1. Introduction

1.1 Foreword

In the investigation of shock waves in solids, the experimenter is placed in the role of indirect observer of the phenomena involved [1]. The duration of the event is far too brief for the eye to observe, and the release of energy which creates the shock waves tends to overwhelm the senses. Thus, much of the progress in understanding shock processes has awaited the development of adequate diagnostic tools to record short-lived, transient phenomena.

To a large extent, the development of theoretical models has paralleled and followed the development of shock wave instrumentation and the production of experimental data. The 1950s and 1960s produced a wealth of experimental techniques and data which rapidly advanced the understanding of the mechanical, thermodynamic, and electromagnetic response of materials to high-intensity waves and provided the framework of modern shock wave physics.

In a seminal 1955 paper, J. M. Walsh and R. H. Christian [2] described measurements of the equations of state of aluminum, copper, and zinc to pressures between 10 and 50 GPa (100 and 500 kilobars). Explosive lenses were used to generate high pressures in specimens, and free surface and shock wave velocities were measured by argon flash gaps and rotating mirror streak cameras.

Other work and experimental techniques quickly followed. Measurements of shock wave profiles by use of shorting pins provided definition of elastic waves preceding the shock wave and led to the discovery by Minshall, Bancroft, and Peterson of Los Alamos of the phase transition in iron [3]. The major developments of the early period were summarized in a 1986 paper by G. E. Duvall [1]. Each discovery was occasioned, to some degree, by the introduction of new experimental techniques, as shown in Table 1.1, adapted from Reference 1.

In addition to developing new methods for measuring shock wave phenomena, new techniques were sought to create well-controlled shock waves in materials. Explosive techniques were augmented by single- and two-stage gas guns [4–5], and the range of pressures achievable was extended both higher and lower, from less than 0.1 GPa to nearly 1 TPa.

Table 1.1. Techniques Utilized to Study Shock Wave Phenomena (Circa 1965)

PHENOMENON	**TECHNIQUE**
Equation of state	Flash gaps, shorting pins, streak camera
Phase transitions	Shorting pins
Electrical conduction	Ionization pins, quartz gage
Charge release-polarization	Piezoresistive gage
Shock demagnetization	Electromagnetic velocity gage
Shock-induced opacity	Laser interferometer
Elastic precursor and decay	Pins and laser interferometer
Residual stress	Recovery

Extremes of pressure have now been achieved by pulsed laser loading of materials and by the deposition of radiation energy in underground nuclear tests. In this manner, the available pressure regime has been raised to tens of TPa.

1.2 Motivation for Research

Following the discovery of new phenomena, the general trend has been to accumulate data sufficient to construct physical models. The process of discovery, model formulation, data accumulation, model refinement, and inclusion in computer routines has been repeated many times over the past fifty years.

An important aspect of this cycle has been the measurement of shock wave parameters under the carefully controlled conditions provided by the impact of flat plates launched by guns. Beginning in the mid-1960s, two types of guns were developed for shock wave studies. Single-stage guns provided measurements to approximately 20 GPa, while two-stage light-gas guns increased this range to over 0.5 TPa.

Of particular significance was the original utilization of a light-gas gun to extend equation of state measurements to above 0.5 TPa [4–5]. Innovations in instrumentation included development of pin techniques with sub-nanosecond accuracy for measurement of high-pressure equations of state and improvements to interferometers capable of measuring shock wave profiles with high accuracy [6–11].

The precision afforded by these launchers and the relative ease (compared to explosive techniques) of applying sophisticated sensors to measure shock wave parameters have led to detailed descriptions of material behavior under shock wave loading [12–13]. Combined with other techniques (static high pressure, material yield under uniaxial and biaxial stress, elastic wave velocities, etc.), these measurements furnish modelers with sufficient information to formulate highly accurate predictive routines.

The studies presented in this book have provided experimental data for a wide variety of materials upon which models of material behavior have been formulated. In general, the emphasis has been on the procurement of data, rather than on its utilization. Experimental techniques were developed or improved upon to measure shock wave parameters. New launchers were built which extended the range of measurements beyond previous limits.

Close coordination with theoretical shock wave physicists provided guidance on the parameters needed for models of material behavior. An iterative approach was utilized that made effective use of available equipment and manpower.

1.3 Chapter Organization

The book is arranged so as first to familiarize the reader with the theoretical and experimental foundations upon which the work is based. A description of the theoretical basis of shock wave formation and propagation is presented in Chapter 2 as a framework for the remainder of the chapters. Chapter 3 describes the experimental techniques employed for the study, with details of launchers, sensors, and auxiliary equipment.

Results of the experimental investigations of material response to dynamic loading in the regime below 20 GPa, where the effects of material strength must be incorporated in models, are presented in Chapter 4, beginning with a summary of the results from the four materials tested and continuing with a detailed description of the response of tantalum.

Chapter 5 describes Hugoniot measurements of eleven materials to 0.5 TPa, using the technique of launching flat plates to 8 km/s against specimens suspended near the gun muzzle. Chapter 6 continues the description of impact tests where the objective is to describe the release behavior of materials from very high pressures.

A qualitatively different class of material response is described in Chapter 7 — that of porous materials. While the equation of state surface of a solid material is independent of the path used to arrive at that point, no such unique relationship exists for porous materials. The mathematical model describing shock wave propagation in this class of materials necessarily contains the thermodynamic path by which the material arrives at its final state. The behavior of porous materials under shock wave loading is described in the chapter, using porous beryllium as the example.

In Chapter 8, the use of laser interferometry is discussed as a method for obtaining highly accurate wave profiles, from which a wealth of shock wave parameters is obtained. The chapter is followed by Appendix A, which catalogs a large number of wave profiles, obtained with interferometry and stress gages.

1.4 Convention for Units

In general, International System (SI) units are used in the text throughout the book. Where tests were conducted before the widespread adoption of SI standards, however, the data are frequently presented using the original units. This convention is especially followed in tables and figures.

The table below allows conversion of values.

Quoted Units	SI Units
1 kilobar (kb)	0.1 Gigapascal (GPa)
1 Megabar (Mb)	0.1 Terapascal (TPa)
1 g	0.001 kg
1 g/cm^3	1,000 kg/m^3

1.5 References

1. Duvall, G. E. "Shock Wave Research: Yesterday, Today, and Tomorrow." *Shock Waves in Condensed Matter*, 1–12. New York and London: Plenum Press, 1986.
2. Walsh, J. M., and R. H. Christian. "Equation of State of Metals from Shock Wave Measurements." *Phys. Rev.* 97:1544 (1955).
3. Bancroft, D., E. L. Peterson, and S. Minshall. "Polymorphism of Iron at High Pressure." *J. Appl. Phys.* 27:291 (1956).
4. Jones, A. H., W. M. Isbell, and C. J. Maiden. "Measurement of Very High Pressure Properties of Materials Using a Light-Gas Gun." *J. Appl. Phys.*, vol. 37 (August 1966).
5. Isbell, W. M., A. H. Jones, and F. H. Shipman. "Use of a Light Gas Gun in Studying Material Behavior at Megabar Pressures." Proceedings of the Symposium on High Dynamic Pressure, Paris, September 1967.
6. Barker, L. M., and R. E. Hollenbach. *Rev. Sci. Instr.* 36:4208 (1965).
7. Barker, L. M., and R. E. Hollenbach. "Laser Interferometer for Measuring High Velocities of Any Reflecting Surface." *J. Appl. Phys.*, vol. 43, no. 11 (November 1972).
8. Isbell, W. M. "Laser Interferometric Techniques for Precision Measurements of Shock Waves in Materials and Structures." *Photomethods* magazine (May 1982) and *High Speed Photography and Photonics* newsletter, vol. 2, no. 1 (winter 1982).
9. Hemsing, W. F. "Velocity Sensing Interferometer (VISAR) Modification." *Rev. Sci. Instr.* 50 (January 1979).
10. Isbell, W. M. "Advances in Laser Interferometer Techniques for Measurement of Dynamic Material Properties." Proceedings of International Congress on Instrumentation in Aerospace Simulation Facilities, Dayton, Ohio, September 30, 1981.

11. Isbell, W. M. "Modern Instrumentation for Measurements of Shock Waves in Solids." Proceedings, Japanese Shock Wave Symposium, Tokyo, Japan, 1999.
12. Isbell, W. M., and W. J. Tedeschi. "Hypervelocity Research and the Growing Problem of Space Debris." Proceedings, Hypervelocity Impact Symposium, 1992.
13. Cunningham, T. M., and W. M. Isbell. "Results from the Satellite Orbital Debris Characterization Test Series." Proceedings, Hypervelocity Impact Symposium, 1992.