rail gun is a device in which a high dc current is discharged into a set of rails. The electrical continuity between the rails is maintained by an arc. The high current establishes a large magnetic field between the rails, and the resulting Lorentz force accelerates the arc and the projectile in front of it. Plastic, cubic projectiles 13 mm on an edge have been accelerated to 6 km/s (Fig. 4).

In the next few years it is likely that a rail gun will be designed and built to launch projectiles a few tens of grams in mass to velocities of approximately 20 km/s or greater. The limiting feature of such a gun for high-pressure and high-temperature physics experiments will be the planarity of the projectiles. Since impactors and targets could be a few millimeters thick, the distance and time scales are about two orders of magnitude larger than the laser and electrical gun experiments and more similar to those used in light-gas guns. Thus, the potential for accurate equation-of-state measurements appears higher.

NUCLEAR EXPLOSIVES

A large number of pioneering experiments have been carried out by Soviet scientists by making relative shock-velocity measurements at tens of megabar pressures using nuclear explosives. Soviet workers did not describe their experimental configuration. However, they could have made all their measurements by standing off from the source a distance far enough to have sufficient neutron and gamma ray shielding in front of the apparatus, but close enough to get ultrahigh pressures. The diagnostics must be shielded from the radiation because it can preheat sample materials and cause an uncertainty in the initial conditions ahead of the shock.

The Soviets used the shock-impedance matching method in which the shock velocity is first measured in a standard material whose equation of state is known and then in a material under study. Their method is basically a measure

FIG. 4. Illustration of rail gun.

of relative compression and depends completely on how well the equation of state of the standard is known for absolute values. They used the equations of state of lead and aluminum as standards and took their equation of state from refinements of Thomas-Fermi theory.

A series of experiments are under way by Los Alamos Scientific Laboratory whereby diagnostics are being developed to measure mass velocity behind the shock as well as shock velocity. The purpose is to generate shock data for a standard material, molybdenum in this case, for impedance matching experiments--either for use with nuclear explosives or perhaps in laser-driven experiments.

SPACE SHUTTLE-BASED COMPRESSION STUDIES

A new class of shock compression and isentropic experiments has recently been proposed to study the properties of elements and compounds over the pressure range up to 15 Mbar. The new concept stems from the ability of NASA's shuttle system to place in polar orbit a permanent instrumented impact station weighing several tons and, in opposing polar orbit, impactors tens of centimeters in diameter that impact at relative velocities of 15 km/s. The high speed interaction is achieved by placing transponders on the shuttle-supplied impact station orbiting the earth in one direction, and thrusters and a sensing system on impactors deployed from a vehicle that is launched at a time so that orbit collision can be achieved by careful tracking and orbit adjustment. These impactors are similar but very much larger than those being used in terrestrial shock-wave laboratories. Upon interaction of the impactors with target or recovery assemblies, dynamic compression data may be obtained, or recovery material collected for processing in terrestrial laboratories.

Impact velocities of 15 km/s, and in principle, somewhat higher, are achievable by releasing impactors and the impact station from different shuttle flights. A number of advantages accrue by carrying out dynamic experiments using the space shuttle. These are high impact velocities, low vacuum level, long duration of high-pressure pulse in large samples, and the capability of handling large quantities of cryogenic materials. These will potentially allow generation of extremely well-defined pressures for both shock and isentropic compressions up to approximately 20 Mbar.

ISENTROPIC COMPRESSION

The least familiar method of achieving high pressures is by isentropic compression. This is a dynamic process carried out in a completely reversible and adiabatic manner. These conditions can nearly be met in practice by experiments in which the compression is rapid enough to prevent heat loss and slow enough to be reversible. This is potentially a very attractive technique and should be capable of achieving the same multimegabar pressures as the shock method but without the attendant high temperatures. The shock and isentropic methods would nicely complement each other--one giving the high-temperature curve and the other a cold curve. Unfortunately, although a limited number of experiments have been carried out to date, both in the U.S. and the U.S.S.R., no real success has been achieved. All such experiments have been carried out in quasi-cylindrical geometry where only density is measured. There have been no direct pressure measurements. In these experiments the density is determined by a flash x-ray shadowgraph that measures the diameter of a cylindrical hydrogen sample. Pressures are obtained from gas-dynamic computations and not measured. We emphasize this point because it is not widely recognized that pressure is not measured directly in the implosion experiments. However, in principle it should be possible to measure electrical conductivity simultaneously with compression, and thereby determine the density when an insulator-metal transition takes place.

A number of the attempts to achieve isentropic compression have utilized magnetic fields to obtain ultrahigh pressures. The simplest concept employs a highly conducting metal coil surrounding a cavity, which upon passage of a large current fills the sample cavity with a high internal pressure. $P = B^2/8\pi$. For a B-field density of 5×10^3 Gauss, a pressure of approximately 1 Mbar can be produced. A concentric explosive system can be added around the cavity, thereby compressing the B field to higher densities. With this method, pressures in the few Mbar range for liquid hydrogen and fused quartz have been reported with uncertainties of nearly 100% in pressure and ± 30 to 40% in density. In these experiments the pressures must be calculated by a magneto-hydrodynamic code using the equations of state of the sample, and the density measured in flash x-ray shadowgraphs. Recently there has been reported a

resistivity measurement for H_2 isentropically compressed of less than $0.04 \text{ ohm}\cdot\text{cm}$ at a density of approximately 1 g/cm^3 corresponding to a pressure of about 2 to 5 Mbar. Whether the observed conductivity represents the metallic state or a thermally excited molecular form of hydrogen is not clear.

Isentropic compression has the potential for material synthesis and some exploratory sample recovery experiments using an explosively induced isentropic flow in plane geometry. Soviet scientists have demonstrated that the enhanced recovery of a high-pressure phase of technological and geophysical interests may be obtained by application of these techniques. It would seem likely that this type of research would complement the very intensive effort presently ongoing in the U.S. with diamond-anvil apparatus synthesizing high-pressure phases.

In short, isentropic compression is a promising technique that has not arrived but would appear to be on the verge of technological feasibility, given sufficient effort and ingenuity. It could fulfill a valuable role in high-pressure physics. It could achieve very high pressures with only modest temperature rise and complementary shock-wave studies, and it also has the potential of carrying out material synthesis.

NEW INITIATIVES USING CURRENT DRIVER TECHNOLOGY

In addition to the pursuit of higher pressures, we anticipate future effort will be directed toward more effectively utilizing the present-day high-pressure systems by employing more sophisticated diagnostic systems, and carrying out novel experiments.

A majority of the dynamic high-pressure studies carried out to date have been directed toward obtaining thermodynamic data. This leaning reflects the focus of interests of shock-wave researchers in the United States and elsewhere, of which most are affiliated with military laboratories. A more balanced scientific research program placing more emphasis on temperature measurements, optical properties, and electrical properties would be welcome and is quite feasible employing current technology and some normal effort and ingenuity. A subject of particular concern is that of temperature measurements for opaque materials. As discussed previously, temperature is not obtained directly

from the Hugoniot measurements of shock and mass velocity; it must be obtained independently. In the past such measurements have been largely unsuccessful, but more recent developments show cause for optimism. The development of routine methods to measure temperature in condensed shocked matter would represent a major innovation and a qualitative improvement in the value of shock data. The most logical temperature probe, as in the case of transparent samples, would be thermal radiation.

SPECTROSCOPIC AND OPTICAL PROPERTIES

Thermal emission spectroscopy and the response of materials to probing radiation can be used to infer information like temperature, broad features of the electronic structure, and molecular vibrational structure at the high densities and temperatures achieved by strong shock loading. For example, emitted thermal radiation can be viewed by a multichannel pyrometer consisting of several fast-response (~ 5 ns) photodiodes or by a dispersive optical grating. In the former case, for example, the output can be fitted to a gray-body spectrum to obtain temperature and emissivity. In the latter case the entire emission spectrum can be measured to determine temperature and/or to study various optical absorption mechanisms like charge transfer absorption features, electronic excitation across small (~ 1 eV) bandgaps in semiconductors or crystal field levels in insulators. Temperature measurements and complete spectrum measurements are very rare in the megabar regime. Such measurements are needed to test quantum and statistical mechanical models in which temperature and volume are the explicit variables, and to carry out the thermal corrections necessary to relate shock-wave data to isotherms.

Raman spectroscopy can be used to study the shift in molecular vibrational frequencies at high densities and temperatures. These measurements are needed to understand the transition from diatomic molecules to monatomic liquids which occur in materials like H_2 and N_2 at high shock pressures, densities, and temperatures. Such spectra are presently being obtained under static conditions using single 25-ps laser pulses. The extension to dynamic experiments lasting about 200 ns is straightforward.

EXPANDED METALS RESEARCH

In a set of experiments recently initiated by Soviet workers, a metal is shock compressed to a few megabars and approximately 1 eV temperature, and allowed to decompress isentropically into the vapor, or liquid-vapor two-phase region. By carrying out a series of experiments, a number of isentropes can be measured and thermodynamic data obtained for expanded metals. This method needs further development. Given sufficient future interest this method of isentropic expansion from the shocked state, a large class of important data are available. Engineering designs and safety analysis in a number of energy-related programs, such as inertial confinement fusion, liquid metal fission reactors, and MHD generators, require thermophysical data for the properties of high-temperature metals, in the expanded liquid or two-phase liquid-vapor region. A host of good experiments and concurrent theoretical efforts will improve our understanding of expanded metal theory and generate a useful thermophysical data base. This appears to be a feasible, desirable program.

FLASH X-RAY DIFFRACTION

The use of flash x-ray diffraction as a probe of material behavior on a microscopic scale during shock compression has proved to be feasible using both high explosively driven shocks and light-gas gun projectile impact techniques. Recent developments demonstrate that crystals such as LiF maintain their crystal structures up to a shock pressure of 1.1 Mbar and a few thousand degrees. The time scale of these experiments is approximately 10 ns. In the next few years, determination of high-pressure and high-temperature structures as well as accurate measurement of crystal volume will be performed.

RMD:dmh