BRIDGMAN'S CONCERN

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In 1956 P. W. Bridgman published a letter to the editor in the Journal of Applied Physics reporting results of electrical resistance measurements on iron under static high pressure. The work was undertaken to verify the existence of a polymorphic phase transition at 130 kbar (13 GPa) reported in the same journal and year by the Los Alamos authors, Bancroft, Peterson and Minshall for high pressure, shock-compression loading. In his letter, Bridgman reported that he failed to find any evidence for the transition. Further, he raised some fundamental concerns as to the state of knowledge of shock-compression processes in solids. Later it was determined that Bridgman's static pressure scale was in error, and the shock observations became the basis for calibration of pressure values in static high pressure apparatuses. In spite of the error in pressure scales, Bridgman's concerns on descriptions of shock-compression processes were perceptive and have provided the basis for subsequent fundamental studies of shock-compressed solids. The present paper, written in response to receipt of the 1993 American Physical Society Shock-Compression Science Award, provides a brief contemporary assessment of those shock-compression issues which were the basis of Bridgman's 1956 concerns.

INTRODUCTION

The development of high pressure shock-compression technology at Los Alamos during and immediately after World War II is one of the most remarkable legacies of the Manhattan Project. Based on development of precisely controlled high explosive technology [1], a group of visionary and dedicated scientists established the new science of very high pressure physics which has had a major impact on our understanding of matter at very high pressure. The well developed experimental and theoretical science was presented to the physics community at large in the 1958 publication by the Los Alamos scientists Rice, Walsh and McQueen [2]. The early history of this shock-compression activity was summarized by Taylor [3] in the 1983 American Physical Society Topical Conference.

The 1958 Los Alamos publication was the basis for the first American Physical Society Shock Compression Science Award which was presented in 1987 [4]. The 1989 Award was presented to Duvall in recognition of his work centered at the Stanford Research Institute and Washington State University [5], while the 1991 Award was presented to Al'tshuler [6] in recognition of his work in the Soviet Union.

A dramatic confrontation between the upstart shock community and the established static pressure community followed the 1956 report of a shock-induced polymorphic phase transformation in iron at 130 kbar (13 GPa) by the Los Alamos scientists Bancroft, Peterson and Minshall [7]. Nobel Prize winner P. W. Bridgman reported that he had failed to observe the transition in his subsequent static experiments [8]. Further, Bridgman expressed concern as to the status of knowledge of the shock-compression process. In later work it became apparent that Bridgman's static pressure scale was in error. As a result of the confrontation, shock data became recognized as the most precise and reliable source of calibration data for static high pressure apparatuses.

The 13 GPa transition study effectively led to a marriage between the shock and static pressure communities which has continued with results apparent in the content of the present proceedings.

It is the objective of the present report to provide a basis for recognition of the critical influence of the Los Alamos and Bridgman papers by providing a contemporary response to the concerns expressed by Bridgman. This objective is accomplished through consideration of the disparate topics of (1) interpretation of mechanical stress waves (in some circumstances shocks), (2) electrical or electronic property studies and (3) mechanical and chemical studies of highly porous powders. A few selected examples are presented in each case. Only in the latter case are new data presented.

What is presented in the report is a highly subjective assessment, and space allocated in the proceedings does not permit detailed documentation. Rather, the basis for response to Bridgman is documented in a recent book [9], in reviews on shock measurements [10,11], overall aspects of shock processes [12] and on phase transformations [13,14]. The author encourages the readers to provide their own responses to Bridgman's expressed concern.

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Bridgman expressed the following concerns in his 1956 letter [8]:

1. Regarding the shock 13 GPa transition, "...it seems to be a widely held opinion that transitions involving changes of lattice type would be unlikely to occur in times as short as a few microseconds."

2. Regarding the 13 GPa wave, "The whole question of what causes such discontinuities seems to be somewhat obscure...".

3. Regarding the 1 GPa Hugoniot elastic limit, "...but the precise mechanism by which reaching the plastic flow point may induce the discontinuity seems not to have been worked out."

The Bridgman concerns are perceptive and raised basic issues not addressed in the 1956 Los Alamos paper. Perhaps the most critical issue is the need for substantially different deformation processes to account for the observation of a speed for solid-solid (or even solid-liquid) transitions which is eight orders of magnitude faster than equivalent static transitions. Study of the deformation process issues in solids has been the principal thrust of research in the intervening 37 years.

INTERPRETATION OF MECHANICAL WAVES

A sketch of a typical experiment to investigate the mechanical response of a solid to high pressure shock loading is shown in Figure 1. The sketch shows a section through a disk of a sample solid with parallel faces. The face on the left is subjected to a rapidly applied impulsive loading -- usually a shock loading -- typically with a controlled impact or the detonation of a high explosive. The face on the right provides a location for sensors which produce a recordable signal describing the arrival of the stress wave produced by the loading. In this configuration the sample responds inertially to the loading and the response is controlled by deformation properties of the solid.

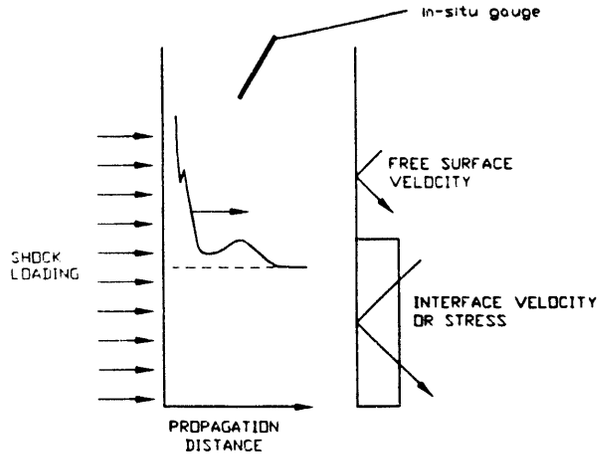

Figure 1. A typical experimental arrangement to study waves in solid samples under rapid impulsive loading involves precise loading and detection of waves controlled by deformation processes.

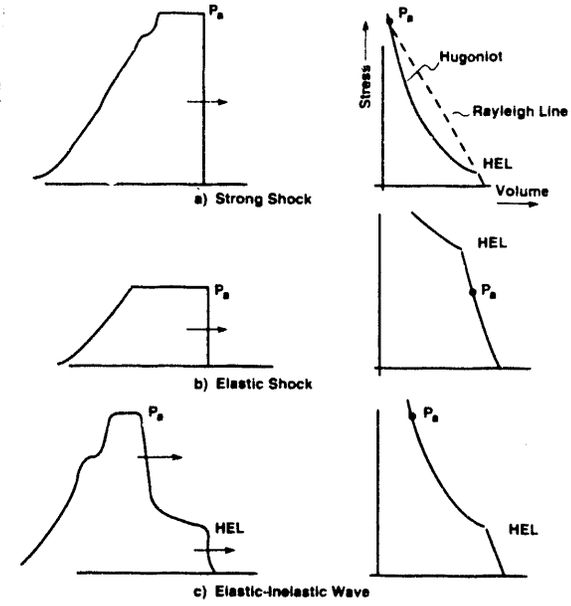

Figure 2. Typical wave profiles and corresponding stress-volume relations for solids under shock loading at various loading pressure values differ qualitatively due to characteristic deformation processes. HEL is a Hugoniot elastic limit.

In essence, the loading is chosen by the scientific investigator to ask specific questions of the sample, and its response provides the answer which is listened for with the instrumentation. A well defined question requires precisely specified and controlled loading. The fidelity of the listening is controlled by precision and time resolution of the instrumentation.

Typical first-order features displayed by solids are shown in Figure 2. Three typical situations are encountered: strong shocks at the highest stresses, elastic shocks at the lowest stresses. and elastic-plastic waves at intermediate stresses. The corresponding stress-volume relationship indicative of the shock condition is shown in the figure as determined from observed wave profiles by use of conservation relations for momentum, mass and energy.

In the elastic range, large-strain, elastic behavior provides data on second-, third-, and fourth- order elastic constants [9]. In the strong shock region the material responses are accurate descriptions of equation of state behavior. If time-resolved measurements of release from pressure are accomplished, data on strength, elasticity and melting can be obtained. In the elastic-plastic range, strength, viscoplasticity and equation of state data are obtained. Strong microstructural influences on the response are evident.

In all cases above the Hugoniot elastic limit, the typically observed materials behavior indicates that stress-volume states close to hydrostatic conditions are obtained. Such observations show that a profound change in solid compressibility leading to fluid-like deformation occurs within the stress front.

The 13 GPa phase transformation study of Minshall and his coworkers [7,15] on iron was conducted with the experimental arrangement as shown in Figure 3. As shown in the figure, a large plane-wave generator, high explosive system was used to provide planar loading over a 220 mm diameter surface. The plane-wave generator, precise explosive systems are the critical experimental legacy of the Manhattan Project [1].

Response of the sample to the loading was detected with a large array of electrically charged pins spaced at various distances from the "free surface" sample face. With small increments of spacing, a detailed arrival-time versus space history was used to determine a free-surface velocity versus time history. As shown in the figure the measurements on the iron transition by Minshall were unusually detailed.

The sample response indicated from the discrete displacement-versus-time data of Figure 4 reveal the presence of three distinct waves: a precursor interpreted as an elastic wave, a wave with a free surface velocity of 0.654 km/sec corresponding to a stress of 13.1 GPa, and a final wave corresponding to a stress of 16.7 GPa.

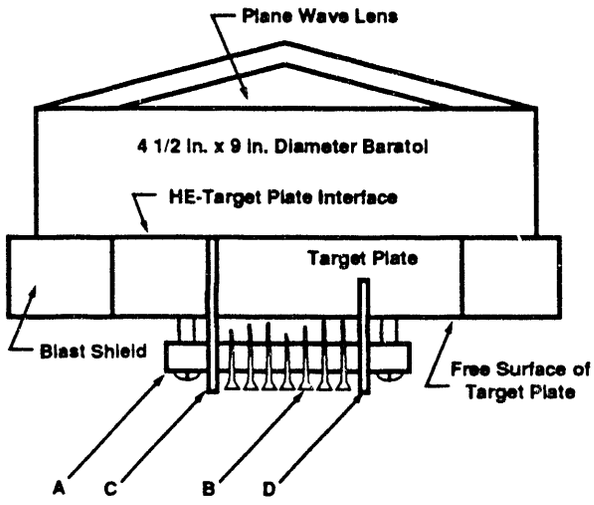

Figure 3. The experimental arrangement of Minshall with plane-wave, high explosive loading and charged pins used to detect the 13 GPa transition in iron. "A" is a holding arrangement. "B" are charged pins. "C" and "D" are fiducial pins.

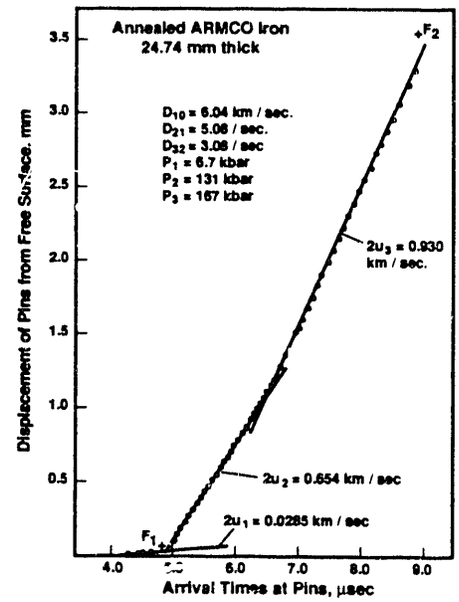

Figure 4. The displacement-versus-arrival time relation observed in Minshall's experiment shows three waves: elastic "$2u_1$", phase transition "$2u_2$", and loading pressure "$2u_3$".

Barker and Hollenbach of Sandia continued the study of iron in 1974 [16]. In their work, as shown in Figure 5, the loading was carried out with the "symmetric impact" of an iron impactor on an iron sample. This configuration provides an unusually well defined loading, and also permits loading over smaller increments of pressure than with high explosives. As shown in Figure 6, the sample response was monitored with the new velocity interferometer which provided a continuous, direct measure of free-surface velocity with time resolution of velocity of a few nanoseconds. Thus, the Barker experiments had the capability of revealing a much more detailed picture of sample response than the earlier work. Further, the Barker work was designed to ask questions on release of pressure and showed hysteretic effects associated with the transformation.

In the Barker work the same materials response answers which were not determined due to a lack of time resolution in the Los Alamos work, provided a more detailed description of the transition showing detailed rate information on both mechanical yielding, viscoplasticity, and transformation rates.

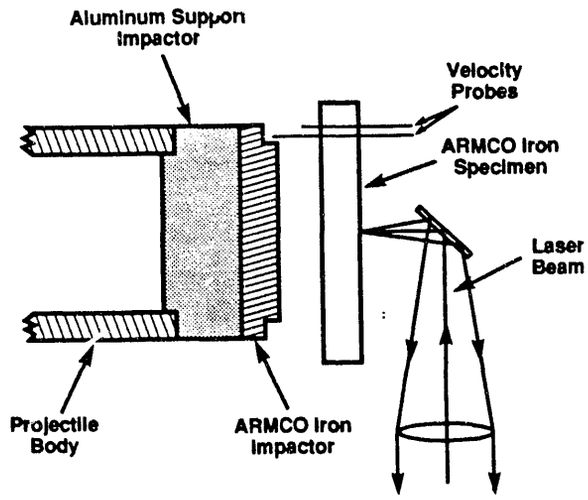

Figure 5. The experimental arrangement of Barker and Hollenbach utilized symmetric impact loading and detected sample response with a velocity interferometer to study the iron transition.

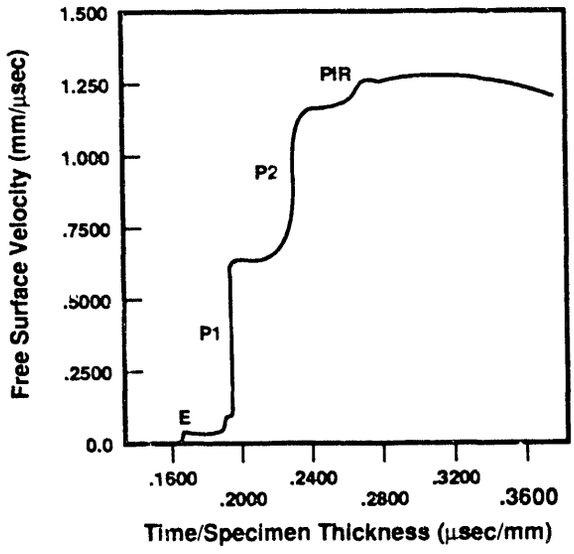

Figure 6. The free-surface velocity-versus-normalized time response of iron by Barker and Hollenbach showed elastic E phase transition P1, loading P2, and reflected P1R waves in considerable detail.

In spite of major differences in loading and sample-response measurements the results of the two studies are remarkably consistent. The mean value for the free-surface velocity of the Barker work for the 13 experiments on 13 different samples was 0.648 km/sec with a range of 6.1%, compared to the Minshall values of 0.651 km/sec with a range of 8.6% for 8 experiments. Beyond the demonstration of experimental credibility from master experimentalists, the reproducibility of the materials behavior among 21 different samples indicates that the processes driving the transformation overcome effects resulting from microstructural differences in materials composition and structure.

Since the early pioneering work there have been numerous studies of shock-induced phase transformations, equations of state, viscoplastic deformation, Hugoniot elastic limits, high pressure strength, and dynamic tensile failure called "spall" [17]. In addition to the extensive data base on the materials aspects there are numerous modeling efforts based on continuum mechanics [18] or constitutive modeling [19]. An evaluation of much of the literature is given in Davison and Graham [12].

The overall picture that emerges from the work to measure and model mechanical responses of solids to rapid impulsive loading is one in which first-order descriptions follow well from prior or related experience and theory. Nevertheless, the more critical second-order descriptions have typically defied consistent definition.

ELECTRICAL AND ELECTRONIC PROPERTIES

Although evaluation of mechanical waves in solids is the base technology underlying all shock-compression studies, considerable attention has been given to characteristics of electrical and electronic properties of solids. These investigations provide independent means to describe shock processes. Answers delivered from solid samples are given through electrical or optical characteristics rather than through the mechanical waves. Two examples of probing electrical responses are presented in the present section: they concern the well established piezoelectric, and the anomalous shock-induced polarization phenomena.

Piezoelectric solids have been extensively studied under high pressure shock compression. As shown in Figure 7, the symmetric impact loading technique has been used to provide precise, well defined loadings to samples of a number of different piezoelectric solids. With the same materials as impactor and sample, the particle velocity imparted to each is precisely one-half of the measured impact velocity. In the present case the impact velocity is determined to an accuracy and precision of less than 0.1%. This precision is the best that can be produced by any high pressure experiment, static or shock, at significantly elevated pressures.

The sample response is monitored with a current-viewing resistor connected between electrodes on the two parallel faces. One-dimensional mechanical and electrical conditions are achieved within the volume of the sample with electrical guard-ring configurations of appropriate dimensions. Under one-dimensional conditions, it can be shown [9] that the piezoelectric current in the external circuit provides a direct, time-resolved measure of piezoelectric polarization, dielectric constant change and electromechanical coupling.

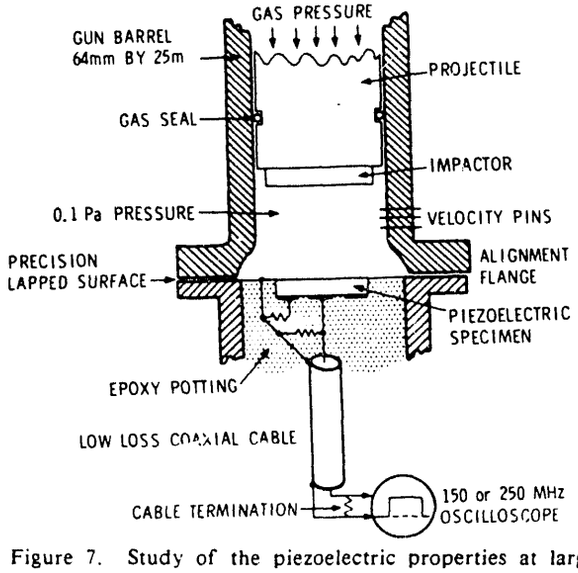

Figure 7. Study of the piezoelectric properties at large strain utilize symmetric impact loading and measurement of the resulting short-circuited current as shown.

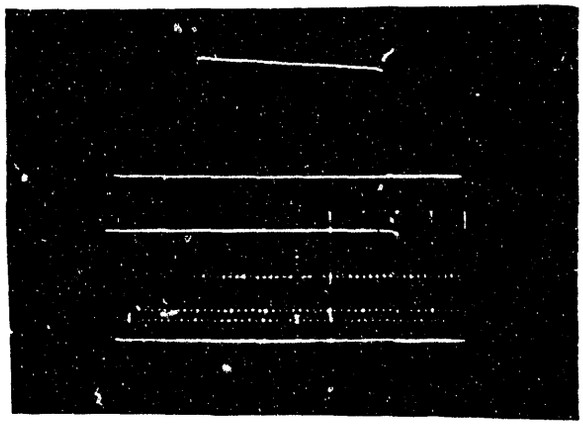

Figure 8. Measured current-versus-time responses as shown in the record of X-cut quartz at 2.5 GPa provide direct data on mechanical and electrical processes between electrodes of shock-loaded, piezoelectric solids. The current record is at the top, while the lower signals are calibration records. Time increases right to left.

A typical current-time observation is shown in Figure 8. Upon impact a rapid rise to a fixed current is observed. The early time to establish an "initial" current is controlled by the "tilt" or misalignment between impacting surfaces. Following the initial current the current is observed to increase linearily in time. The initial current is a direct measure of the piezoelectric current. The increase in current is controlled by the impact-induced strain in the sample (known from the impact conditions), the change in dielectric constant, and electromechanical coupling.

Based on such interpretations with a nonlinear elastic, nonlinear dielectric, nonlinear piezoelectric model, piezoelectric polarization-versus-strain behavior can be established through experiments on various samples subjected to the controlled impacts over a wide range of strain. Typical mathematical fits to the data are shown in Figure 9 for x-cut quartz and z-cut lithium niobate. The nonlinear contributions are readily apparent when the observations are compared to the linear fit.

Observations in the elastic range yield precise, well defined values for linear and nonlinear piezoelectric behavior. Distortions to the piezoelectric current pulses for quartz above 2.5 GPa result from electronic conduction and mechanical relaxation processes induced by the stress amplitude and electric field. Above 6 GPa the current pulse shapes correspond to the first-order behavior expected from an elastic-plastic behavior. Due to the various complex behaviors involving stress-induced defect configurations, the higher stress data do not yield accurate values of piezoelectric polarization. Lithium niobate shows similar features but specific details differ significantly.

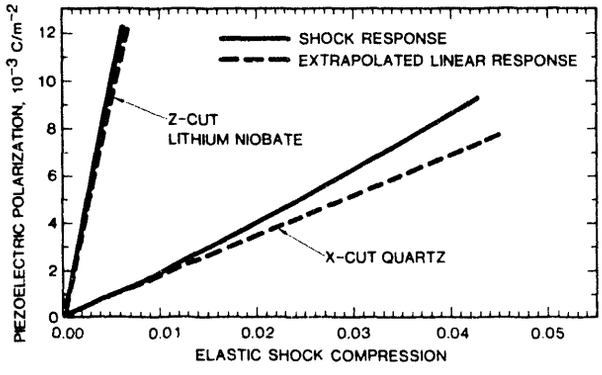

Figure 9. Based on a number of experiments within the elastic range, the linear and nonlinear piezoelectric properties are apparent from the amplitude-versus-strain data.

Ionic and polymeric solids exhibit electrical signals under shock compression characteristic of shock-induced volume polarization effects. These signals are particularly interesting messages from the samples as the processes producing the signals do not correspond to known physicochemical mechanisms encountered under other circumstances. A summary of the extensive work on ionic crystals is given by Mineev and Ivanov [20], and on polymers by the present author [21].

An overall perspective on volume polarization effects observed under shock-compression loading is shown in Figure 10. The log-log presentation shows the value of polarization observed as a function of volume compression. The largest polarization is that of the ferroelectric ceramic PZT 95-5. Piezoelectric responses are shown for quartz, lithium niobate and the ferroelectric polymer PVDF. These responses can be understood, to first order, by known physical properties of the solids. The polarizations of the various ionic crystals and polymers are shown to be typically feeble compared to piezoelectric solids. Further, unlike piezoelectrics, the polymers shown a threshold at large

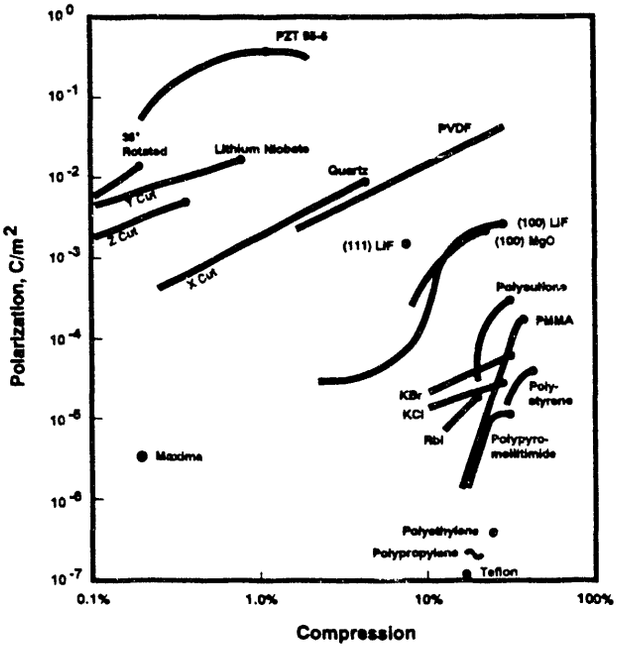

Figure 10. Shock-induced, volume polarizations of piezoelectrics, ferroelectrics, (upper portion of figure) polymers and ionic solids have been measured. The ionic and polymeric solids show electrical responses not observed with known physicochemical processes. Note the large compression thresholds for the latter solids.

compressions (about 20 to 30%) for initiation of the signals. The thresholds for initiation of signals from the ionic solids have not been studied, but in the case of LiF it corresponds to the onset of mechanical yielding.

The Soviet authors provide clear evidence for a defect model to describe the ionic solid responses [20]. In those solids, the dipole creating the volume polarization is shown to result from separation of cationic and anionic defects resulting from the plastic deformation. Acceleration within the shock-loading front results in charge separation leading to the dipole. A similar model involving mechanically induced damage to polymers and charge separation within the shock front provides the model most consistent with the polarization data [21].

There are numerous other studies of physical properties of dielectrics, semiconductors, ferromagnetics and metals [9]. Unique observations of properties at large uniaxial strain have been obtained. Upon mechanical yielding, or at stresses at which microyielding can occur within the elastic range, it has not proven possible to characterize physical properties due to the uncertain nature of the defects. The influence of such defects has also been noted in spectroscopic measurements [22].

Generally, within the elastic range, physical properties including nonlinear contributions can be characterized with precision to second order. When defect contributions resulting from plastic deformation become significant, first-order models may be substantially in error.

MECHANICAL AND CHEMICAL PROPERTIES OF HIGHLY POROUS SOLIDS

Porous solids have been widely studied under high pressure shock compression [9, 23]. Traditionally, the behavior of a solid in a distended state has been used to determine or to test prediction of thermal contributions to equations of state. As the increase in thermal energy results from the pressure-volume work, a first-order model in which the distended solid is uniformly compressed in thermodynamic equilibrium without heterogeneous effects provides a basis for computation of the additional temperature for compression to the same pressure or volume of a solid density sample. Such a model ignores details of the deformation process, energy localization effects, or microstructural changes in the powder materials which can lead to alterations in mechanical, chemical or physical properties.

The use of a thermodynamic model to test equations of state determined in the solid-density state is well illustrated by the work on iron by Kerley [24] as shown in Figure 11. Data on shock velocity versus particle velocity of solid density and porous samples are compared to calculations with Kerley's equation of state. To first order, the equation of state predictions and experimental observations appear to be in agreement.

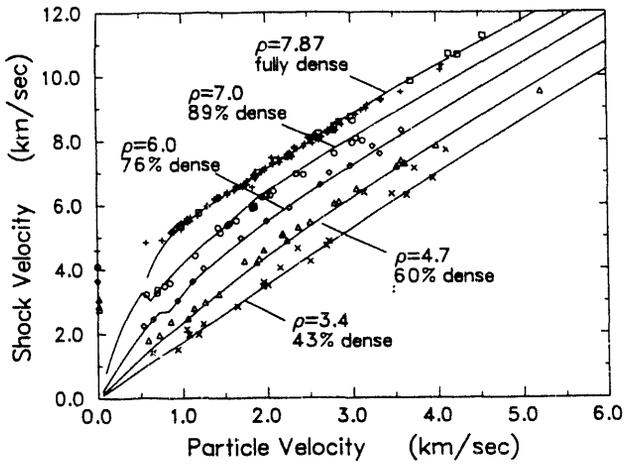

Figure 11. Conventional shock velocity-versus-particle velocity data on porous solids can be used to test or determine equation-of-state models as shown by Kerley.

Shock-induced solid state chemistry has become of interest for materials synthesis and as a probe of shock-compression processes. The desired chemical changes are typically only observed in the porous state; hence, knowledge of shock-compression processes in porous solids is crucial to prediction and interpretation of experiments. The conditions encountered in chemically reacting powder mixtures are poorly defined and description of the processes requires qualitatively different questions than invoked to describe shock compression of fully dense solids.

Two different experimental techniques have been used to develop an understanding of shock-induced solid state chemical processes. Perhaps the most useful has been the sample preservation technique in which a sample is subjected to controlled shock compression and preserved for post-shock analysis. With this technique the full array of modern materials science technology can be applied to describe the material condition. The second technique utilizes time-resolved pressure measurements on shock-compressed powder mixtures. The time-resolved pressure measurements provide considerable critical detail on compression processes and direct evidence for chemical reaction.

There is considerable detail published on sample preservation data on numerous substances [9,25,26]. Behaviors are materials specific, as would be expected, but an overall conceptual framework has been proposed to identify the nature of the materials behavior to be described. The conceptual model CONMAH encompasses the processes thought to be important in shock-induced, solid state chemical reactions [27].

CONMAH is an acronym for considerations of configuration and shock-induced configuration changes, mixing or formation of more intimate contact between particles with plastic deformation and kinetic energy, activation or enhancement of solid state reactivity with shock deformation, heating or the thermal environment. The conceptual model explicitly recognizes the qualitative changes that occur in highly porous powder mixtures under high pressure shock loading. Without consideration of the CONMAH processes, shock-induced chemical changes cannot be adequately predicted nor can existing data on materials behavior explained. The problem remains to describe these CONMAH processes in appropriate mathematical models [28].

Time-resolved pressure measurements in porous powders are limited in prior work and there is little data on details of of shock-deformation behavior of highly porous materials of interest. Materials behaviors of interest include stress-pulse rise time or dispersion. Crush strength or shock pressure required to compress a powder to solid density is a critical issue. It is expected that the crush strength will depend on porosity and powder morphology (CON). Direct evidence for chemical reaction is expected to be evident in wave speed measurements [29].

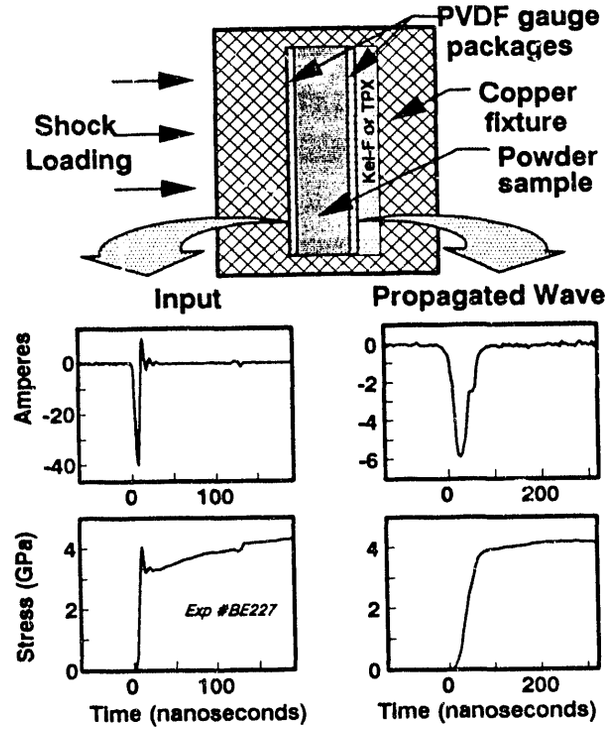

Figure 12. Piezoelectric polymer, PVDF, gauges are used to monitor input and propagated stresses in highly porous powder mixtures. Typical response measurements are shown.

The experimental arrangement used to study shock compression of porous powder samples is shown in Figure 12 along with the measured signals from the gauges and the relevant stress-versus-time records. Controlled shock loading is applied with either symmetric impact or plane wave explosive loading. A PVDF stress-rate gauge is placed at the input side of powder samples and another gauge is located at the rear of the sample to monitor the transmitted stress. Stress-rate signals (current versus time) are obtained at each location with explicit information on materials response. The gauges provide a precise measure of wave speed through the powder.

Related papers in this proceedings show powder responses on a single component powder, rutile [30], an unreacting powder mixture, $2Al + Fe_2O_3$ [31], and a reacting powder mixture, 5Ti + 3Si [32]. The wave shapes are quite dispersive and hence provide only an approximate measure of volume compression. Given the large compressions, this measure is sufficiently descriptive to provide an identification of the processes. As shown in Figure 13, the stress-pulse rise times observed for various highly porous materials are strongly dependent on input stress [30]. At pressures less than crush strength the risetimes are hundreds of nanoseconds. In all cases, however, the rise times are quite long considering the 4 mm wave-propagation distance.

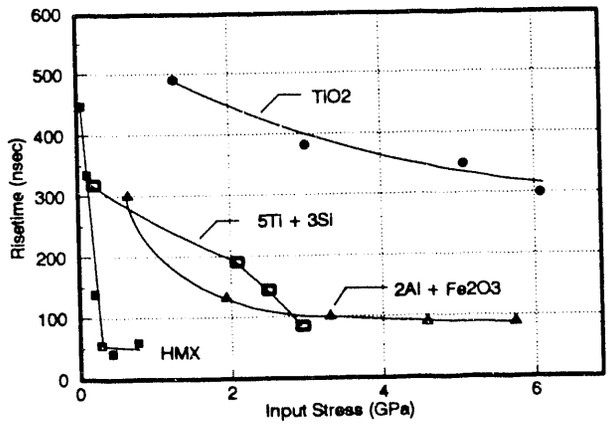

Figure 13. Propagated wave profiles are observed to be strongly dispersive in highly porous solids with the rise time strongly dependent on stress level.

The PVDF gauge technique permits detailed study of the early interaction of the loading wave from the driver plate into the powder samples. Based on wave-speed measurements in the powder sample, an input stress can be calculated from the known properties of the standard driver. Such interpretations are the basis of most of the porous solid data in the literature. In the work reported at this conference there is considerable difference between the calculated and measured stresses. These differences suggest that highly porous solids exhibit responses strongly influenced by internal, interparticle stresses with configurations that are strongly stress and deformation dependent.

The PVDF gauge technique clearly has potential to provide the necessary resolution to define the critical features of shock-compressed powders. The behaviors indicated in the present work demonstrate that the first-order models of shock compression of highly porous powders do not provide a quantitative picture of the processes. Progress in this area requires much more complex modeling than has been available in the past [33].

RESPONSES TO BRIDGMAN'S CONCERNS

The examples given above provide a framework for recognition of the nature of a variety of materials behaviors observed under controlled shock compression; from that framework responses to Bridgman's concerns can be formulated. The examples serve to indicate that study of fundamental processes in shock-compressed solids involves a significantly broader area than the conventional equation-of-state measurements

Today, perhaps responses to Bridgman's concerns can best be based on (1) the status of shock-compression science as a credible scientific endeavor, (2) in terms of whether the work has satisfied the sponsor, and (3) whether the science of shock compression is "well worked out" scientifically.

It can be stated with confidence that shock-compression science is a well established, credible scientific enterprise. Experimental capabilities are sophisticated and versatile and provide detail on shock-compression processes not even contemplated 25 years ago. Both loading methods and sample-response technologies provide an unusually strong capability to ask a range of detailed scientific questions of materials. Theory is readily applied to describe physical, chemical and mechanical aspects of observed materials behaviors. Mathematical models give explicit form to the theories and the models are the basis of descriptions of shock processes in complex computer codes. First-order descriptions of processes are typically in good agreement with observations. That shock-compression data are used as the standards for pressure calibration of static high pressure apparatuses provides explicit evidence on the scientific credibility of the field.

As to whether the work in shock-compression science has satisfied the sponsor, one must look to the advance in technology from science to engineering that has occurred over the years. As in the first question above, there seems little question that the requirements of sponsoring agencies have been fully met. A strong scientific foundation has been laid which provides predictive capability in a range of shock environments, the ability to design structures and components based on materials response knowledge, and provides the basis for shock-compression engineering on a reasonably routine basis. Given the cost and destructive nature of explosive experimentation, predictive capability is strongly cost effective. An enormous return has resulted from the research investment.

Even though the sponsors have achieved full measure for their investment, it can be questioned whether the present state of the experimental, theoretical and modeling capability will be sufficient for future needs. In spite of the availability of the technology in an advanced state, future needs place much more demanding requirements on the science to predict the behavior of ever more complex materials in a wider range of environments. Present capabilities are unlikely to be sufficient for future demands, and in some instances such as the problems in highly porous solids, the present capabilities are completely inadequate.

Whether the scientific knowledge is "well worked out" is questionable. Certainly impressive progress made toward understanding the scientific aspects of shock-compression processes, but to date the progress has largely been limited to identification of problems to be developed scientifically. The databases on shock-compression, pressure-volume relations are truly an international treasure as is the data on elastic, viscoelastic, and viscoplastic behavior. Equally impressive are the data on structural phase transitions and solid-to-liquid melt. Nevertheless, there are significant differences between theory and experiment. These differences are most likely based on unidentified or improperly described processes.

What are the processes that lead to conversion of a solid to a fluid-like state under high pressure shock compression? Even this most basic, first-order question of shock-compression is undefined. Such behavior, which is basic to interpretation of all equation-of-state data, is not defined in scientific terms. Certainly the creation and flow of defects is qualitatively involved, but we have little ability to quanitatively describe the process except in a few limited cases. The basic deformation processes are essentially undefined. Descriptions of defect states are largely undefined. Properties of the solids in the high pressure defect state in terms of compressiblities, phase stability, melting, physical and chemical properties are undefined. Thus, from a basic scientific viewpoint work to date has largely only succeeded in identifving the overall nature of the underlying processes.

Shock Compression Paradigms--Progress toward scientific description of shock-compression processes and shock-compressed solids requires a careful study of paradigms. The literature contains many examples of fundamentally different basic assumptions. The differences typically reside in whether the shock-compressed solid is treated in perfect-crystal-lattice, or in a defective, heterogeneous-solid interpretations.

Perhaps the best statement of the shock-compressed defect solid is given by Kormer [34] as:

> "The shock wave is a powerful generator of defects, formed during the strong plastic deformation taking place at the wave front. These disturbances of the ideal crystal lattice, as under normal conditions, determine to a large extent the electrical, optical and other physical characteristics of the material. The generation of imperfections brings about an acceleration of phase transformations and is the reason for relatively high conductivity, the absorbing power, and possibly the polarizaton of shock-compressed dielectrics reported by a number of investigators."

Other descriptions of the shock-compression process based on a defective solid paradigm include the description of Swegle and Grady [35]:

> "The underlying mechanisms governing shock viscosity or the risetime of plastic shock waves, and their behavior in the shock process are not yet well understood. Viscouslike flow within the shock is thought to be associated with the microscopic processes of dislocation multiplication and motion, twinning, vacancy production, precipitate alteration, etc."

Regarding phase transformation mechanisms, Al'tshuler [36] has observed:

> "On the other hand, the formation of the high pressure phase is preceded by the passage of the first plastic wave. its shock front is a surface on which point, linear and two-dimensional defects, which become crystallization centers at super-critical pressures, are produced in abundance."

The description of Dremin and Breusov [37] on physical and chemical phase transformation processes in 1968 provides an early example of deformation modeling based on heterogeneous concepts.

The author has termed the basic paradigm of the perfect crystal lattice in thermodynamic equilibrium as a "benign-shock" paradigm [9]. The defective solid paradigm has been termed a "catastrophic-shock" paradigm [9]. The benign shock paradigm is clearly an approximation, and it has served the scientific community well in many circumstances; nevertheless, the catastrophic solid paradigm provides the appropriate concepts needed to addres; the fundamental issues of shock deformation of solids, and is the only basis on which much of the literature can be interpreted.

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