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(6) COMPILATION OF DYNAMIC EQUATION OF STATE DATA FOR SOLIDS AND LIQUIDS.

by

(10) John S. Rinehart.

~~Rinehart and Associates~~

ABSTRACT. This compilation is a discussion of basic shock wave equations and theory of hydrodynamic impact. The impedance match method for determining Hugoniots is outlined. Empirical data from the Hugoniot can be used to calculate temperatures associated with the passage of shock waves. The bases for these calculations are described. A number of empirical equations, some of which are useful for computer calculations and others for graphical description are tabulated.

It has been found that in most instances, a linear relationship exists between shock and particle velocities. Constants appearing in this relationship are listed for a large number of materials.

The bulk of the compilation consists of graphs and tables of shock velocity, particle velocity, pressure, relative volume and temperature associated with shocks. For almost all materials, shock velocity is plotted against pressure and pressure against relative volume. In some instances where shock velocity is not linearly related to particle velocity, graphs relating the two have been drawn.

The final section is a reasonably complete bibliography listing the papers, reports, and books which contain dynamic equation of state data.

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AN ACTIVITY OF THE BUREAU OF NAVAL WEAPONS

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FOREWORD

This report is a compilation that discusses the basic shock wave equations and theory of hydrodynamic impact. It is part of an applied research program that was conducted in earth and rock mechanics in support of explosive ordnance problems at the U. S. Naval Ordnance Test Station.

This publication is a facsimile of the report prepared by Rinehart and Associates. It is issued as a Station technical publication to facilitate distribution to other interested agencies.

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CONTENTS

Compilation of Dynamic Equation of State Data for Solids and Liquids

INTRODUCTION

There has been a rapid accumulation of data pertaining to the behavior of materials, metals, plastics, liquids, and ionic compounds, subjected to intense, dynamic loading. Much of these data relate to the volume changes occurring under compression, known as dynamic equation of state information or Hugoniot data. The experimental results have provided the constants needed to fix in a quantitative fashion, the thermodynamic parameters associated with dynamic compression. These data have been widely scattered and not readily accessible to the numerous investigators who have use for them. This compilation brings all of the available data together in one place in an easily usable form. It contains discussions of the essentials of shock wave theory, numerous tables and graphs, empirical equations, and a comprehensive bibliography.

Most of the empirical data used in determining Hugoniot curves have been obtained by making velocity measurements. In most of the early work, shock velocity and particle velocity were measured simultaneously and the conservation equations were used to compute pressure-volume relationships and other thermodynamic constants. Later, after Hugoniots had been well established for some materials, the impedance match method became more popular since it involved only the determination of shock velocity. Some attempts have been made to measure density changes directly using flash X ray techniques, but, in general, these have not given very accurate results. Direct measurements of pressure are being made successfully at present using piezoelectric quartz crystals, although the upper limit of pressure by this technique is only about forty kilobars.

Several methods have been used to generate shocks. In the early tests, an explosive charge was detonated in intimate contact with the material under study using explosive plane wave generators. A severe limitation of this technique was the fact that a wide variation of shock pressure could not be achieved. An important later modification of the method was the introduction of an impactor plate which was propelled by the explosive charge so as to strike the specimen. By judicious choice of impactor plate material, and explosive charge size, a very wide range of pressures were possible.

More recently, a number of laboratories have developed gun impactor devices for generating shocks. These devices have the big advantage of accurately preselecting and controlling initial conditions. With guns, extremely high pressures, several thousand kilobars, are possible.

Pin contactors to measure free surface velocity gave the first quantitative data on particle velocity, the assumption being made that free surface velocity was just twice that of particle velocity. The technology of the pin contactor has reached an exceedingly high level of development although other techniques are gradually replacing this one. One such technique utilizes the fact that argon becomes luminescent when subjected to high intensity shock, making it possible to measure times of arrival by observing, with a streak camera, onsets of luminosity. In another technique, surface velocity is monitored continuously by means of a resistance wire. Condenser techniques have also been found useful.

No attempt has been made in this compilation to delineate detailed experimental methods used in obtaining data. It is felt that anyone interested in full descriptions of experimental methods can obtain these best by going to the original source.

Basic shock wave equations

A shock wave is in essence a moving discontinuity in pressure, temperature, particle velocity, density, and internal energy. For all practical purposes, the shock wave converts instantaneously a fluid of low density, temperature, and pressure to one of high density, temperature and pressure. The following equations, which can be readily derived on the basis of Newton's laws of motion and the conservation laws, (Cole, 1948; Duvall, 1961) describe fully the progress of the shock wave and the conditions ahead of and behind a shock moving through a material which is initially at rest.

Conservation of mass: $\rho (U - u) = \rho_o U$ (1)

Conservation of momentum: $P - P_o = \rho_o u U$ (2)

Conservation of energy: $P u = \rho_o U (E - E_o + u^2 / 2)$ (3)

where U is the velocity with which the shock front is moving; u is the translational particle velocity, the velocity with which a point in the compressed material behind the shock front is moving in the direction of motion of the front; ρ_o and ρ are the respective densities of the material in front of the shock and behind it; and E_o and E are the respective energies of the material before and after compression.

A most useful equation, from a thermodynamic point of view, is obtained if equations (1) and (2) are combined, giving the relationship

$$E - E_0 = 1/2\ (P + P_0) \left[(1/\rho_0) - (1/\rho) \right] . \qquad (4)$$

This relationship is frequently called the Rankine-Hugoniot relation.

These four equations containing as they do five parameters, are not adequate to determine uniquely the four parameters. Another equation is required, an equation of state which, when combined with equation (4), results in a relation between ρ and v, where $v = 1/\rho$, known as the Hugoniot ρ-v relation, or simply, the Hugoniot. This Hugoniot relation defines the locus of all points that will be reached by a shock transition from the initial state P_0, ρ_0.

Solving equations (1) and (2) for shock velocity and particle velocity in terms of the pressure and density behind the front yields

$$U = \left[(\rho/\rho_0)\ (P - P_0) / (\rho - \rho_0) \right]^{\frac{1}{2}} \qquad (5)$$

and

$$u = \left[(\rho - \rho_0) / \rho \right] U \quad . \qquad (6)$$

Equations (5) and (6) are useful in calculating shock velocity and particle velocity as a function of pressure when the equation of state is known.

It is also apparent from equations (5) and (6), particularly equation (6), that a simultaneous experimental determination of shock velocity and particle velocity is sufficient to establish a point on the Hugoniot ρ-v curve and that a series of such measurements will define the entire curve.

Extensive single Hugoniot measurements on a large number of substances (Al'tshuler, Krupnikov and Brazhnik, 1958) indicate that for almost all substances, shock velocity and particle velocity are linearly related. The reason for this linear relationship:

$$U = a + b\,u \qquad (7)$$

where a and b are constants characteristic of the material, is not understood. It holds, however, for ionic, molecular, and metallic crystals and includes liquids as well as solids and alloys. Sand (Bass, Hawk and Chabai, 1963) is a notable exception. A specific linear relation holds only for a single phase. When a material undergoes a phase change, the slope changes at the pressure where the phase change occurs. This fact is used to discover and to locate more precisely where phase transitions occur. Such transitions have been observed in bismuth (Walsh, Rice, McQueen and Yarger, 1957 ; Al'tshuler, Krupnikov and Brazhnik, 1958), granite (Alder, 1963; Grine, 1960; and Lombard, 1961), iron and steel (Minshall, 1955), marble (Lombard, 1961; Dremin and Adadurov, 1959), playa (Bass, Hawk and Chabai, 1963), pyrolytic graphite (Wagner, Waldorf and Louie, 1962), taconite (Lombard, 1961), and tuff (Lombard, 1961; Bass, Hawk and Chabai, 1963)

When shock velocity and particle velocity are linearly related, the equation of state can be written explicitly in terms of the constants a and b of equation (7). Substituting in equation (2) the expression for U of equation (7) yields

$$P = \rho_o u (a + b u) \tag{8}$$

when P_o, usually equal to one atmosphere, is considered negligibly small compared to P. Equation (6) can then be written in the form

$$v / v_o = \left[a + (b - 1) u \right] / (a + b u) . \tag{9}$$

Eliminating u between equations (8) and (9) gives

$$P = \rho_o a^2 \eta / (1 - b \eta_1)^2 \tag{10}$$

where

$$\eta = 1 - v / v_o .$$

The equation of state, expressed by equation (10) is extremely useful in computing thermodynamic quantities. It should be noted, however, that equation (10) is applicable only when shock velocity and particle velocity are linearly related. Numerous investigators (Al'tshuler, Krupnikov and Brazhnik, 1958; Wagner, Waldorf and Louie, 1962) have expressed their experimental results in the form of equation (10) although other more empirical equations of state are often given. The Los Alamos group (Walsh, Rice, McQueen and Yarger, 1957) for instance, have published much of their equation of state data in the purely empirical and analytic form

$$P = A\mu + B\mu^2 + C\mu^3$$

where

$$\mu = (\rho/\rho_0) - 1$$

and A, B, and C are material dependent constants.

Theory of Hydrodynamic Impact

Consider the hypothetical case of two semi-infinite bodies colliding along a plane interface, one body, medium 1, moving with velocity, V, in a direction perpendicular to the interface (see figure); the other, medium 2, is stationary. Plane shocks will be propagated from the interface into both colliding bodies as indicated in the second figure. For most practical as well as theoretical purposes, each shock front may be considered a zone of infinitesimal width across which there is a discontinuous jump of pressure and velocity of the medium.

The following relationships have been derived for the changes across the shock front, propagated into a body at rest, from the laws of conservation of mass, momentum, and energy:

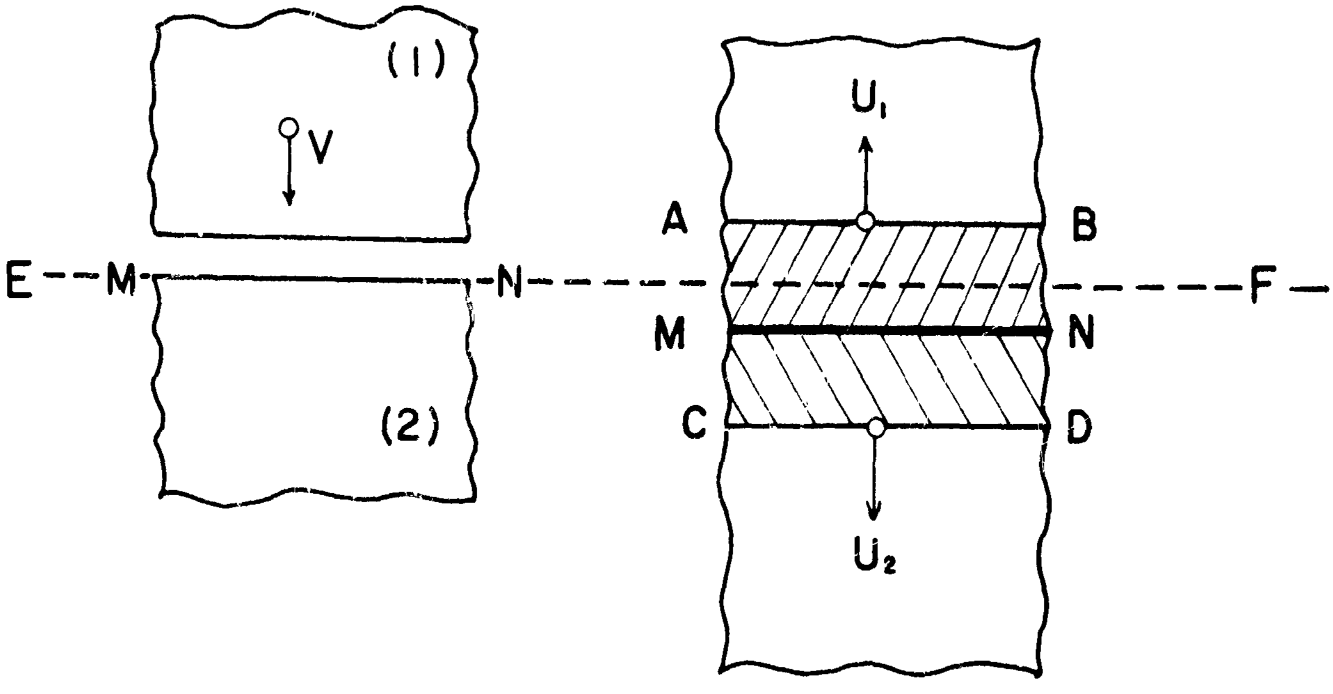
$$U \rho_0 = (U - u)\rho \qquad (1)$$

$$P = \rho_0 U u \qquad (2)$$

and

$$E = P / 2 (1 / \rho_0 - 1 / \rho) \qquad (3)$$

where U is shock velocity; u is particle velocity behind the shock front; ρ_0 is the initial density; ρ is the density behind the shock front; P is the change in pressure across the shock front; and E is the change in internal energy across the shock front. These conditions must hold at all



(1)
V
E
M
N
(2)
U₁
A
B
F
M
N
C
D
U₂

times during the course of the impact.

Two boundary conditions further connect the shocks in the two bodies: because the two bodies must remain in contact during the collision, the velocities of the two materials on both sides of the interface must be the same, which is the boundary condition of continuity of particle velocity; and secondly, from Newton's third law, action equals reaction, the pressures in the two shocks must be equal -

$$P_1 = P_2 \quad \text{(continuity of pressure).}$$

Viewed from coordinates fixed with reference to the interface, MN, the particle velocity between the two shocks is zero: the material on each side of the interface appears to an observer, riding on the interface, to be at rest, with shock fronts, AB and CD, moving out into each respective medium at a velocity determined by momentum considerations. In homogeneous media, the shock velocities will remain constant.

Consider now what happens to the several planes: AB, the front of the shock moving upward into medium 1; MN, the plane of common contact between medium 1 and 2; and CD, the front of the shock moving dowaward into medium 2. EF is a fixed plane of reference, at impact being coincident with MN. After unit time, MN will have moved down from EF a distance u, u being the particle velocity in the shock waves; CD will have moved a distance U_2 into medium 2 from EF and will be a distance $(U_2 - u)$ from MN, U_2 being the velocity of the shock in medium 2; and AB will have moved a distance U_1 into medium 1 and will lie at a distance $(U_1 - v)$ upward from EF where U_1 is the shock velocity in medium 1. AB will lie a distance $(U_1 - V) + u$ from MN.

Look now at the compression of the two bodies:

$$\delta_1 = (\rho_1 - \rho_{10}) / \rho_1 = (v_{10} - v) / v_{10} \qquad (4a)$$

$$\delta_2 = (\rho_2 - \rho_{20}) / \rho_2 = (v_{20} - v_2) / v_{20} \qquad (4b)$$

where δ_1 is the compression of medium 1; δ_2 is the compression of medium 2; ρ_{10} and ρ_{20} are the original densities of mediums 1 and 2, respectively; ρ_1 and ρ_2 are densities of compressed mediums 1 and 2, respectively; and the v's are specific volumes.

The mass, m_1, of medium 1 which before impact was contained in the volume U_1, after unit time resides in volume $(U_1 - V + u)$; and the mass, m_2, of medium 2, originally residing in the volume U_2, now resides in volume $(U_2 - u)$. Thus, since by definition

$$\rho_1 = m_1 / (U_1 - V + u) \quad ; \quad \rho_{10} = m_1 / U_1$$

$$\rho_2 = m_2 / (U_2 - u) \quad ; \quad \rho_{20} = m_2 / U_2 \quad ,$$

equations (4 a and b) lead to

$$\delta_1 = \left[m_1 / (U_1 - v + u) - m_1 / U_1 \right] / \left[m_1 / (U_1 - V + u) \right]$$

$$\delta_2 = \left[m_2 / (U_2 - u) - m_2 / U_2 \right] / \left[m_2 / (U_2 - u) \right]$$

which reduce to

$$U_1 = (V - u) / \delta_1 \tag{5}$$

and

$$U_2 = u / \delta_2 \quad . \tag{6}$$

From conservation of momentum

$$m_1 V = u (m_1 + m_2)$$

so that

$$m_2 = m_1 (V - u) / u \quad . \tag{7}$$

By definition and substitution from equations (5) and (6) it follows that

$$m_1 = U_1 \rho_{10} = (V - u) \rho_{10} / \delta_1 \tag{8}$$

and

$$m_2 = U_2 \rho_{20} = u \rho_{20} / \delta_2 \quad . \tag{9}$$

Combining equations (7), (8), and (9) and solving for V yields

$$V = u \left[1 \pm (\rho_{20} \, \delta_1 / \rho_{10} \, \delta_2)^{\frac{1}{2}} \right]$$

and as u cannot exceed V under compression, only the positive root has physical significance. Solving for u gives

$$u = V / \left[1 + (\rho_{20} \, \delta_1 / \rho_{10} \, \delta_2)^{\frac{1}{2}} \right] \qquad (10)$$

and using equation (6) gives

$$U_2 = V / \delta_2 \left[1 + (\rho_{20} \, \delta_1 / \rho_{10} \, \delta_2)^{\frac{1}{2}} \right]. \qquad (11)$$

Now from equation (2)

$$P_2 = \rho_{20} \, U_2 \, u_2 \qquad (2a)$$

where u_2 and U_2 are, respectively, particle and shock velocities measured with respect to the unshocked material. In the original frame of reference, medium 2 is initially at rest so that u_2 equals u, the velocity with which the interface between the two mediums moves, and equation (2a) becomes

$$P = \rho_{20} \, U_2 \, u$$

since $P_2 = P_1 = P$. Note, however, that it is not true that particle velocity, v_1, in medium 1, measured with respect to the unshocked medium, is equal to u. Rather

$$u_1 = V - u$$

and

$$P = \rho_{10} U_1 u_1 = \rho_{10} U_1 (V - u) \quad .$$

Use of equation (2a) leads finally to

$$P = (\rho_{20} / \delta_2) \left\{ V / \left[1 + (\rho_{20} \delta_1 / \rho_{10} \delta_2)^{\frac{1}{2}} \right] \right\}^2$$

which becomes

$$P = \left\{ V / \left[(\delta_2 / \rho_{20})^{\frac{1}{2}} + (\delta_1 / \rho_{10})^{\frac{1}{2}} \right] \right\}^2 \quad . \quad (12)$$

Equations (11) and (12) permit calculations of shock velocity U_2 and contact pressure P for a given impact velocity V, provided the respective equations of state of the two mediums are known.

On the other hand, by measuring V, the velocity of impact, u, particle velocity at the interface, and U_2, the velocity of the shock in the impacted medium, equations (11) and (12) contain only two unknowns, δ_1 and δ_2, hence can be used to compute an equation of state.

If the impact is between two like materials, then from equation (10)

$$u = V / 2$$

that is, particle velocity or interface velocity is exactly one half the velocity of impact and equation (12) becomes

$$P = (\rho_{20} / \delta_2) \quad (V / 2)^2$$

or

$$P = (1 / v_{20}) \left[1 - (v / v_{20}) \right] \quad (V / 2)^2 \quad .$$

Now employing the condition

$$P = \rho_{20} \, u \, U_2 = \rho_{10} \, u_1 \, U_1 = \rho_{10} \, (V - u) \, U_1$$

where u_1 is the particle velocity in medium 1 behind the shock and U_1 is the shock velocity in medium 1, both velocities relative to unshocked medium 1, that is $u_1 = V - u$, it can be shown by substitution that

$$V = u_1 \left[1 + (\rho_{10} \, \delta_2 / \rho_{20} \, \delta_1)^{\frac{1}{2}} \right]$$

and

$$V = \delta_1 \, U_1 \left[1 + (\rho_{10} \, \delta_2 / \rho_{20} \, \delta_1)^{\frac{1}{2}} \right] . \qquad (13)$$

Impedance match method for determining Hugoniot

When a shock wave encounters an interface between two dissimilar materials, as indicated in the figure, two new waves will be generated, a transmitted shock wave and a reflected wave. The relative intensities of these new waves are governed by the respective compressibilities and densities of the two interacting materials. This fact has been used extensively by experimental investigators to establish Hugoniot curves. (Duvall, 1961; Al'tshuler, Krupnikov and Brazhnik, 1958; Walsh, Rice, McQueen and Yarger, 1957; McQueen and Marsh, 1960) Themethod is known as an impedance match method. The basic stratagem is to generate a shock of known or measurable strength in a material whose Hugoniot curve is well established, allow the shock to be reflected at an interface between the "known" material (medium I in figure) and the material for which the Hugoniot is being sought (medium II in figure), and then measure the velocity of the transmitted shock. This procedure is repeated for shocks of several strengths in order to obtain the points needed to trace a full Hugoniot curve.

The basis of the method lies in judicious application of the conservation equations and appreciation of the boundary conditions. At the interface, two boundary conditions must be met: continuity of pressure, and continuity of particle velocity. The system of reflected and transmitted shocks which developsafter the shock reaches the interface is

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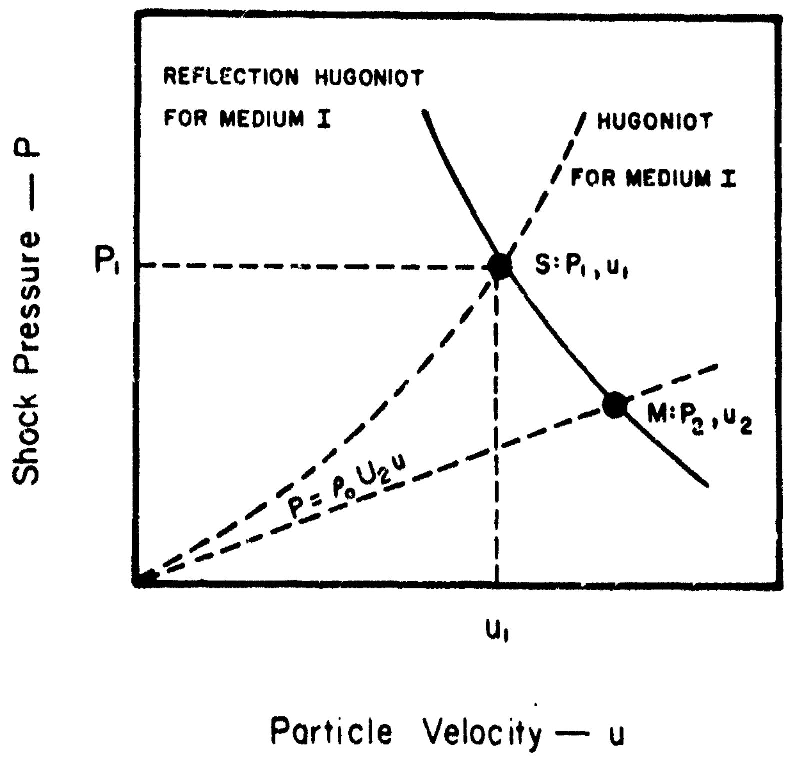
The basis of the method lies in judicious application of the conservation equations and appreciation of the boundary conditions. At the interface, two boundary conditions must be met: continuity of pressure, and continuity of particle velocity. The system of reflected and transmitted shocks which developsafter the shock reaches the interface is illustrated in the figure. The pressure, P_2, at the interface is the pressure of the transmitted shock and at the same time represents the sum of the pressure, P_1, of the incident wave and P_1', the pressure of the reflected wave. The pressure, P_1', may be either positive or negative, depending upon the impedance match between the two materials. The situation at the interface can be defined by the point (P_2, u_2) on a pressure versus particle velocity diagram. Each shock of a different strength locates a new point and the locus of all such points defines the unknown Hugoniot. The problem is to locate each of the (P_2, u_2) points. Three pieces of information are sufficient to establish any one point such as M in the figure: the pressure, P_1, of the incident shock, the Hugoniot curve for medium I, and the velocity of the shock transmitted into medium II. The pressure, P_1, the Hugoniot, and conservation equations fix the point S which has the coordinates P_1 and u_1. A curve, the reflection Hugoniot or cross curve, is drawn through S. This curve is a mirror image about the point S of the P-u curve or Hugoniot for medium I, which is assumed known, and portrays on the P-u diagram possible states of material I with respect to the state (P_1, u_1). The point M representing the state (P_2, u_2) must lie on this curve. The point M must also lie on the line

$$P = \rho_0 U_2 u ,$$

where U_2 is the velocity of the shock transmitted in medium II.


REFLECTION HUGONIOT
FOR MEDIUM I
HUGONIOT
FOR MEDIUM I
S: P_1, u_1
M: P_2, u_2
$P = \rho_0 U_2 u$
P_1
u_1
Shock Pressure — P
Particle Velocity — u

This relationship follows from application of the conservation equations. With ρ_0 and U_2 both known, the line can be drawn and its intersection with the reflection Hugoniot locates M.

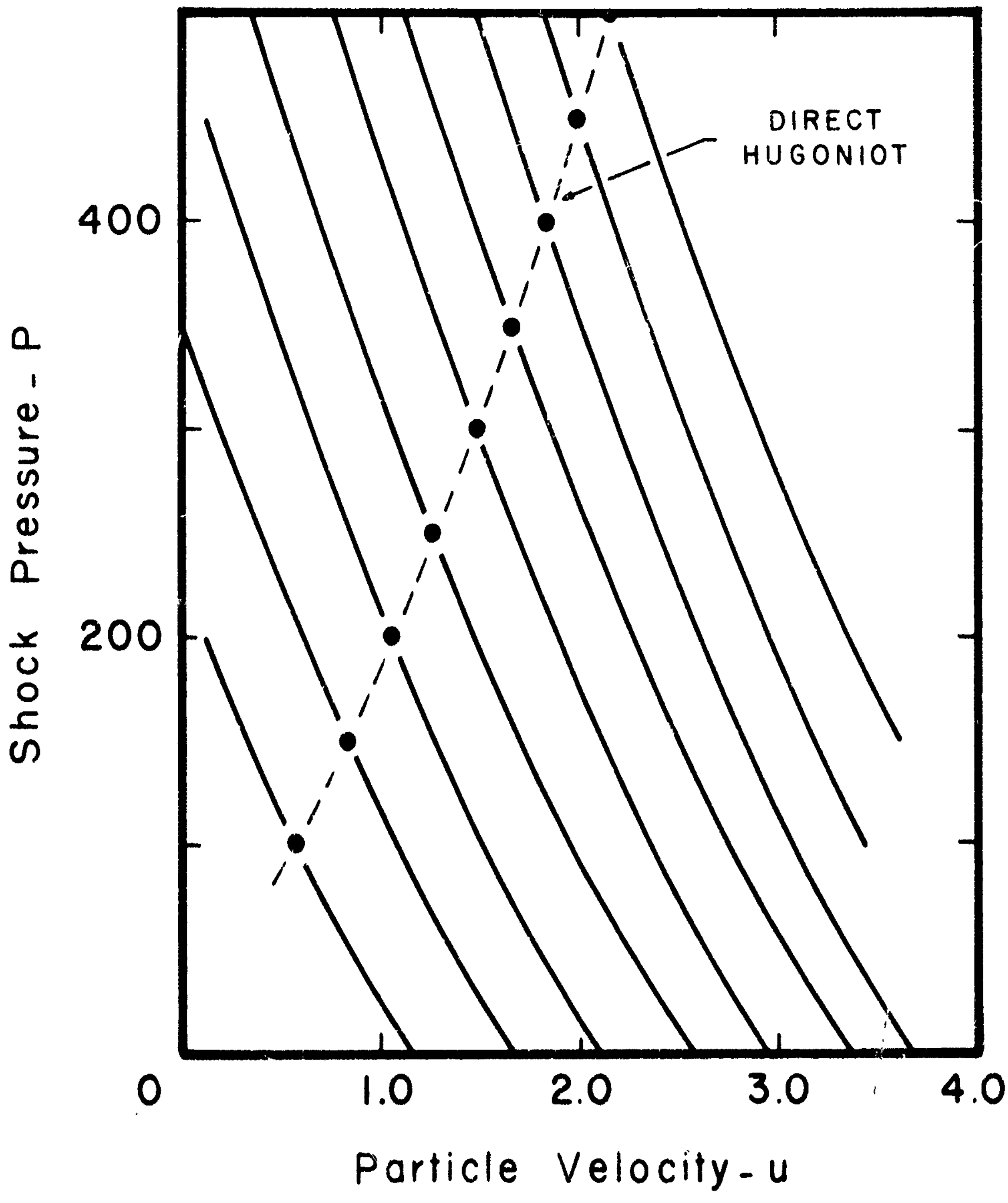
One of the best established Hugoniots is that for 24 ST aluminum (Rice, McQueen and Marsh, 1958). A number of cross curves for this material are given in the accompanying table.

Pressure versus particle velocity curves for 24 ST aluminum*

P	Particle velocity								
0	1.17	1.66	2.10	2.53	2.95	3.38	3.63	-	-
100	0.58	1.08	1.78	1.96	2.35	2.75	3.08	3.45	-
150	0.34	0.83	1.29	1.71	2.10	2.49	2.83	3.19	3.61
200	0.12	0.61	1.06	1.48	1.88	2.26	2.61	2.96	3.38
250	-	0.40	0.85	1.27	1.66	2.04	2.39	2.74	3.13
300	-	0.20	0.65	1.07	1.47	1.84	2.20	2.54	2.95
350	-	0.01	0.47	0.88	1.28	1.65	2.01	2.35	2.69
400	-	-	0.29	0.70	1.11	1.47	1.83	2.18	2.51
450	-	-	0.12	0.53	0.94	1.30	1.66	2.00	2.34
500	-	-	-	0.36	0.77	1.14	1.50	1.84	2.15

Source: Rice, McQueen and Walsh, 1958

* Each underlined number is a particle velocity in mm/μsec for the corresponding shock pressure in kilobars. Remaining numbers in a given column trace out associated cross curves.



DIRECT
HUGONIOT
400
200
Shock Pressure - P
0
1.0
2.0
3.0
4.0
Particle Velocity - u

Calculation of temperatures

associated with passage of shock wave

The temperature behind the shock, T_H, is calculated from the equation

$$T_H = T_o \exp \gamma(1 - v_1 / v_o) +$$

$$\exp \gamma(v_1/v_o) \int_{v_o}^{v_1} \left\{ (1/2) \left[(dP/dv)(v_o - v) + P \right] \exp \gamma(v/v_o)/C_v \right\} dv_{HUG.}$$

where γ is Grüneisen's constant given by

$$\gamma = (dP / dT)_v (v_o / C_v) \quad .$$

The integration is performed numerically along the Hugoniot curve.

The equation is exact but the variation of C_v and $(\partial P / \partial T)_v$ with volume is not known. In most calculations these are assumed constant. When the Debye temperature is low, as it is for alkali halides, the assumption of constant specific heat, C_v, is reasonable.

The calculation of the residual or final temperature, T_A, after passage of the shock is made utilizing the relationship

$$T_A = T_H \exp (\partial P/\partial T)_v (1/C_v)(v_H - v) = T_H \exp \gamma\left[(v_H/v_o) - (v/v_o)\right]$$

where T_H and v_H are the known conditions at any point, taken here as the Hugoniot point. To fix the final temperature and volume, the known relation

$$(v - v_0)_{P = 0} = v_0 \alpha (T - T_0)_{P = 0}$$

along the P = 0 isobar is used. Here T_0 and v_0 refer to the temperature and specific volume and α is an average value of the thermal coefficient of volume expansion.

Source: Walsh and Christian, 1955

Empirical equations

Much of the Hugoniot data can be summarized in the form of empirical equations and several of the investigators have done this. The equations which they give are extremely useful in making thermodynamic computations. Some, such as the analytical form used by the Los Alamos group (Rice, McQueen and Walsh, 1958) are particularly adaptable to computer calculations. Others (Wagner, Waldorf and Louie, 1960; Al'tshuler, Krupnikov and Brazhnik, 1958) have a more theoretical basis, their derivation depending upon the empirical linear relationship between shock velocity and particle velocity.

A number of these empirical relationships plus appropriate constants are given on the following pages.

Empirical equation

Aluminum

Relationship: Pressure versus volume change

Material: 6061-T6 aluminum

Source: Lundergan, 1961a

Equation:

$$P = 1046.8 \left[1 - (v / v_0) \right] \quad \text{kilobars} \quad P < 6.3$$

$$P = 795.5 - 794.0 \, (v / v_0) \quad \text{kilobars} \quad 6.3 < P < 31$$

Relationship: Pressure as function of free surface velocity

Material: 24 ST aluminum

Source: Walsh and Rice, 1957

Equation:

$$U = 5.190 + 20.77 \log_{10} \left[(u_{fs} + 10.895) / 10.895 \right]$$

where u_{fs} is free surface velocity. Velocities are in kilometers per second. Equation is applicable in pressure range 30 to 500 kilobars.

Empirical equation

Metals

Relationship: Pressure versus volume change

Materials: Several metals and Lucite

Sources: Rice, McQueen and Walsh, 1958; Walsh, Rice, McQueen and Yarger, 1957

Equation: Analytical fits of Hugoniot curves having form

$$P = A\mu + B\mu^2 + C\mu^3$$

where $\mu = (\rho/\rho_0) - 1$ and A, B, and C are constants. Actually this is a two parameter fit of data since the ratio B/A is determined by theory.

Table: Values of constants. Pressure range in which fit has been made is up to about 500 kilobars.

Metal	A	B	C
Beryllium	1182	1382	0
Cadmium	479	1087	2829
Chromium	2070	2236	7029
Cobalt	1954	3889	1728
Copper	1407	2871	2335
Gold	1727	5267	0
Lead	417	1159	1010
Magnesium	370	540	186
Molybdenum	2686	4243	733
Nickel	1963	3750	0
Silver	1088	2687	2520

Table: continued

Metal	A	B	C
Thorium	572	646	855
Tin	432	878	1935
Titanium	990	1168	1246
Zinc	662	1577	1242
24 ST aluminum	765	1659	428
Brass	1037	2177	3275
Indium	496	1163	0
Niobium	1658	2786	0
Palladium	1744	3801	15230
Platinum	2760	7260	0
Rhodium	2842	6452	0
Tantalum	1790	3023	0
Thallium	317	938	1485
Zirconium	934	720	0
Lucite	83	163	322

Empirical equation

Metals

Relationship: Pressure versus volume change

Materials: Several metals

Source: Al'tshuler, Krupnikov and Brazhnik, 1958

Equation:

$$P = a^2 (v_o - v) / (b - 1)^2 v^2 \left\{ \left[b / (b - 1) \right] - v_o / v \right\}^2$$

where a and b are constants in relationship

$$U = a + b u$$

between shock velocity U and particle velocity u. Equation is applicable in range 300 to 3000 kilobars

Table: Values of constants

Material	a (mm/μsec)	b	ρ g/cc
Copper	3.90	1.46	8.93
Zinc	3.20	1.45	7.14
Silver	3.30	1.54	10.49
Cadmium	2.65	1.48	8.64
Gold	3.15	1.47	19.30
Lead	2.30	1.27	11.34
Bismuth	2.00	1.34	9.80
Iron	3.80	1.58	7.80

Empirical equation

Plastics

Relationship: Pressure versus density change

Materials: Plastics and plastic composites

Source: Wagner, Waldorf and Louie, 1962

Equation:

$$P = A\,(\eta - 1)\,\eta / (K - \eta)^2 \text{ kilobars}$$

where $\eta = \rho / \rho_0$, and A and K are constants given in table.

Table: Values of constants

Material	A	K	Pressure range (kilobars)
Chopped Nylon Phenolic	59.1	2.24	39-274
Series 124 Resin	46.3	1.96	45-147
Avcoat	56.1	2.29	14-150
AVCO Phenolic Fiberglass	2,530	7.44	0-180
Tape Wound Nylon Phenolic	1.020	3.38	20-86
GE Phenolic Fiberglass	60,200	18.0	28-111
Oblique Tape Wound Refrasil	322,000	94.6	20-84
RAD 58B	184	-2.17	5-46
Avcoite	33.6	1.40	34-118
Pyrolytic Graphite	40.8	1.40	50-470
Kel-F	170.2	2.65	32-97
Polyethylene	11.9	1.73	2-65
Nylon	154	2.60	4-80
Plexiglas	217	2.80	17-160
Polystyrene	230	2.66	4-59
Teflon	45.1	2.08	10-76

Empirical equation

Rocks

Relationship: Pressure versus volume change

Materials: Tuff, sand, and shale

Source: Anderson, Fisher, McDowell and Weidermann, 1963.

Data taken from Lombard, 1961

Equation:

$$P = C\left[(v_0 / v)^n - 1\right] / \left[\mu - (v_0 / v)\right]$$

where C, μ, and n are constants, values of which are given in table below; v_0 is specific volume of zero pressure; and v is the volume of the same mass at pressure P.

Table: Values of constants

Material	μ	n	C (kb)	v_0	Approx. pressure range of original data (kilobars)
Tuff, Wet Volcanic	4	2	260	0.535	53-270
Tuff, Dry Volcanic	4	4	26	0.588	31-202
Sand (wet)	4	2	317	0.523	90-26
Oil shale (wet)	4	2	180	0.663	110-164
Oil shale (dry)	4	2	400	0.607	100-300

Empirical equation

Granite

Relationship: Pressure versus volume change

Material: Granite

Source: Lombard and Adelman, 1961

Equation:

$$P = 194\ (\Delta v / v_o) / \left[\ 1 - 1.42\ (\Delta v / v_o)\ \right]^2 \text{ kilobars}$$

$$200 < P < 900$$

where $\Delta v = v - v_o$

Empirical equation

Marble

Relationship: Pressure versus density change

Material: Marble, light gray with an initial density of 2.70 gm/cc

Source: Dremin and Adadurov, 1959

Equations:

$$P = 42.6 \left[(\rho/\rho_o)^{7.23} - 1 \right] \text{ kilobars} \quad 0 < P < 147$$

and

$$P = 106 \left[(\rho/\rho_o)^{4.1} - 1 \right] \text{ kilobars} \quad 156 < P < 500$$

Phase change occurs between 147 and 156 kilobars

Summary of data and calculations

for metals at 3,500 kilobars

Metal	Relative compression at 3,500 kb	Gram atomic volume		Ratio of gram atomic volume at zero pressure to gram atomic volume at 3,500 kb
		zero pressure	3,500 kb	
Iron	1.67	7.12	4.26	1.7
Copper	1.70	7.11	4.18	1.7
Zinc	1.89	9.16	4.84	1.9
Silver	1.71	10.28	6.01	1.7
Cadmium	1.93	13.01	6.72	1.9
Tin	2.16	16.30	7.54	2.2
Gold	1.59	10.22	6.43	1.6
Lead	2.21	18.27	8.25	2.2
Bismuth	2.27	21.32	9.39	2.3

Metal	Shock velocity mm/ sec		Ratio of shock velocity at 3,500 kb to shock velocity at zero pressure
	zero pressure	3,500 kb	
Iron	4.63	10.53	2.3
Copper	3.95	9.75	2.5
Zinc	2.92	10.19	3.5
Silver	3.08	8.96	2.9
Cadmium	2.34	9.15	3.9
Tin	2.64	9.44	3.6
Gold	2.98	6.99	2.4
Lead	1.91	7.5	3.9
Bismuth	1.85	7.99	4.3

Source: Al'tshuler, Krupnikov and Brazhnik, 1958

CONSTANTS RELATING SHOCK VELOCITY, U, TO PARTICLE VELOCITY, u, IN LINEAR RELATIONSHIP

$$U = a + b u$$

Material	a (mm/µsec)	b	Pressure range (kilobars)	Reference
Alluvium, Dry Desert	1.80	1.11	38-351	(1)
Alluvium, Nevada	1.3	1.35	39-502	(2)
Aluminum, 24 ST	5.30	1.43	42-209	(3)
Aluminum, 2S	5.26	0.70	141-333	(4)
Andesite	4.08	1.54	42-115	(5)
Antimony	2.06	1.61	248-1175	(6)
Avcoat	1.75	1.78	14-150	(7)
Avcoite	3.01	3.53	34-118	(7)
Basalt	5.24 2.58	-0.39 1.64	40-234 234-769	(1);(5)
Beryllium	7.98	1.09	142-283	(8);(9)
Bismuth	2.12 1.26	1.31 2.00	185-446 446-3450	(8);(10)
Brass	3.47	1.69	221-473	(8)
Cadmium	2.44	1.67	228-3490	(6);(8);(10)
Chromium	5.22	1.47	235-1379	(6);(8)
Cobalt	4.75	1.33	244-1603	(6);(8)
Copper	3.99	1.50	216-3800	(6);(8);(10)
Dolomite	6.64	0.47	223-417	(5)
Gold	3.11	1.50	273-5130	(6);(8);(10)
Granite	5.41 2.61	0.18 1.41	68-337 337-884	(5);(11);(12)
Granite, Shoal	4.30	0.87	160-285	(1)

$U = a + b u$

Material	a (mm/μsec)	b	Pressure range (kilobars)	Reference
Graphite, Pyrolytic	2.80	4.66	50-85	(7)
	4.75	1.72	85-116	(7)
	4.06	1.76	30-470	(13)
	4.31	1.69	100-300	(14)
Halides:				(5);(15)
Cesium Bromide (single crystal)	2.10	1.36	146-328	
Cesium Chloride	2.14	1.50	60-318	
Cesium Iodide (single crystal)	1.80	1.38	140-324	
Lithium Bromide	2.80	1.27	136-300	
Lithium Chloride	4.15	1.25	121-263	
Lithium Fluoride	5.00	1.50	155-328	
Lithium Iodide	2.89	0.89	205-320	
Potassium Bromide	1.50	1.75	112-264	
Potassium Chloride	1.92	1.75	40- 229	
Potassium Fluoride	2.44	1.60	117-266	
Potassium Iodide	1.55	1.50	110-278	
Rubidium Bromide	1.52	1.55	112-286	
Rubidium Chloride	1.52	1.63	109-268	
Rubidium Iodide	1.33	1.50	117-279	
Sodium Bromide	2.59	1.33	58-305	
Sodium Chloride (rock salt; single crystal)	3.60	1.27	52-882	
Sodium Iodide	2.15	1.38	134-312	
Indium	4.85	1.17	213-405	(8)
Iron	3.8	1.58	358-4000	(8);(10)
Kel-F	1.73	1.61	32-97	(7)

$U = a + b u$

Material	a (mm/μsec)	b	Pressure range (kilobars)	Reference
Lead	2.03	1.52	203-1383	(6);(8)
	2.30	1.27	390-3700	(10)
Limestone	1.30	3.33	53-130	(5)
	3.92	0.95	130-420	(5)
	1.11	2.07	420-817	(5)
Liquids:				(16)
Acetone	1.88	1.39	46-106	
Benzene	1.88	1.53	52-121	
Bromoethane	1.54	1.37	68-157	
Carbon Disulfide	2.02	0.95	59-130	
Carbon Tetrachloride	1.56	1.47	74-171	
Ethyl Ether	1.65	1.47	42-96	
Ethyl Alcohol	1.68	1.38	47-110	
Glycerine	2.41	1.63	76-169	
Hexane	1.87	1.42	42-96	
Mercury	1.58	1.96	226-463	
Methanol	1.73	1.50	47-110	
Mononitrotoluene	2.17	1.50	66-152	
N-Amyl Alcohol	1.98	1.55	51-115	
Toluene	1.72	1.66	52-122	
Water	2.20	1.33	32-419	
Magnesium	4.49	1.27	116	(8);(9)
Marble (dark)	1.66	4.00	156-296	(5)
	6.36	0.65	296-468	
Marble (light)	5.41	1.38	171-297	(5)
	6.63	0.53	297-418	
Marble (USSR)	3.43	2.00	49-146	(17)
	4.03	1.31	146-529	

$U = a + b\,u$

Material	a (mm/μsec)	b	Pressure range (kilobars)	Reference
Molybdenum	5.16	1.24	254-1633	(6);(8)
Nickel	4.65	1.45	235-1490	(6);(8)
Niobium	4.45	1.21	245-482	(8);(9)
Nylon	2.29	1.63	5-80	(7)
Oil-Sand	2.98	1.17	98-634	(5)
Oil-Shale (dry)				
High grade	3.15	1.38	96-219	(5)
Medium grade	4.23	1.01	119-279	
Low grade	3.55	1.43	117-286	
Oil-Shale (wet)	3.34	0.68	110-164	(5)
Palladium	3.76	1.99	263-531	(8)
Phenolic, AVCO Phenolic Fiberglass	2.29 1.31	0.87 2.00	50-180 0-50	(7)
Phenolic, G E Phenolic Fiberglass	3.27	1.06	28-111	(7)
Phenolic, Chopped Nylon Phenolic	1.80	1.81	39-274	(7)
Phenolic, Tape Wound Nylon Phenolic	3.17	1.35	20-86	(7)
Platinum	3.67	1.41	295-868	(8);(9)
Playa	0.49 2.50	2.00 0.76	40-87 87-271	(1)
Plexiglas	2.38	1.56	17-160	(7)
Polyethylene	1.57	2.38	2-65	(7)
Polystyrene	2.82	1.60	4-59	(7)
RAD 58B	1.20	0.69	5-46	(7)
Refrasil, Oblique Tape Wound	2.45	1.01	20-84	(7)
Resins, Series 124	2.02	2.04	45-147	(7)

$U = a + b u$

Material	a (mm/μsec)	b	Pressure range (kilobars)	Reference
Rhodium	4.68	1.65	278-551	(8);(9)
Sand, Dry Silica (porosity 22%)	Is not a straight line.		58-153	(1)
Sand, Dry Silica (porosity 41%)	See supple-		75-197	(1)
Sand, Water Saturated (porosity 41%)	mentary curves.		90-216	(1)
Silver	3.27	1.54	216-4010	(6);(8);(10)
Steel, Low Carbon	indeterminable		121-305	(3)
Taconite				(5)
Iron	3.58	1.18	126-1140	
Rock	2.80	1.16	74-679	
Tantalum	3.13	1.56	272-547	(8)
Teflon	1.34	1.93	10-76	(7)
Thallium	1.86	1.52	213-1517	(6);(8)
Thorium	2.13	1.28	203-1405	(6);(8)
Tin	2.66	1.47	175-3100	(6);(8);(10)
Titanium	4.78	1.09	168-1060	(6);(8)
Tuff, Dry Volcanic	0.60	0.52	31-82	(1);(5)
	2.28	0.38	82-202	
Tuff, Wet Volcanic	2.21	1.38	53-188	(1);(5)
	4.13	0.50	188-270	
Tungsten	4.01	1.27	395-2074	(6)
Vanadium	5.11	1.21	204-1241	(6)
Zinc	3.71	1.45	186-3260	(6);(8);(10)
Zirconium	3.95	0.78	208-407	(8)

References

(1) Bass, Hawk and Chabai, 1963

(2) McQueen and Marsh, 1961

(3) Katz, Doran and Curran, 1959

(4) Walsh and Christian, 1955

(5) Lombard, 1961

(6) McQueen and Marsh, 1960

(7) Wagner, Waldorf and Louie, 1962

(8) Walsh, Rice, McQueen and Yarger, 1957

(9) Rice, McQueen and Walsh, 1958

(10) Al'tshuler, Krupnikov and Brazhnik, 1958

(11) Alder, 1963

(12) Grine, 1960

(13) Coleburn, Drimmer and Liddiard, 1962

(14) Doran, 1963

(15) Christian, 1957

(16) Walsh and Rice, 1957

(17) Dremin and Adadurov, 1959

TABLES AND GRAPHS

Shock velocity, particle velocity,
pressure, relative volume, and temperature

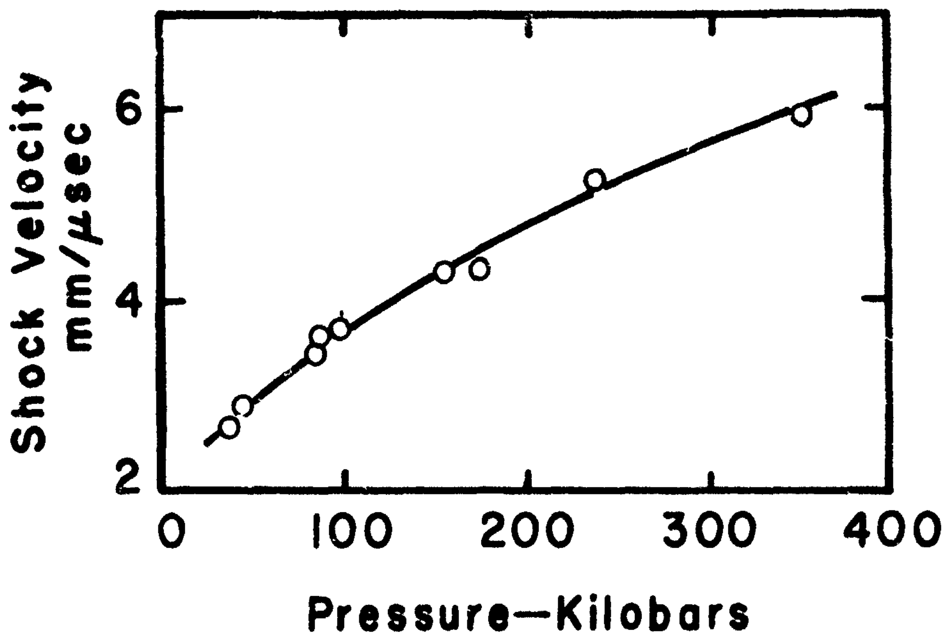
DRY DESERT ALLUVIUM*

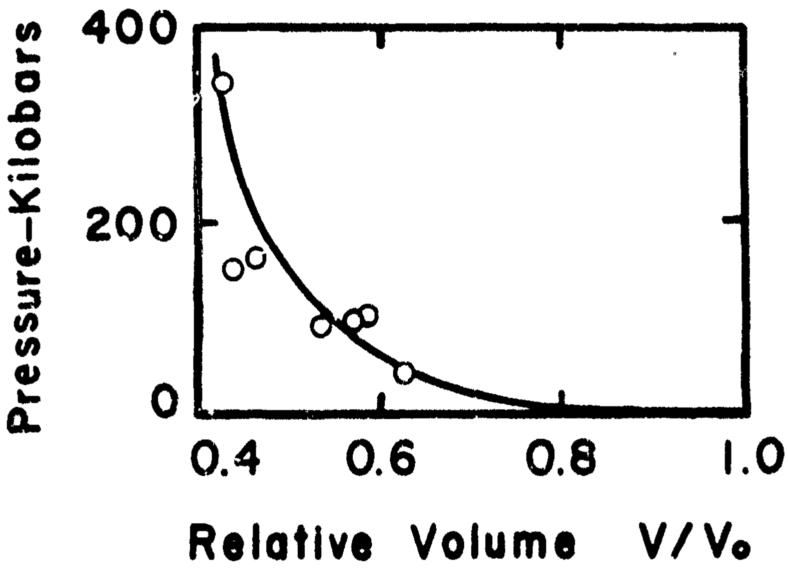
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
2.66	1.00	38	0.624
2.90	0.97	44	0.666
3.41	1.58	83	0.537
3.65	1.57	86	0.570
3.70	1.52	96	0.589
4.35	2.45	156	0.437
4.36	2.39	171	0.462
5.25	3.27	237	0.377
5.89	3.37	351	0.428

$\rho_0 = 1.38 - 1.77$

Source: Bass, Hawk and Chabai (1963)

* Nevada Test Site Area 3





DESERT DRY ALLUVIUM

NEVADA ALLUVIUM

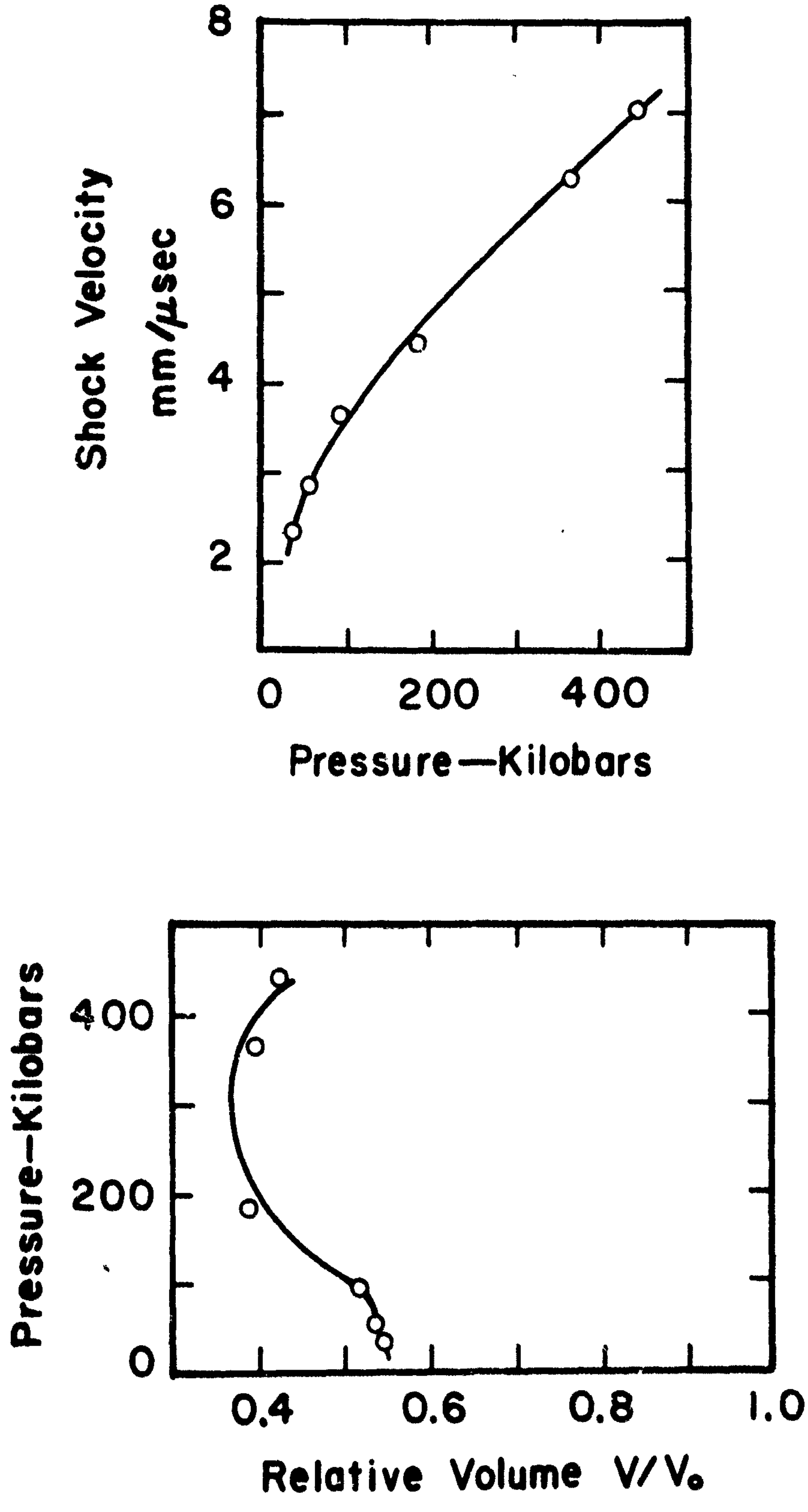
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Fine particles			
2.363	1.074	39.1	0.545
2.892	1.340	59.7	0.537
3.656	1.770	99.7	0.516
4.47	2.737	188.4	0.388
6.274	3.815	368.6	0.392
7.042	4.068	441.1	0.422

$\rho_0 = 1.54$

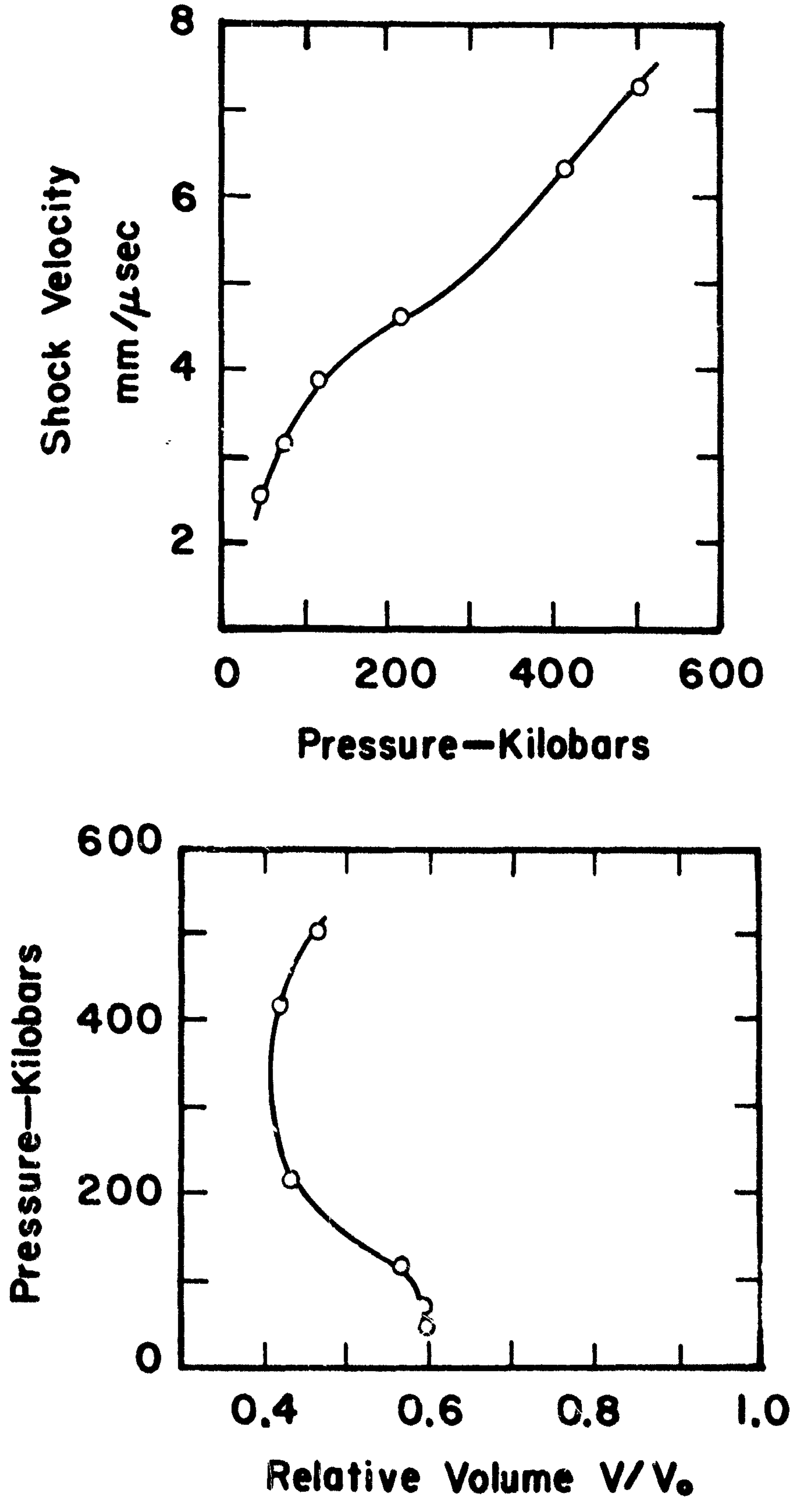
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Coarse particles			
2.553	1.026	47.1	0.598
3.131	1.274	71.8	0.593
3.882	1.678	117.2	0.568
4.597	2.613	216.0	0.432
6.300	3.651	414.0	0.420
7.226	3.859	501.7	0.466

$\rho_0 = 1.8$

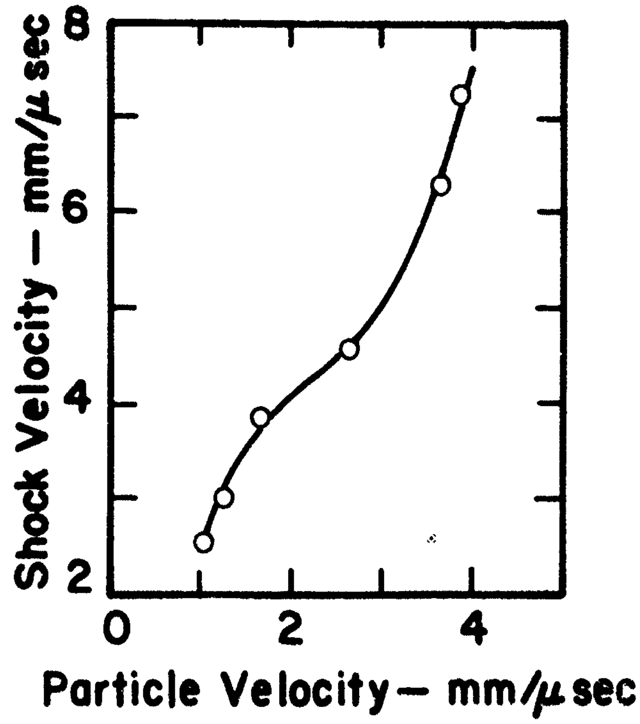
Source: McQueen and Marsh (1961)



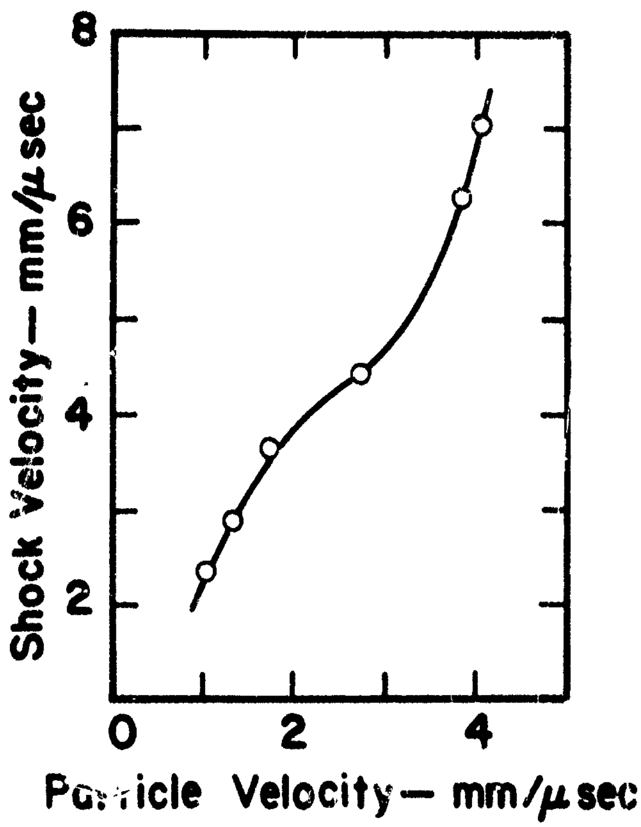
NEVADA ALLUVIUM — Fine Particles



NEVADA ALLUVIUM—Coarse Particles



NEVADA ALLUVIUM— coarse particles



NEVADA ALLUVIUM—fine particles

24ST ALUMINUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.70	0.266	42.27	0.953
5.72	0.291	46.41	0.949
5.78	0.317	51.04	0.945
5.81	0.341	52.32	0.941
5.86	0.368	60.12	0.937
5.91	0.393	64.75	0.934
5.94	0.423	70.05	0.929
6.00	0.455	76.11	0.924
6.06	0.492	83.21	0.919
6.12	0.531	90.77	0.913
6.17	0.582	100.1	0.906
6.30	0.667	117.2	0.894
6.36	0.781	138.6	0.877
6.43	1.267	209.3	0.818

$\rho_0 = 2.785$

Source: Katz, Doran and Curran (1959)

24ST ALUMINUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
6.125	0.571	100	0.9043
6.305	0.712	125	0.8873
6.475	0.831	150	0.8716
6.640	0.947	175	0.8573
6.793	1.057	200	0.8441
6.940	1.165	225	0.8322
7.082	1.267	250	0.8210
7.220	1.368	275	0.8104
7.350	1.465	300	0.8008
7.476	1.561	325	0.7912
7.598	1.654	350	0.7824
7.718	1.744	375	0.7740
7.836	1.832	400	0.7661
7.950	1.920	425	0.7585
8.062	2.003	450	0.7513
8.171	2.082	475	0.7445
8.276	2.170	500	0.7380

$\rho_0 = 2.785$

Source: Walsh, Rice, McQueen and Yarger (1957)

Note: The data presented above is not experimental data, but it is calculated from a great wealth of data run on 24ST aluminum, and is probably the most accurate data available.

24ST ALUMINUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
6.28	0.765	133.9	0.878
6.32	0.761	134.1	0.880
6.34	0.775	136.8	0.878
6.86	1.140	218.0	0.834
7.12	1.304	258.6	0.817
7.12	1.276	253.2	0.821
7.14	1.282	254.9	0.820
7.27	1.396	282.9	0.808
7.26	1.427	288.7	0.804
7.41	1.546	318.9	0.791
7.47	1.570	326.6	0.790
7,46	1.556	323.3	0.791
		328.4	0.789
7.52	1.625	340.2	0.784
7.53	1.646	347.0	0.780

$\rho_0 = 2.785$

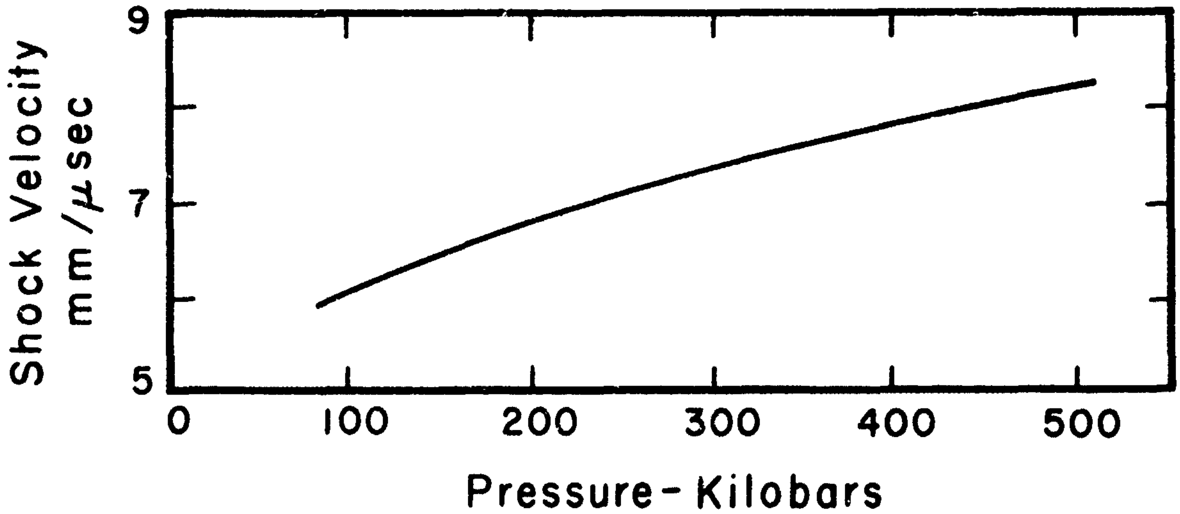
Source: Walsh and Christian (1955)

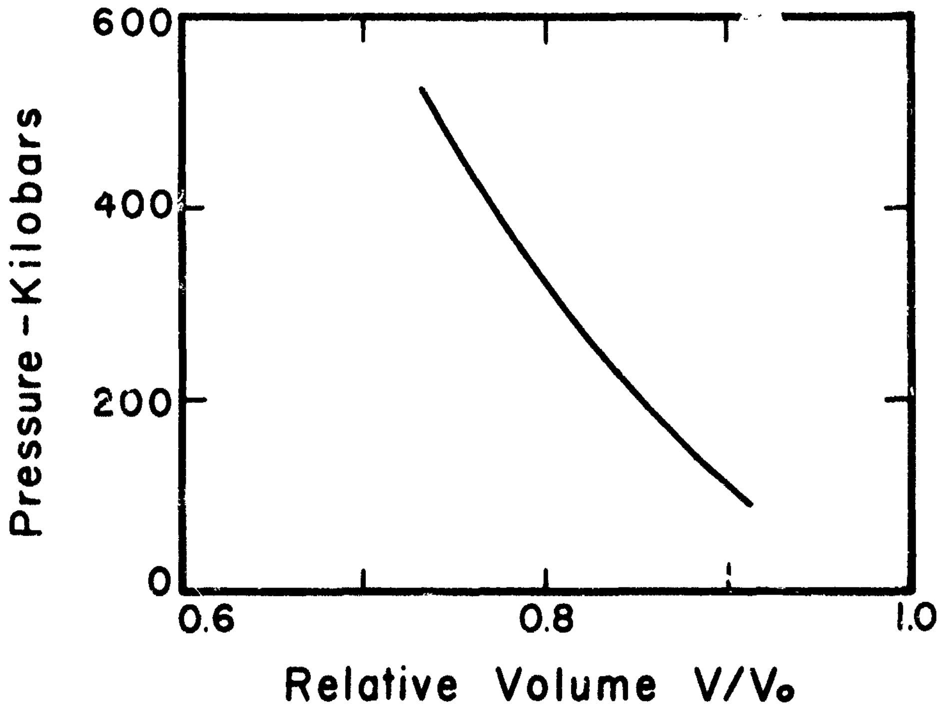
2S ALUMINUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
6.42	1.627	141.3	0.873
6.94	2.355	221.3	0.830
7.44	2.931	295.0	0.803
7.58	3.250	333.3	0.786

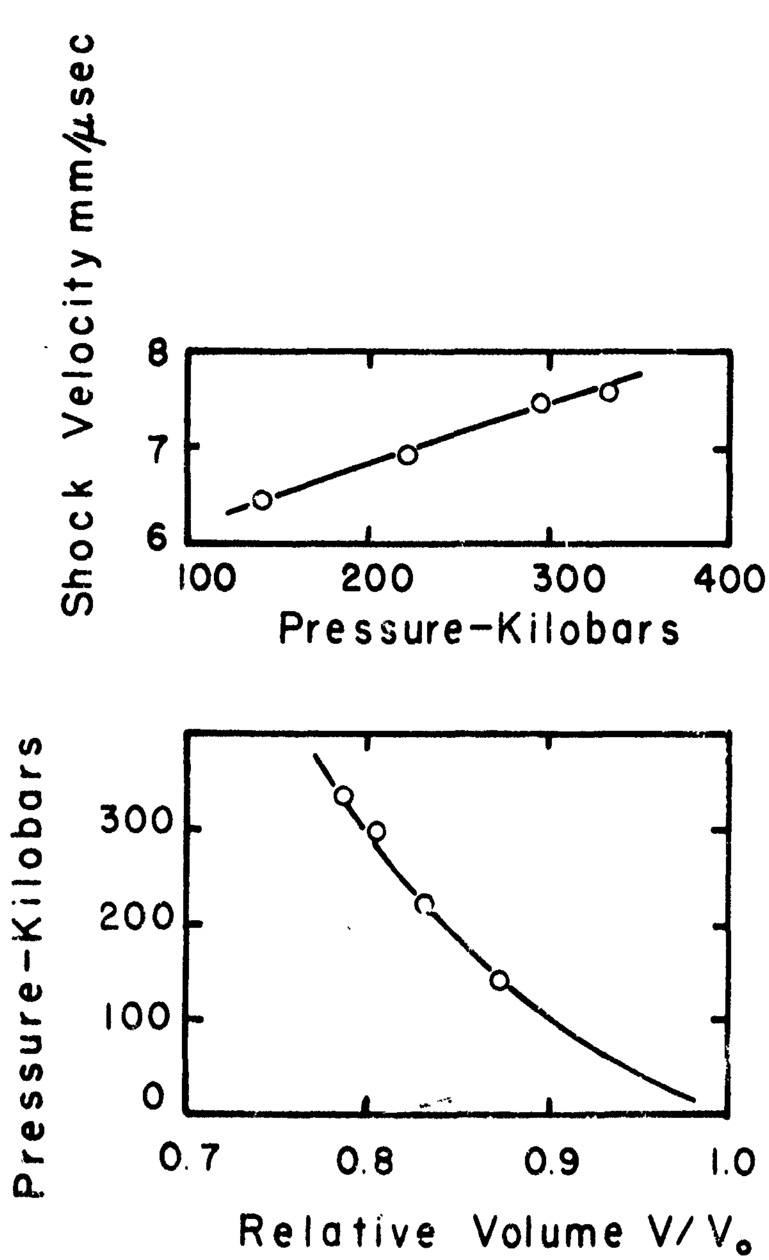
$\rho_0 = 2.706$

Source: Walsh and Christian (1955)

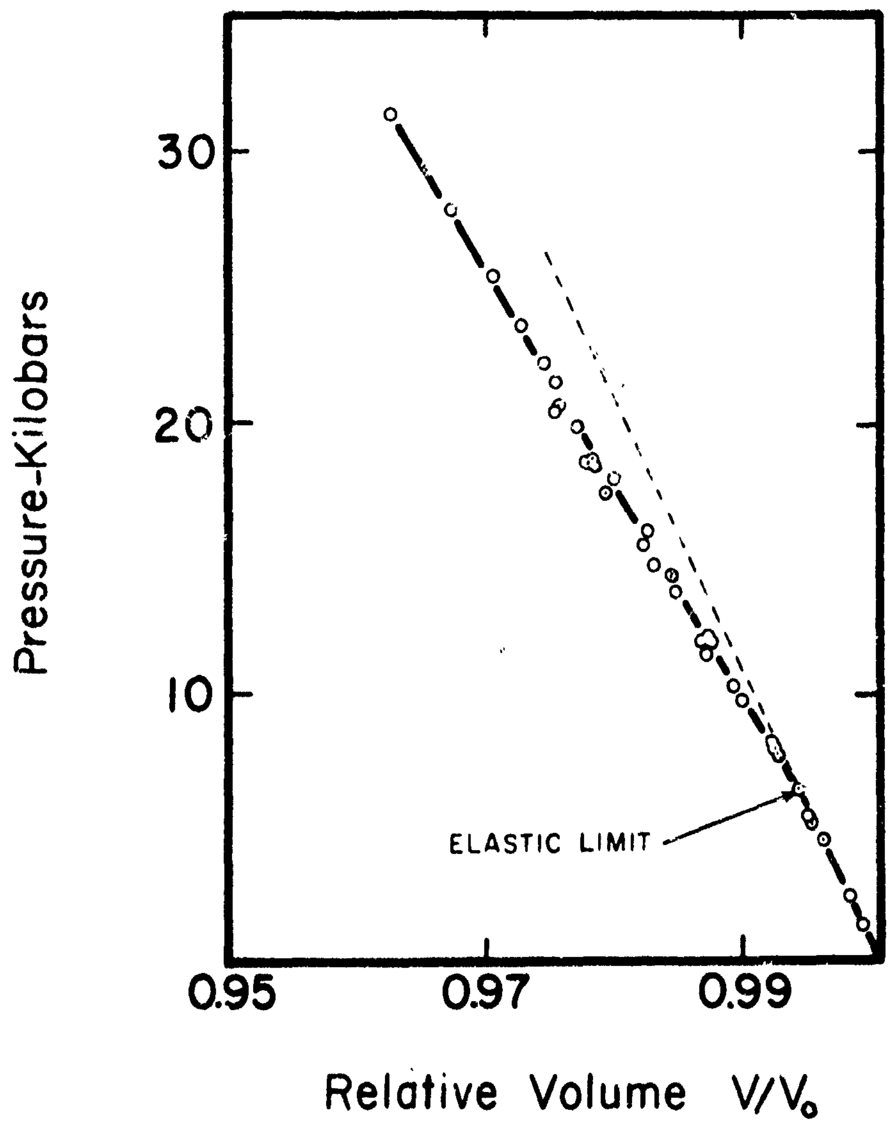




24 ST ALUMINUM


Shock Velocity mm/μsec
8
7
6
100
200
300
400
Pressure-Kilobars
Pressure-Kilobars
300
200
100
0
0.7
0.8
0.9
1.0
Relative Volume V/V₀

2S ALUMINUM



6061–T6 ALUMINUM

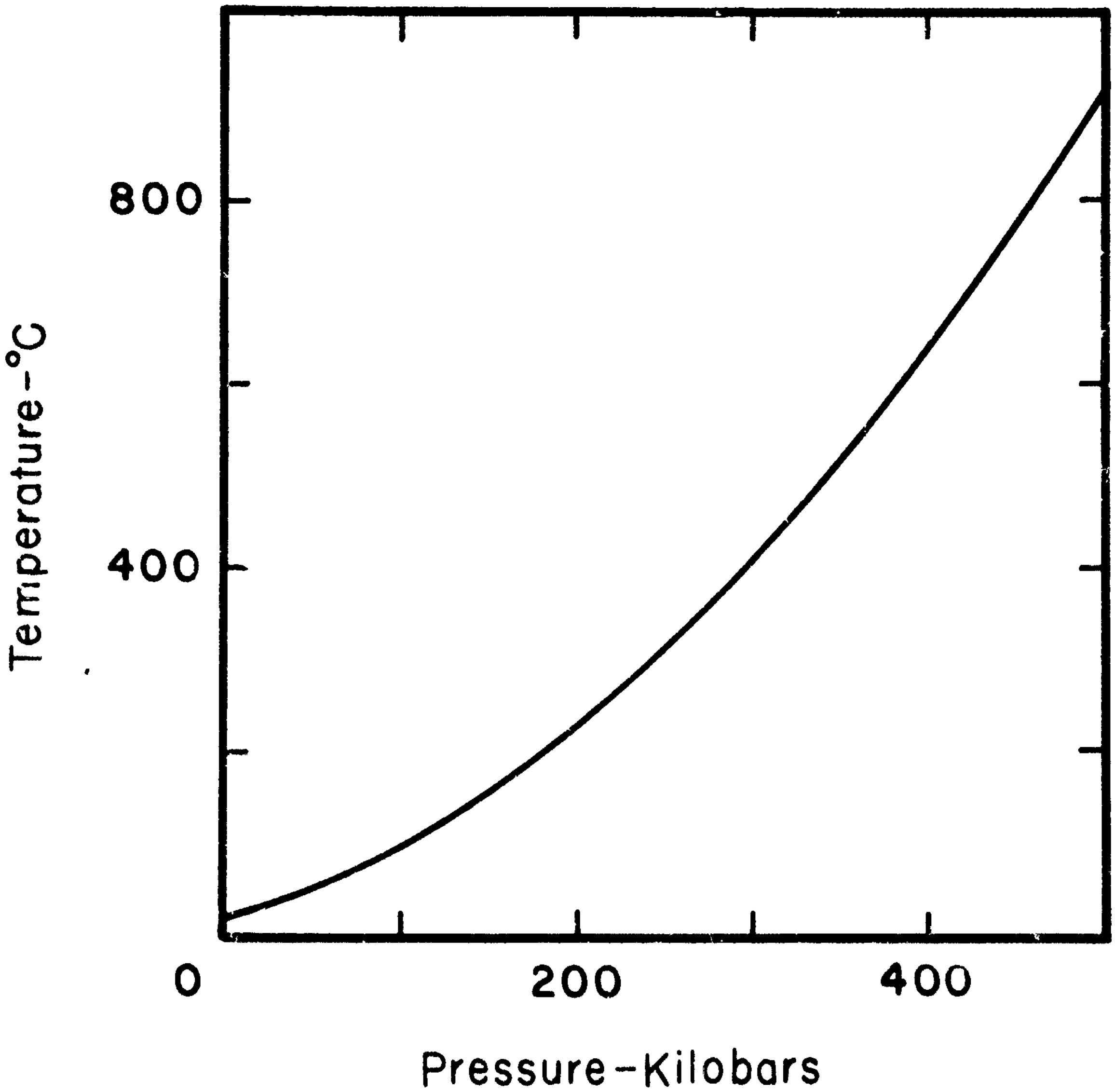
Source: Lundergan, 1961a

Temperatures associated with shock

Aluminum

Pressure (kilobars)	Temperature behind shock (C^o)	Residual temperature (C^o)
0	20	
100	94	
150	153	
200	223	
250	308	
300	405	
350	513	
400	637	
450	770	
500	909	

Source: Rice, McQueen and Walsh, 1958



ALUMINUM

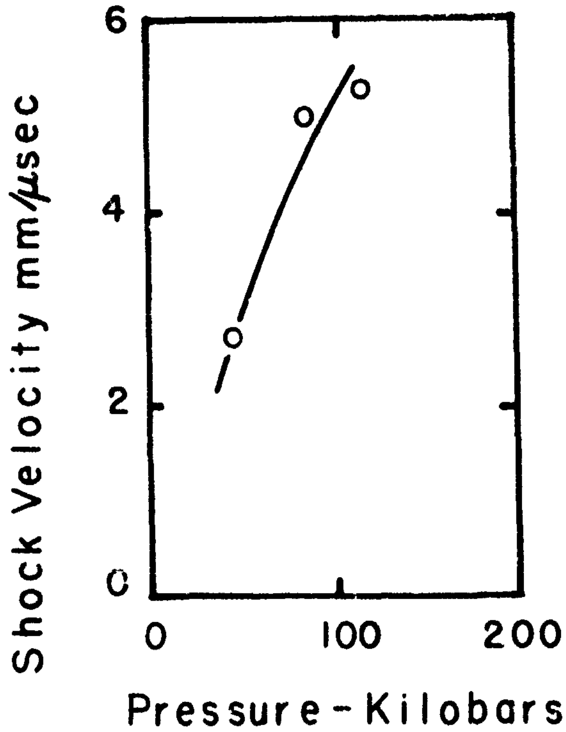
ANDESITE*

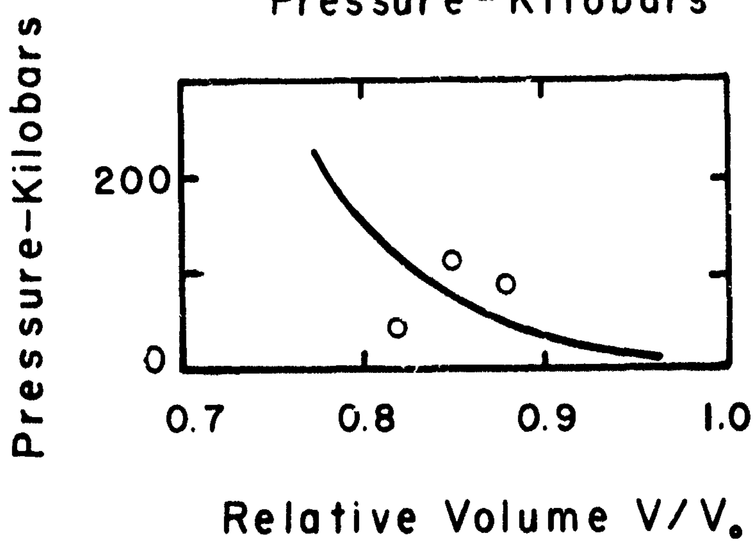
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
2.70	0.51	42	0.815
5.038	0.619	83	0.877
5.344	0.82	115	0.846

$\rho_0 = 2.64$

Source: Lombard (1961)

* Quarried in Marin County, California


6
4
2
0
0
100
200
Shock Velocity mm/μsec
Pressure-Kilobars


200
0
0.7
0.8
0.9
1.0
Pressure-Kilobars
Relative Volume V/V₀

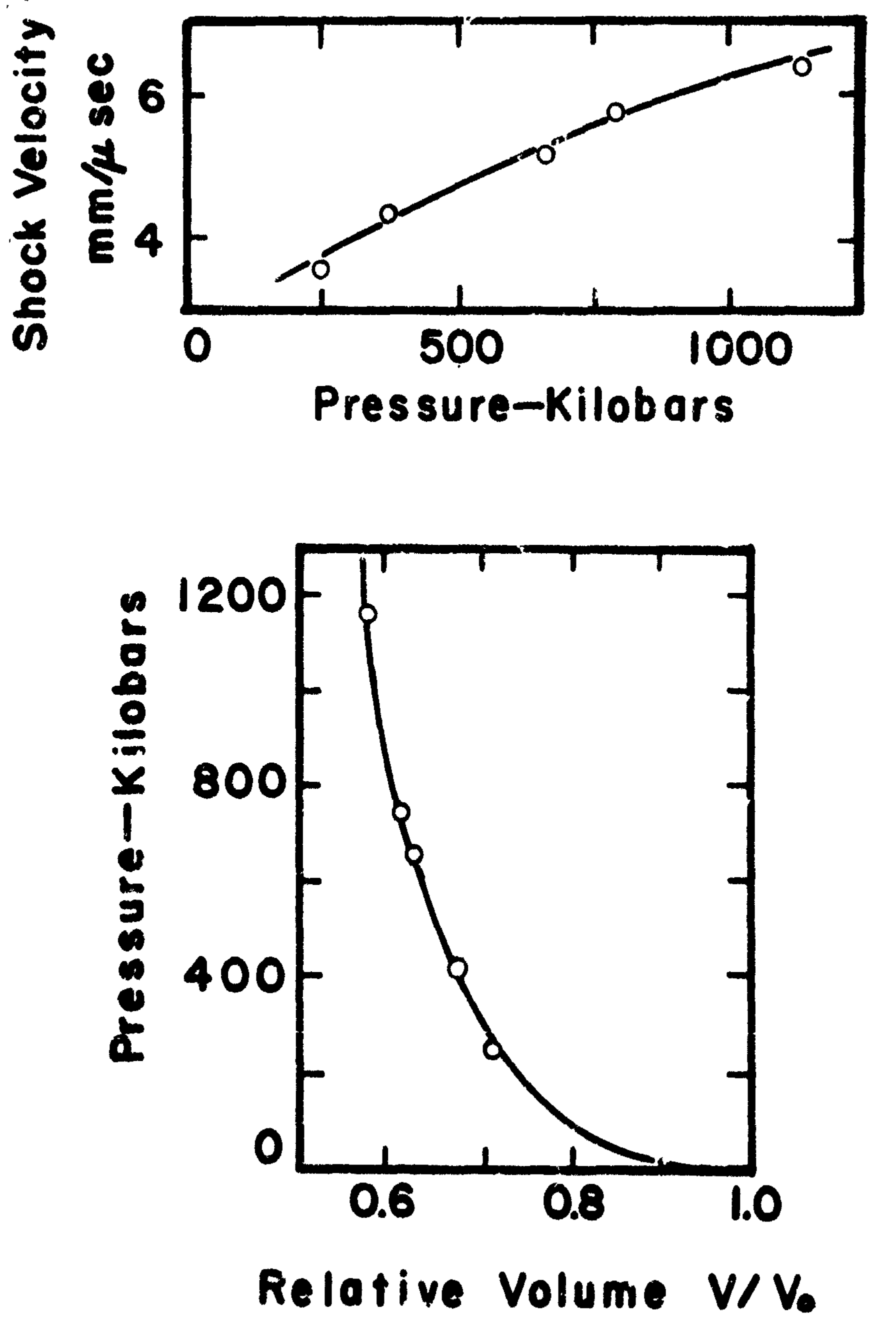
ANDESITE

ANTIMONY

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.61	1.03	248	0.716
3.59	1.03	248	0.713
3.63	1.02	249	0.720
4.30	1.39	400	0.678
4.33	1.38	401	0.681
5.12	1.96	673	0.617
5.06	1.88	637	0.629
5.64	2.19	828	0.611
5.72	2.19	838	0.618
5.71	2.20	843	0.614
6.31	2.70	1142	0.572
6.34	2.73	1158	0.569
6.43	2.73	1175	0.576

$\rho_0 = 6.6$

Source: McQueen and Marsh)1960)


Shock Velocity mm/μ sec
4
6
0
500
1000
Pressure—Kilobars
Pressure—Kilobars
0
400
800
1200
0.6
0.8
1.0
Relative Volume V/V₀

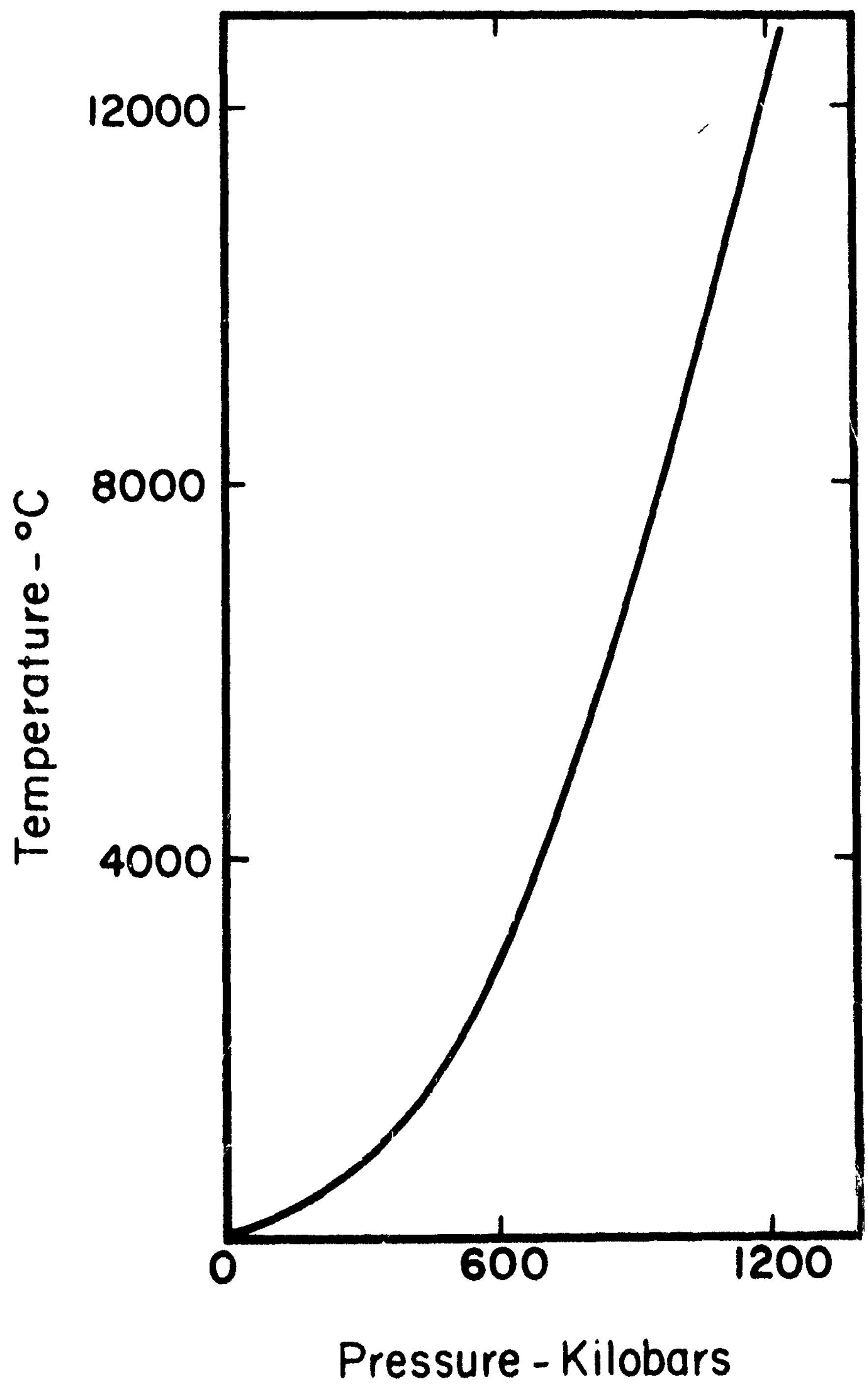
ANTIMONY

Temperatures associated with shock

Antimony

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	
250	577	
500	1827	
750	4727	
1000	8427	
1250	12827	

Source: McQueen and Marsh, 1960



ANTIMONY

AVCOAT

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
2.59	0.477	13.6	0.816
2.83	0.614	19.1	0.784
3.39	0.954	35.6	0.719
4.48	1.46	71.9	0.674
5.82	2.33	149.0	0.600

$\rho_o = 1.10$

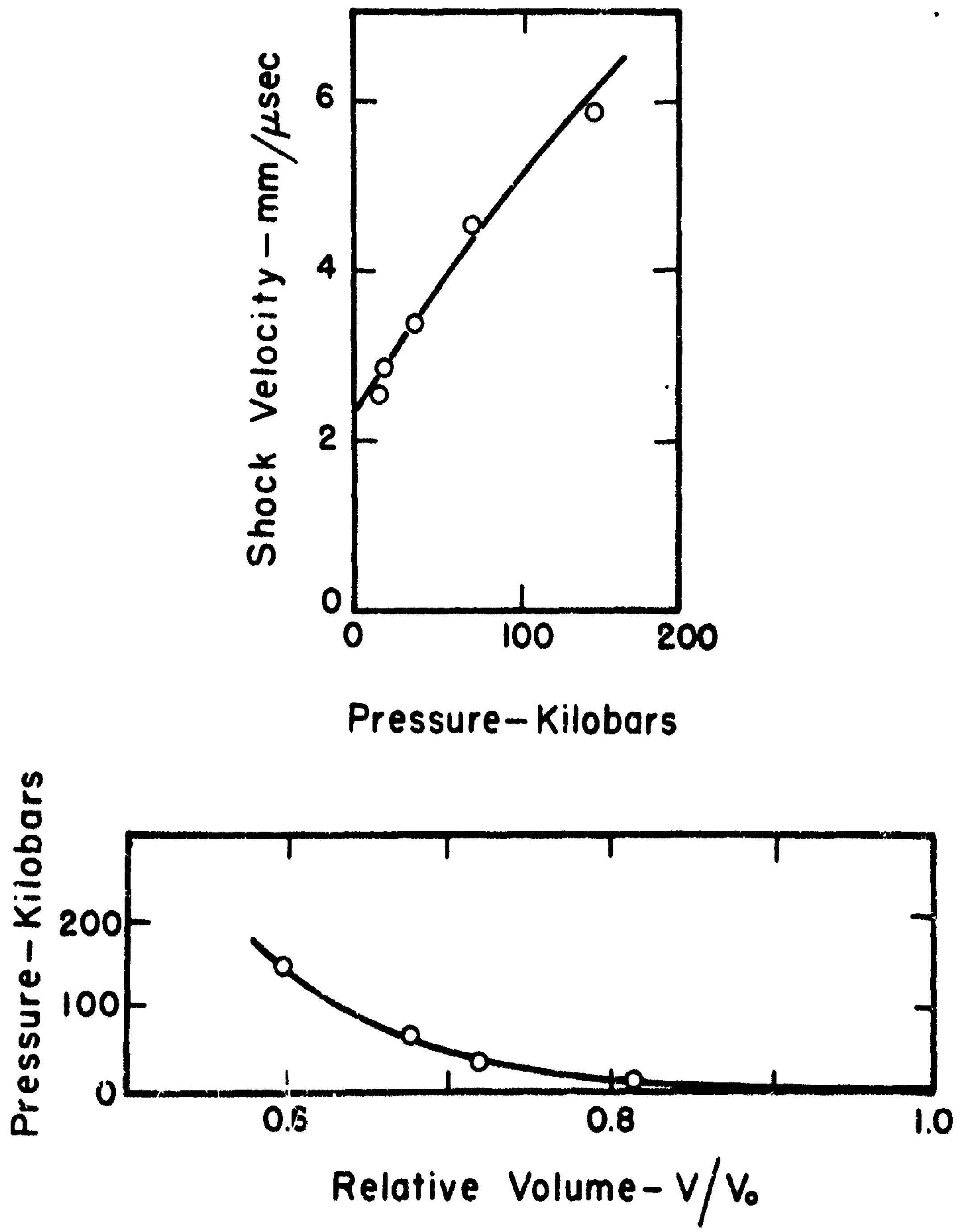
Source: Wagner, Waldorf and Louie (1962)

AVCOITE

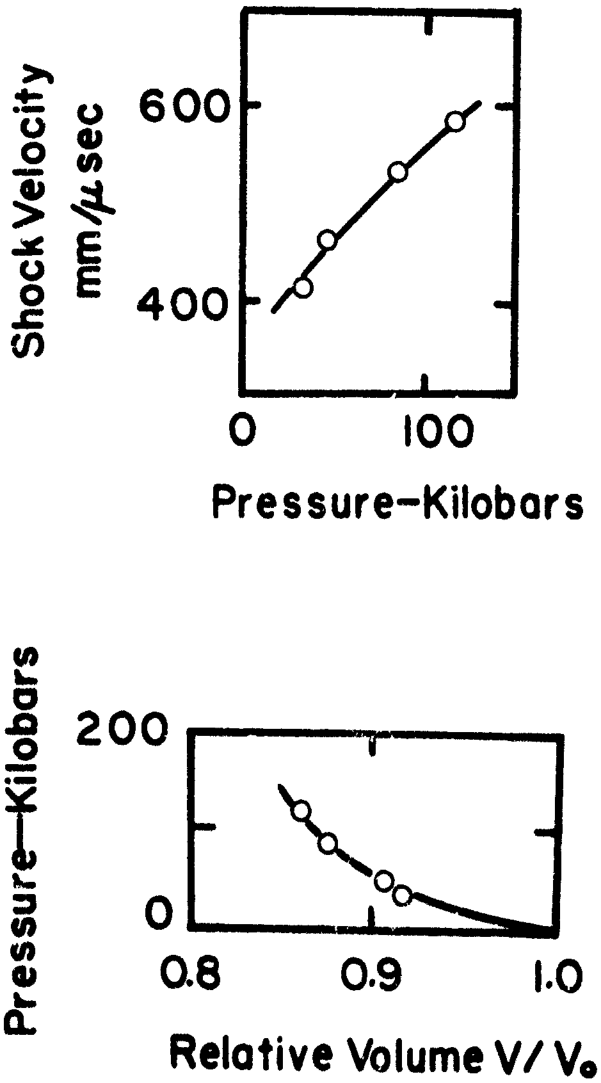
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.15	0.345	33.9	0.916
4.64	0.434	47.7	0.906
5.38	0.667	85.0	0.876
5.94	0.841	118.0	0.858

$\rho_o = 2.37$

Source: Wagner, Waldorf and Louie (1962)


Shock Velocity – mm/μsec
0
2
4
6
0
100
200
Pressure – Kilobars
Pressure – Kilobars
0
100
200
0.6
0.8
1.0
Relative Volume – V/V₀

AVCOAT



Shock Velocity
mm/μsec
600
400
0
100
Pressure–Kilobars
Pressure–Kilobars
200
0
0.8
0.9
1.0
Relative Volume V/ V₀

AVCOITE

BASALT*

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.24	0.29	40	
4.85	1.02	127	0.840
6.80	2.58	468	0.621
6.85	2.57	470	0.625

$\rho_o = 2.67$

Source: Bass, Hawk and Chabai (1963)

* Buckboard hole no. 3, 36 ft, 40-mile Canyon, Nevada Test Site

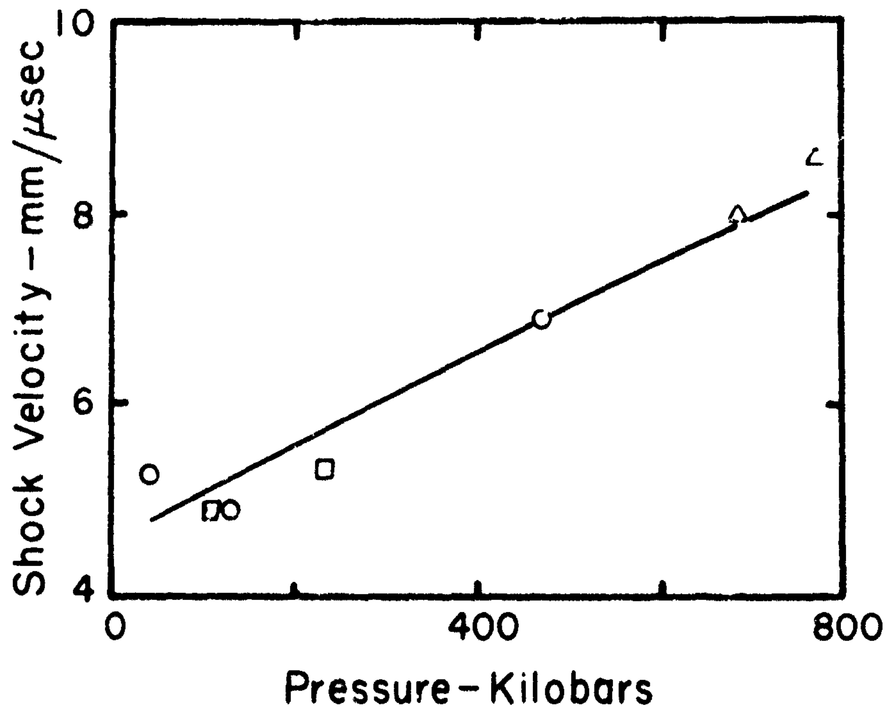
BASALT+

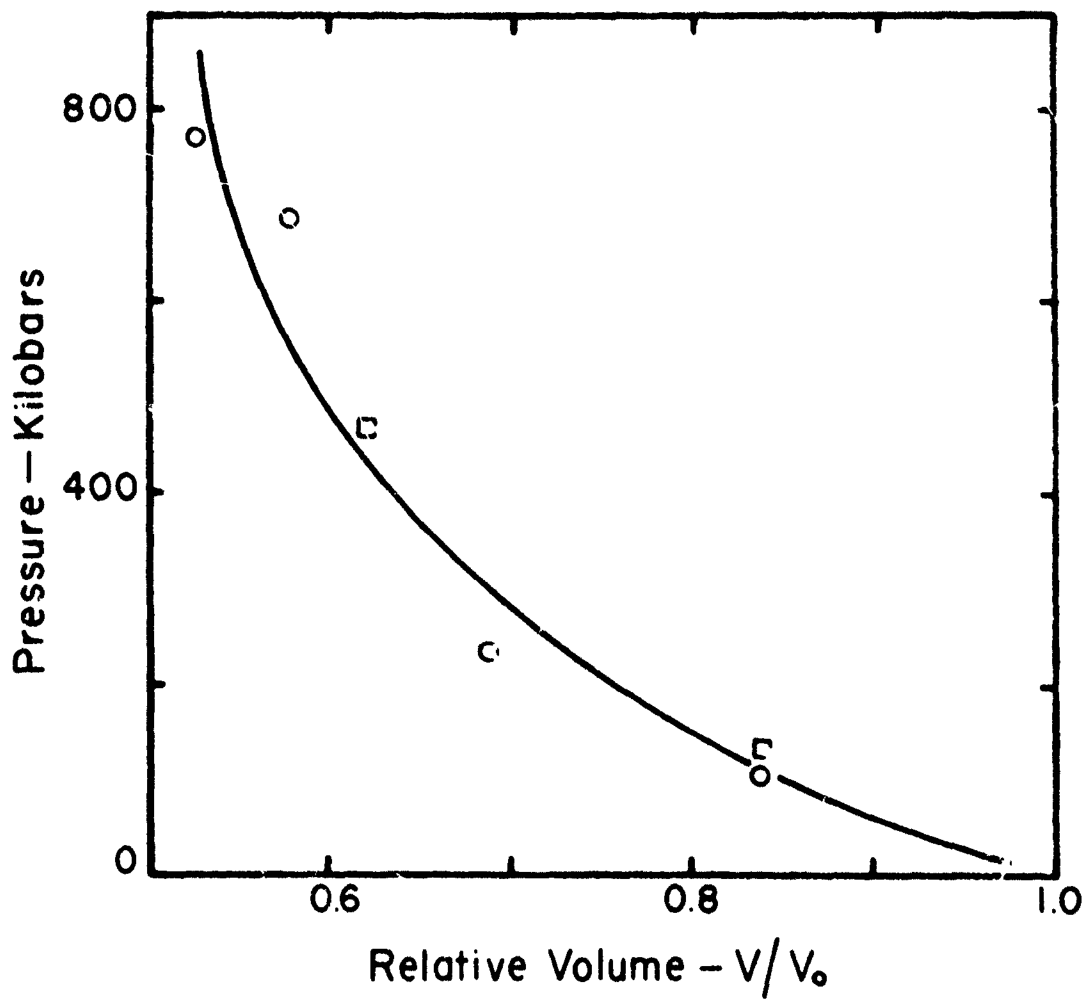
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.867	0.794	103	0.837
5.24	1.63	234	0.689
7.97	3.29	684	0.578
8.588	3.71	769	0.524

$\rho_o = 2.67$

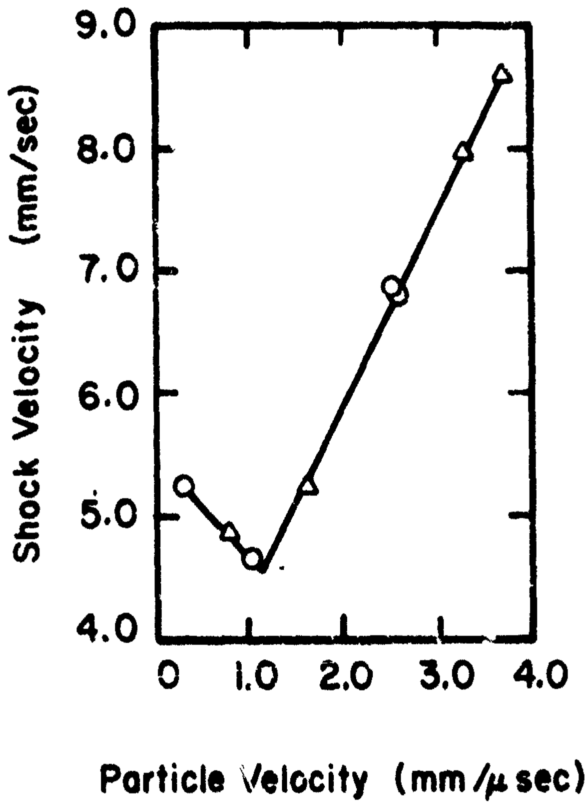
Source: Lombard (1961)

+ Nevada Test Site, Area 18. The Hugoniot elastic limit 40 kb and elastic precursor velocity 5.24 mm/msec


Shock Velocity - mm/μsec
10
8
6
4
0
400
800
Pressure - Kilobars


Pressure - Kilobars
800
400
0
0.6
0.8
1.0
Relative Volume - V/V₀

BASALT



9.0
8.0
7.0
6.0
5.0
4.0
Shock Velocity (mm/sec)
0
1.0
2.0
3.0
4.0
Particle Velocity (mm/μ sec)

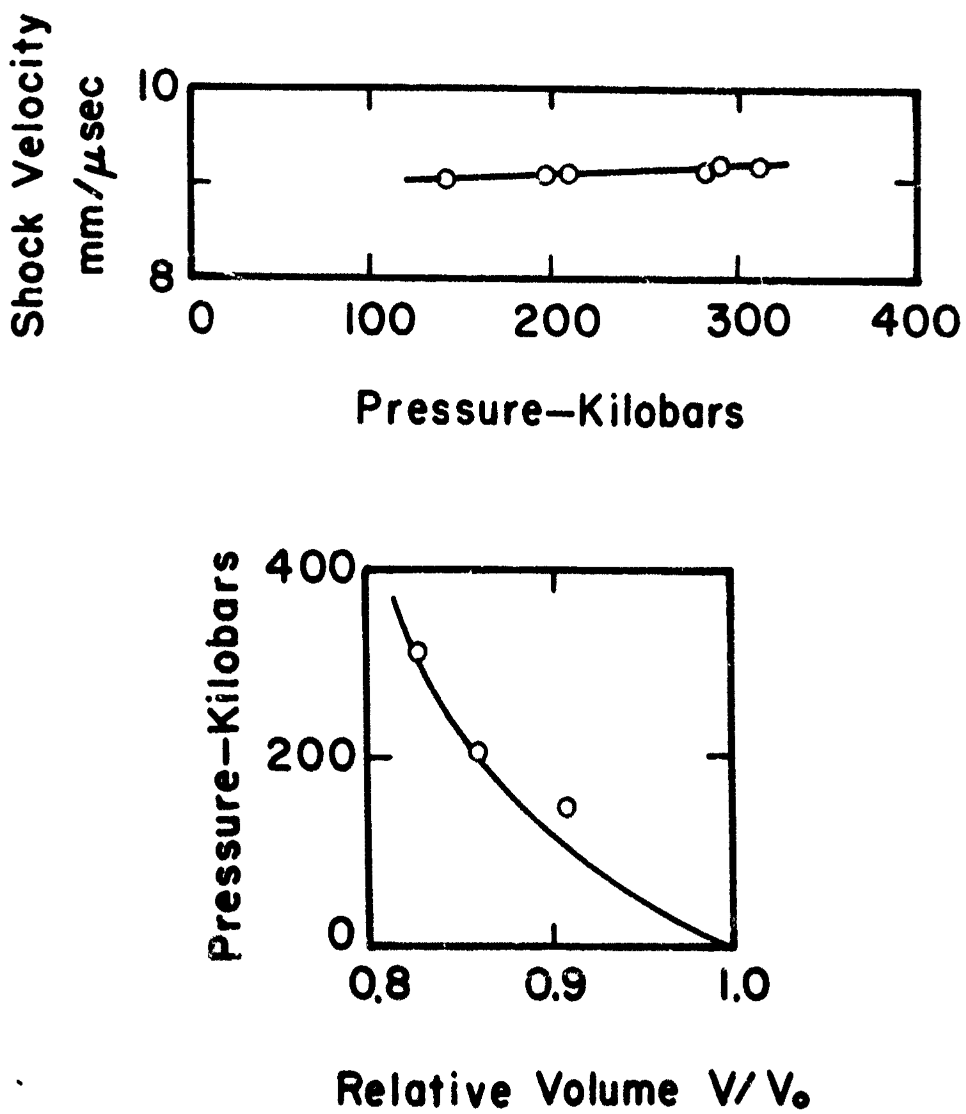
BASALT

BERYLLIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
8.934	0.865	142.6	0.9032
9.044	0.847	141.3	0.9063
9.112	1.189	199.9	0.8659
9.332	1.221	210.2	0.8692
9.633	1.592	282.9	0.8347
9.832	1.609	291.9	0.8364
9.851	1.730	314.4	0.8244

$\rho_0 = 1.845$

Source: Walsh, Rice, McQueen and Yarger (1957)


Shock Velocity mm/μsec
10
8
0
100
200
300
400
Pressure—Kilobars
Pressure—Kilobars
400
200
0
0.8
0.9
1.0
Relative Volume V/V₀

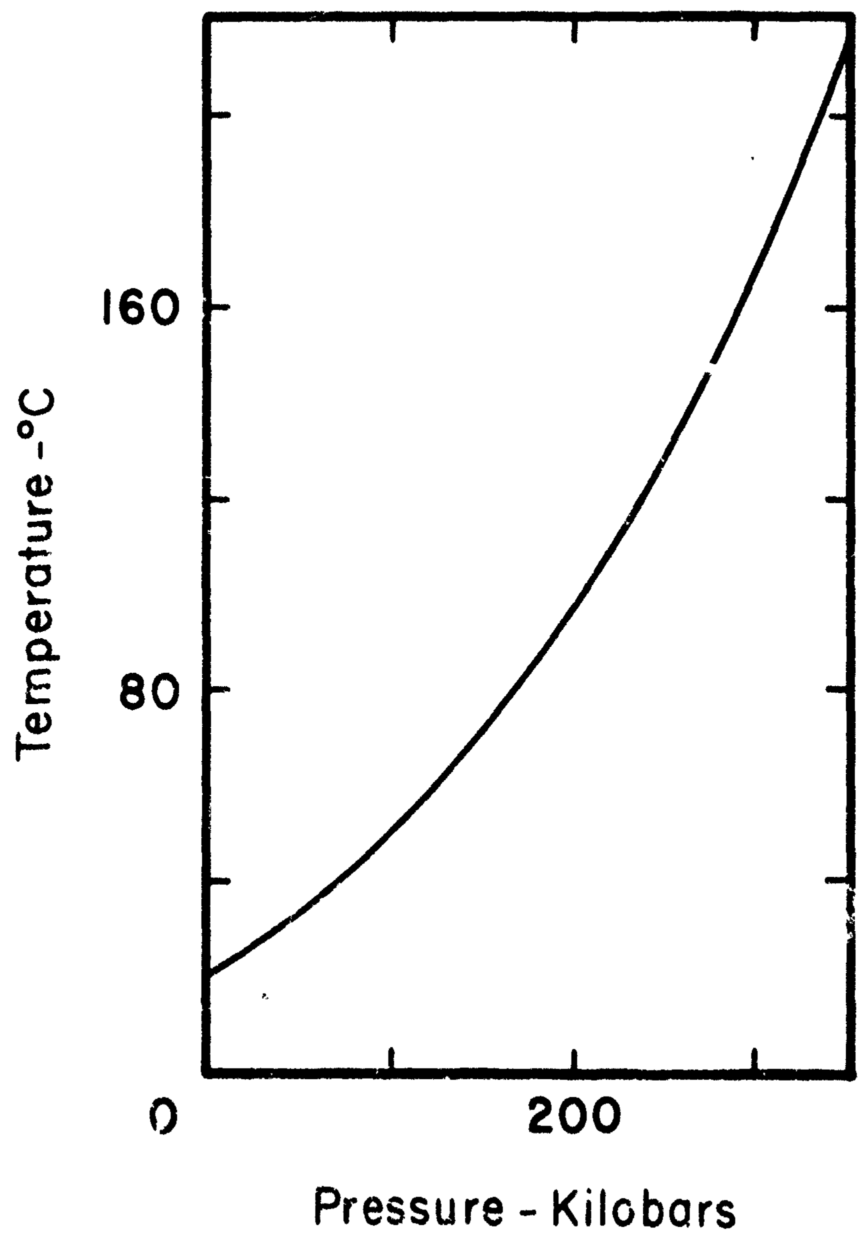
BERYLLIUM

Temperatures associated with shock

Beryllium

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	
100	50	
150	70	
200	97	
250	127	
300	168	
350	213	

Source: Rice, McQueen and Walsh, 1958



BERYLLIUM

BISMUTH

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
2.696	0.718	189.5	0.7337
2.585	0.676	171.1	0.7385
3.075	0.914	275.2	0.7028
3.084	0.922	278.4	0.7010
3.682	1.212	436.9	0.6708
3.659	1.122	437.7	0.6660

$\rho_0 = 9.80$

Source: Walsh, Rice, McQueen and Yarger (1957)

BISMUTH

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.37	1.05	350	0.690
6.36	2.47	1300	0.539
7.94	4.45	3450	0.439

$\rho_0 = 9.80$

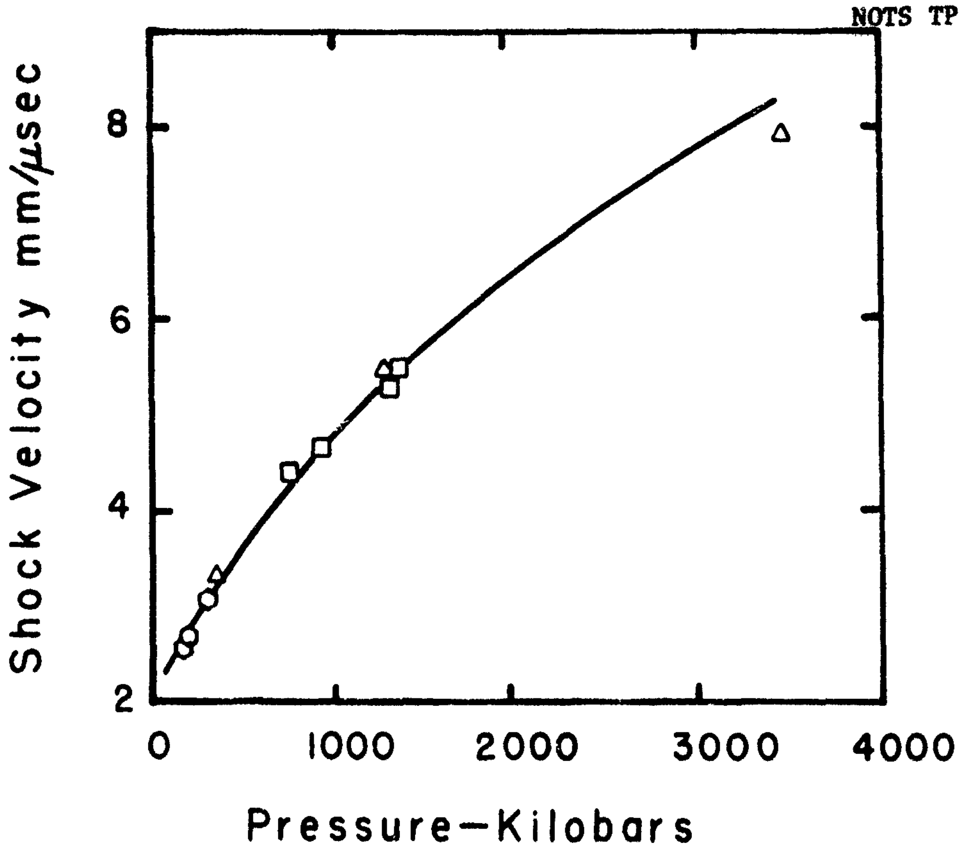
Source: Al'Tshuler, Krupnikov and Brazhnik (1958)

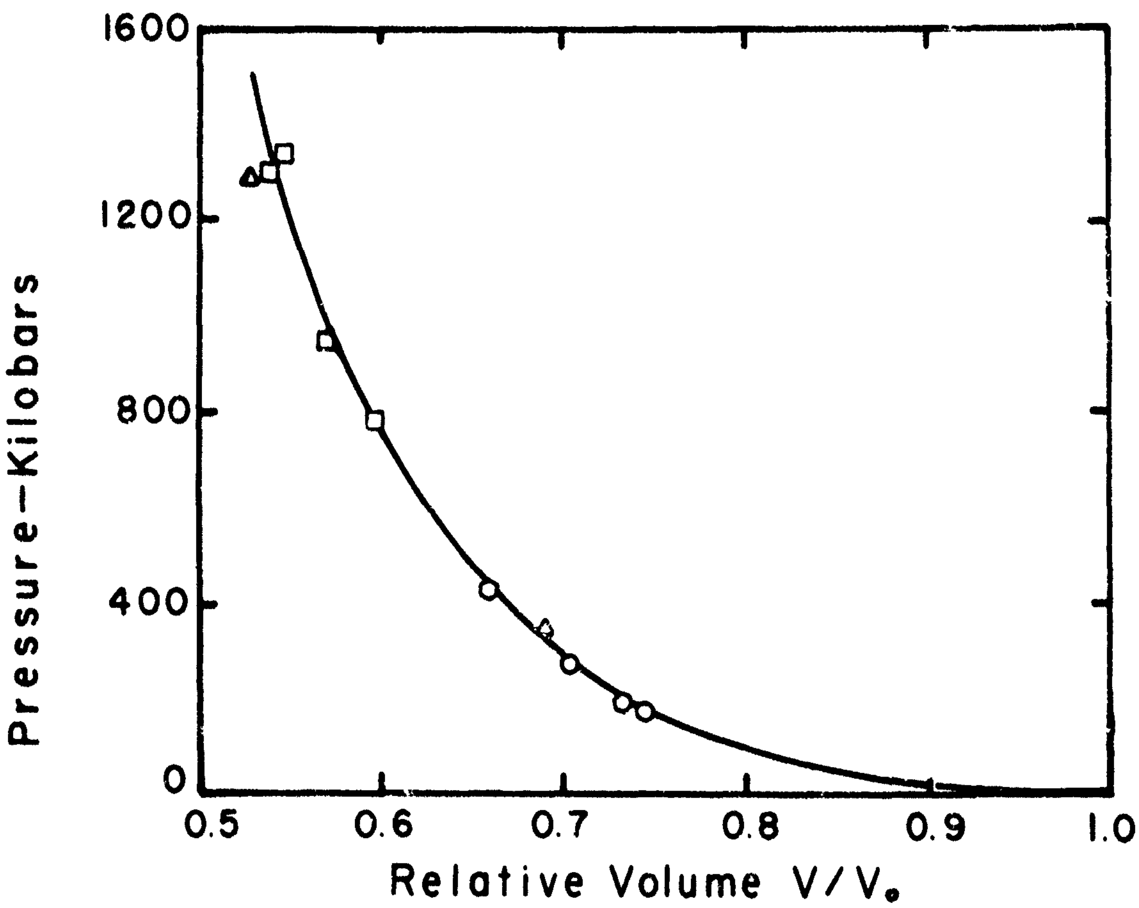
BISMUTH

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.67	1.23	444	0.665
3.64	1.23	443	0.661
4.44	1.80	786	0.596
4.42	1.79	781	0.594
4.46	1.79	787	0.599
4.75	1.97	923	0.585
4.66	2.06	945	0.558
4.73	2.00	931	0.577
5.33	2.47	1299	0.536
5.36	2.47	1303	0.540
5.51	2.51	1360	0.545
5.49	2.48	1344	0.548
5.49	2.47	1335	0.551

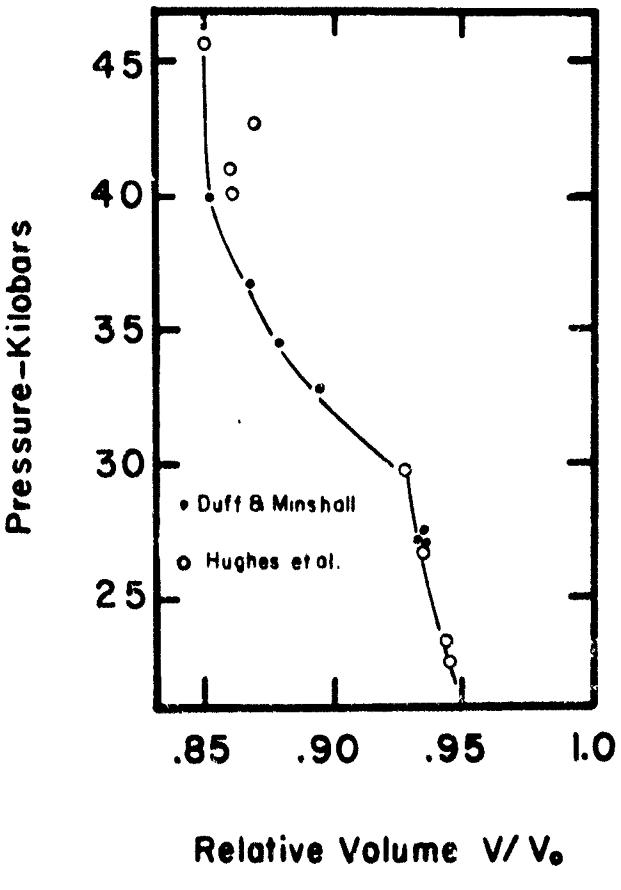
$\rho_c = 9.80$

Source: McQueen and Marsh (1960)


Shock Velocity mm/μsec
2
4
6
8
0
1000
2000
3000
4000
Pressure—Kilobars


Pressure—Kilobars
0
400
800
1200
1600
0.5
0.6
0.7
0.8
0.9
1.0
Relative Volume V/V₀

BISMUTH


Pressure-Kilobars
45
40
35
30
25
• Duff & Minshall
o Hughes et al.
.85
.90
.95
1.0
Relative Volume V/ V₀

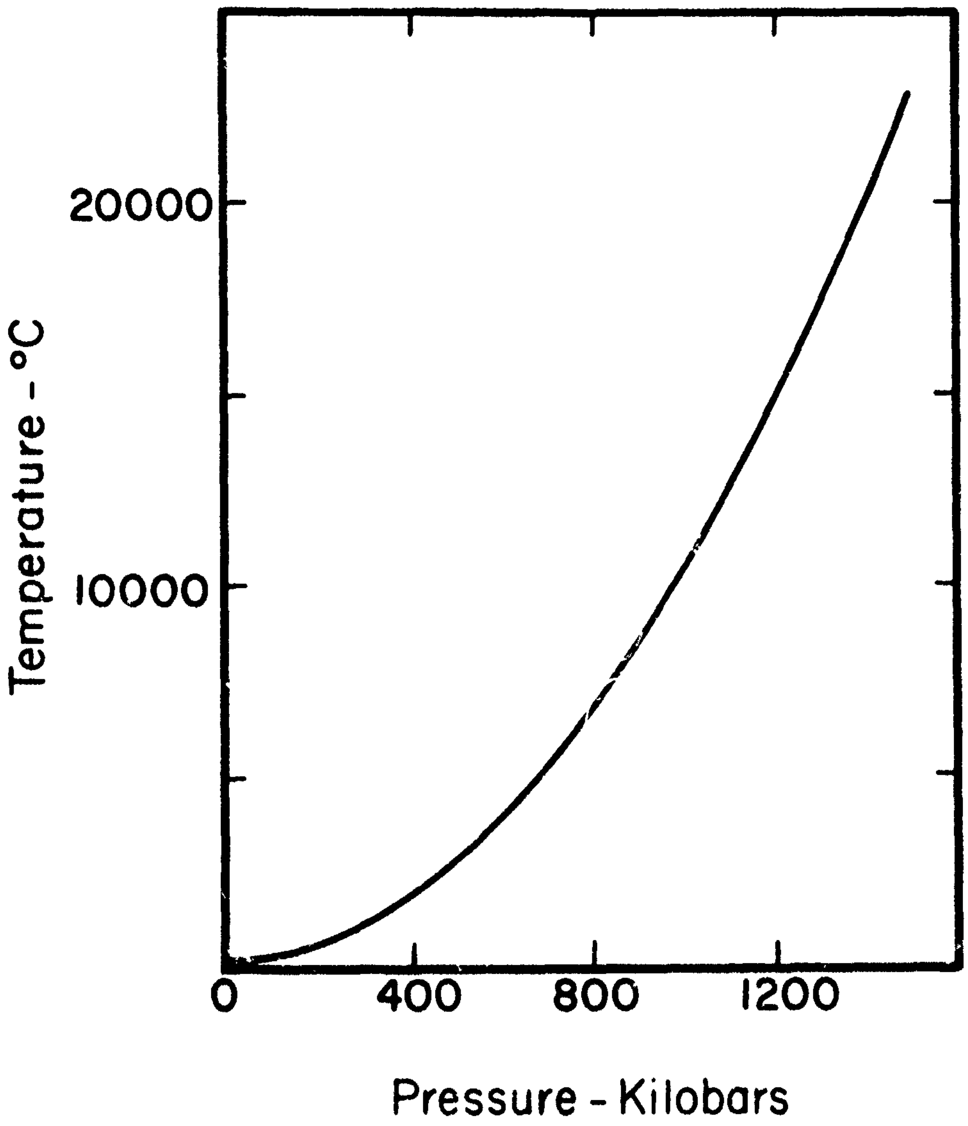
BISMUTH

Temperatures associated with shock

Bismuth

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	
500	2527	
750	6027	
1000	10627	
1250	16327	
1500	22827	

Source: McQueen and Marsh, 1960



BISMUTH

BRASS

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.446	0.590	220.7	0.8673
4.440	0.571	213.3	0.8714
4.731	0.791	314.8	0.8328
4.726	0.770	306.2	0.8371
5.236	1.085	478.0	0.7928
5.220	1.077	473.0	0.7937

$\rho_0 = 8.6$

Source: Walsh, Rice, McQueen and Yarger (1957)

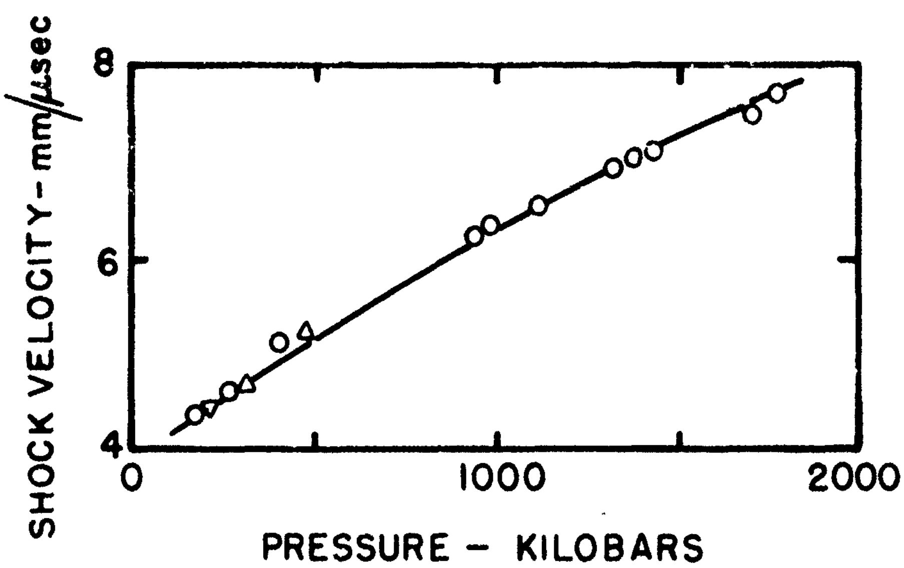
BRASS

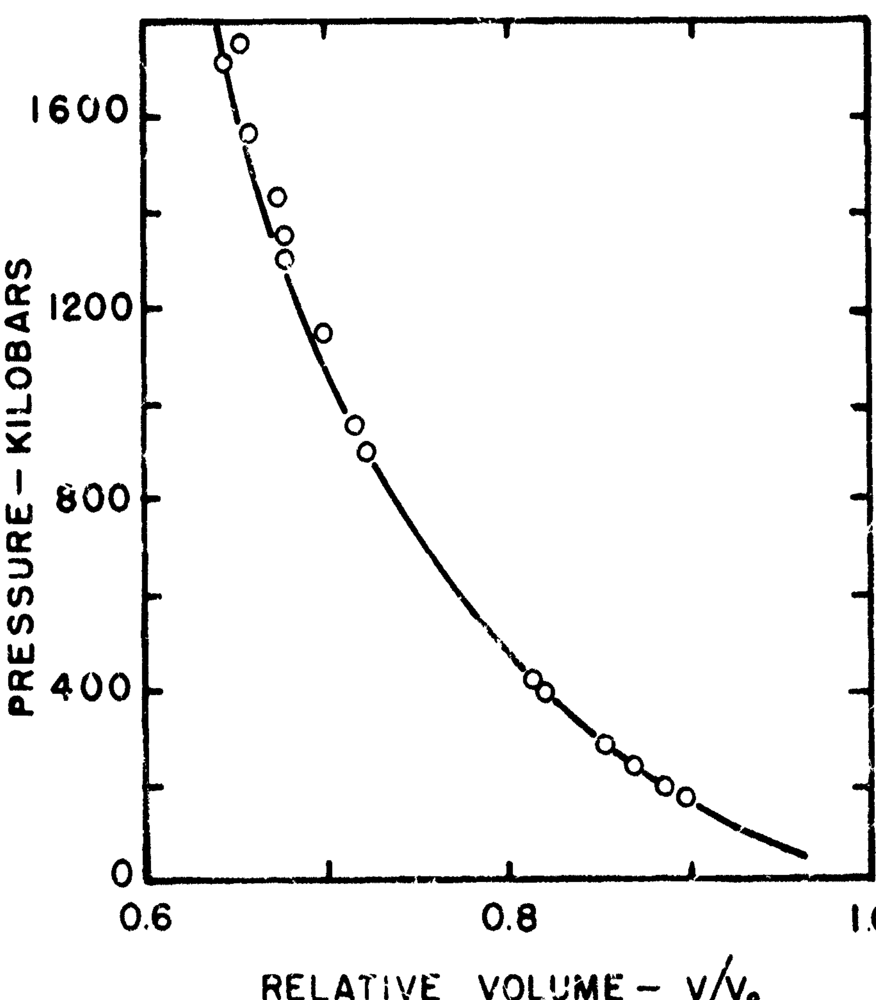
Cu/Zn/Pb/Fe ; 61.5/36.0/2.5/<0.05

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.38	0.45	167	0.897
4.41	0.45	168	0.898
4.50	0.50	192	0.888
4.51	0.50	191	0.889
4.54	0.56	214	0.877
4.56	0.59	229	0.869
4.77	0.70	282	0.853
4.79	0.70	284	0.853
5.10	0.91	391	0.822
5.14	0.90	389	0.826
5.15	0.96	415	0.814
5.15	0.91	394	0.824
5.17	0.94	411	0.818
5.19	0.94	412	0.819
6.22	1.72	906	0.723
6.29	1.78	947	0.717
6.39	1.82	985	0.715
6.59	1.99	1108	0.698
6.92	2.24	1308	0.677
6.97	2.28	1342	0.673
7.04	2.26	1348	0.679
7.05	2.29	1365	0.675
7.17	2.34	1420	0.674
7.54	2.66	1694	0.648
7.57	2.66	1702	0.649
7.77	2.69	1764	0.654

$\rho_0 = 8.6$

Source: McQueen and Marsh (1960)


SHOCK VELOCITY - mm/μsec
8
6
4
0
1000
2000
PRESSURE - KILOBARS


PRESSURE - KILOBARS
1600
1200
800
400
0
0.6
0.8
1.0
RELATIVE VOLUME - V/V₀

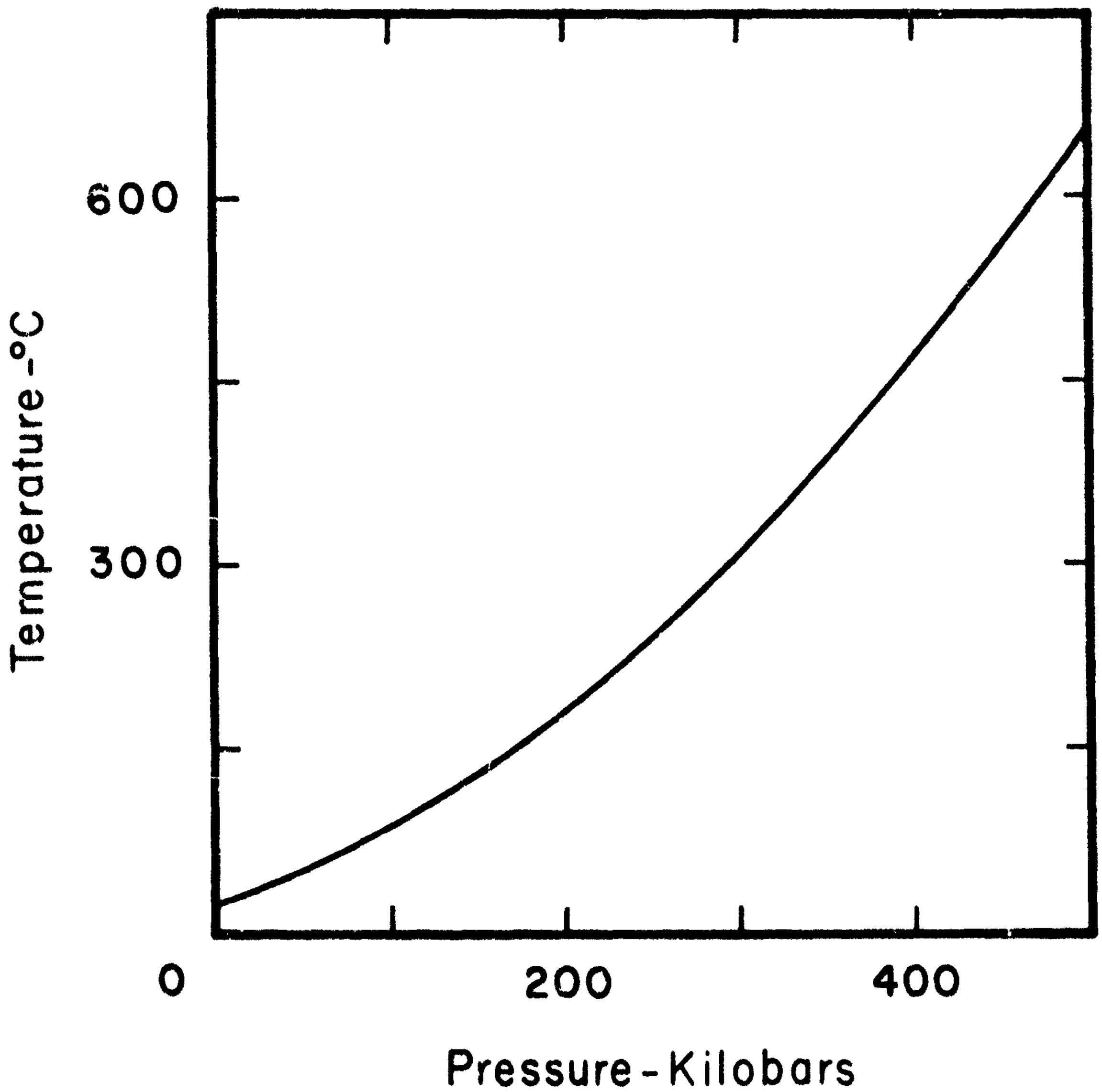
BRASS

Temperatures associated with shock

Brass

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	
100	89	
150	129	
200	175	
250	235	
300	305	
350	382	
400	467	
450	557	
500	651	

Source: Rice, McQueen and Walsh, 1958



BRASS

CADMIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.66	1.96	957	0.654
5.78	1.96	976	0.662
5.77	1.96	980	0.663
5.77	1.97	982	0.558
6.45	1.98	986	0.657
6.48	2.40	1339	0.628
6.48	2.40	1345	0.629
6.39	2.43	1339	0.620
6.43	2.43	1351	0.622

$\rho_0 = 8.64$

Source: McQueen and Marsh (1960)

CADMIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.599	0.690	214.5	0.8083
3.421	0.619	182.9	0.8191
3.918	0.850	287.6	0.7830
4.450	1.190	457.3	0.7326
4.324	1.120	418.2	0.7410

$\rho_0 = 8.64$

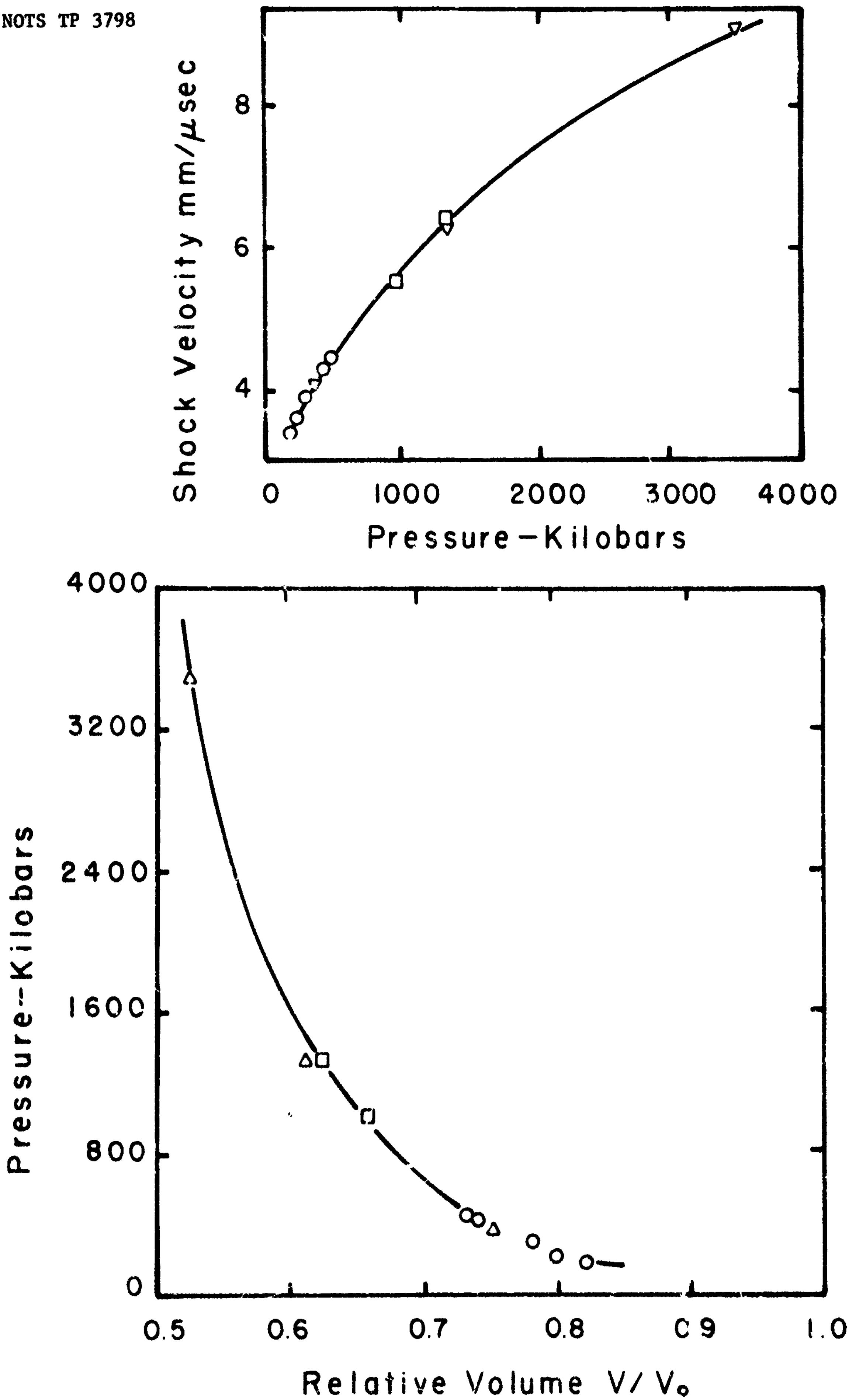
Source: Walsh, Rice, McQueen and Yarger (1957)

CADMIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.10	1.02	360	0.751
6.32	2.44	1330	0.612
9.14	4.42	4390	0.515

$\rho_0 = 8.64$

Source: Al'tshuler, Krupnikov and Brazhnik (1958)


Shock Velocity mm/μsec
8
6
4
0
1000
2000
3000
4000
Pressure—Kilobars
4000
3200
2400
1600
800
0
Pressure--Kilobars
0.5
0.6
0.7
0.8
C 9
1.0
Relative Volume V/ Vo

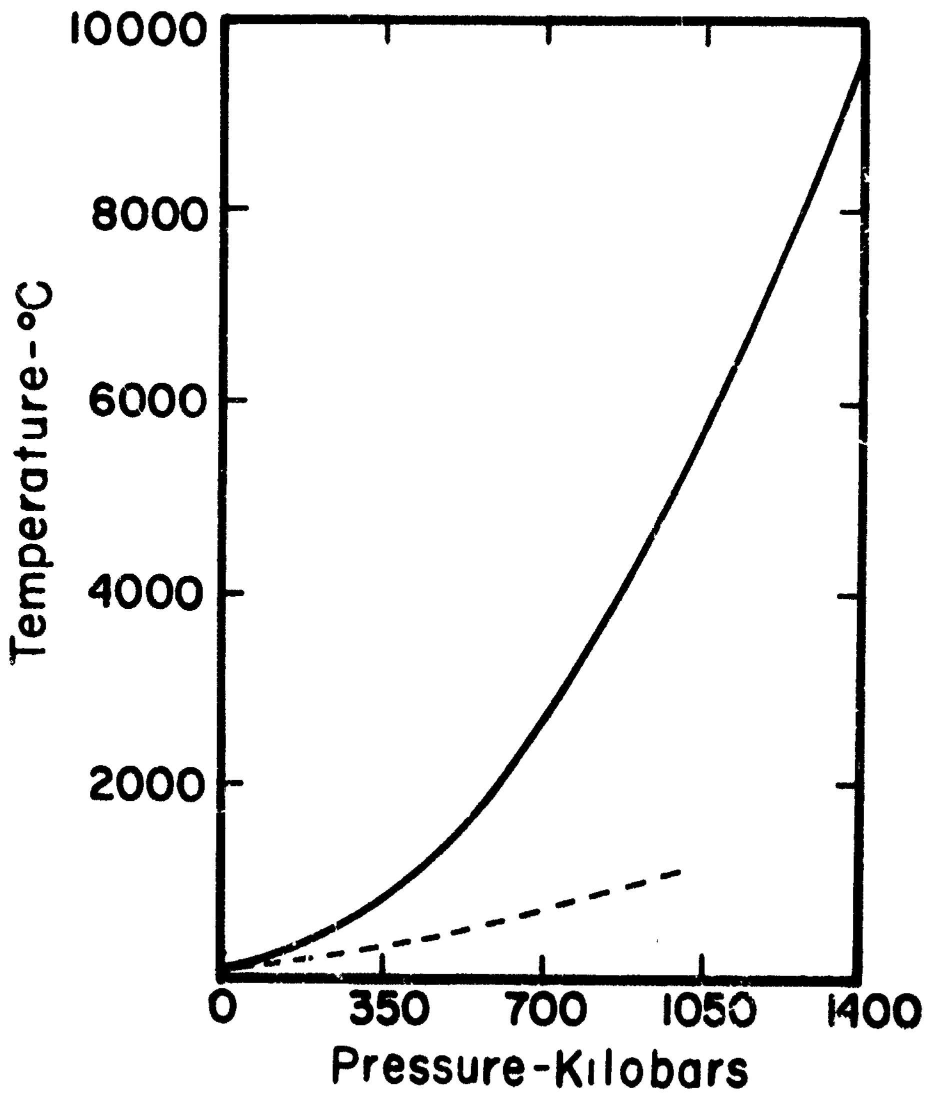
CADMIUM

Temperatures associated with shock

Cadmium

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	161	55
200	401	157
300	722	283
400	980	321
500	1339	377
600	1974	533
700	2710	687
800	3535	836
900	4431	979
1000	5383	1117
1100	6379	-
1200	7403	-
1300	8453	-
1400	9503	-

Source: McQueen and Marsh, 1960


10000
8000
6000
4000
2000
Temperature-°C
0
350
700
1050
1400
Pressure-Kilobars

CADMIUM

CHROMIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
7.63	1.71	924	0.777
7.59	1.71	922	0.775
8.44	2.25	1347	0.734
8.57	2.27	1382	0.735
8.63	2.25	1379	0.739

$\rho_o = 7.10$

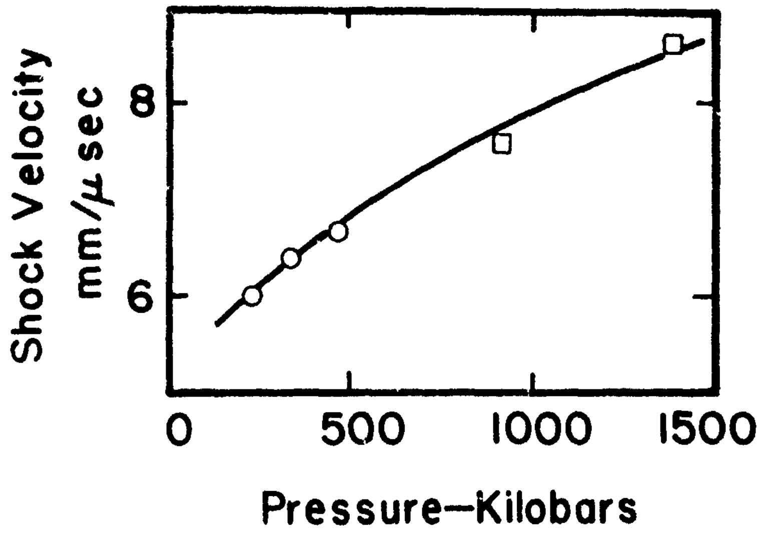
Source: McQueen and Marsh (1960)

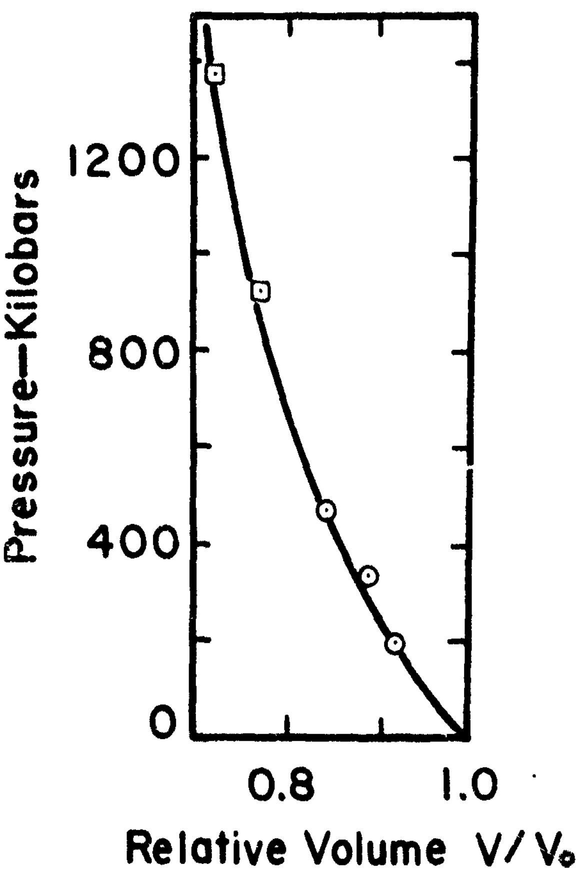
CHROMIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
6.043	0.5448	234.5	0.9098
5.923	0.5395	233	0.9089
6.381	0.7436	338	0.8835
6.370	0.7449	338	0.8831
6.355	0.7407	336	0.8834
6.357	0.7403	336	0.8835
6.660	1.007	478	0.8488
6.674	1.008	479	0.8490

$\rho_o = 7.13$

Source: Walsh, Rice, McQueen and Yarger (1957)


Shock Velocity mm/μ sec
8
6
0
500
1000
1500
Pressure—Kilobars


Pressure—Kilobars
1200
800
400
0
0.8
1.0
Relative Volume V/V₀

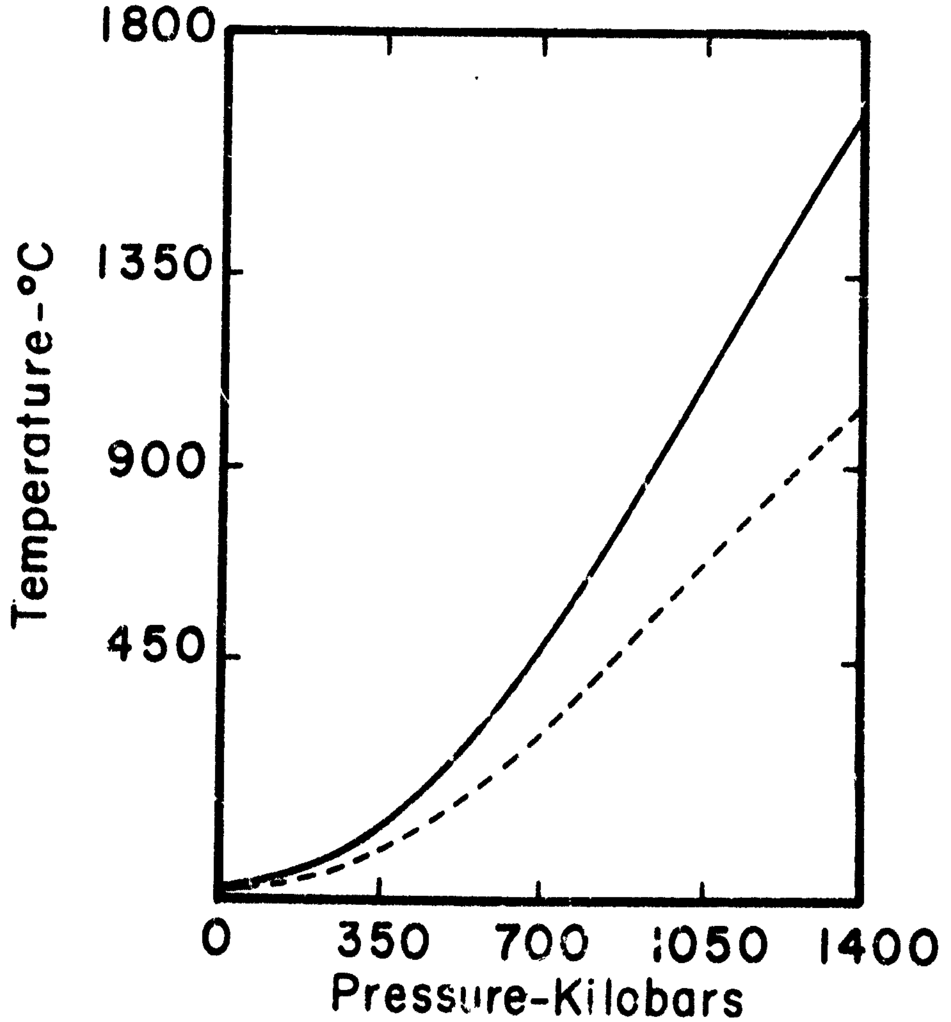
CHROMIUM

Temperatures associated with shock

Chromium

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	41	23
200	73	39
300	123	71
400	194	119
500	285	182
600	396	258
700	523	345
800	666	439
900	820	539
1000	983	643
1100	1151	746
1200	1319	846
1300	1482	938
1400	1641	1024

Source: McQueen and Marsh, 1960


1800
1350
900
450
Temperature-°C
0
350
700
1050
1400
Pressure-Kilobars

CHROMIUM

COBALT

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
7.15	1.79	1121	0.750
7.15	1.80	1137	0.748
7.12	1.83	1148	0.743
7.50	2.06	1362	0.726
7.45	2.07	1358	0.723
7.43	2.07	1357	0.721
7.81	2.30	1584	0.706
7.79	2.30	1581	0.705
7.77	2.30	1577	0.703
7.88	2.31	1603	0.707
7.83	2.32	1603	0.703

ρ_o = 8.82

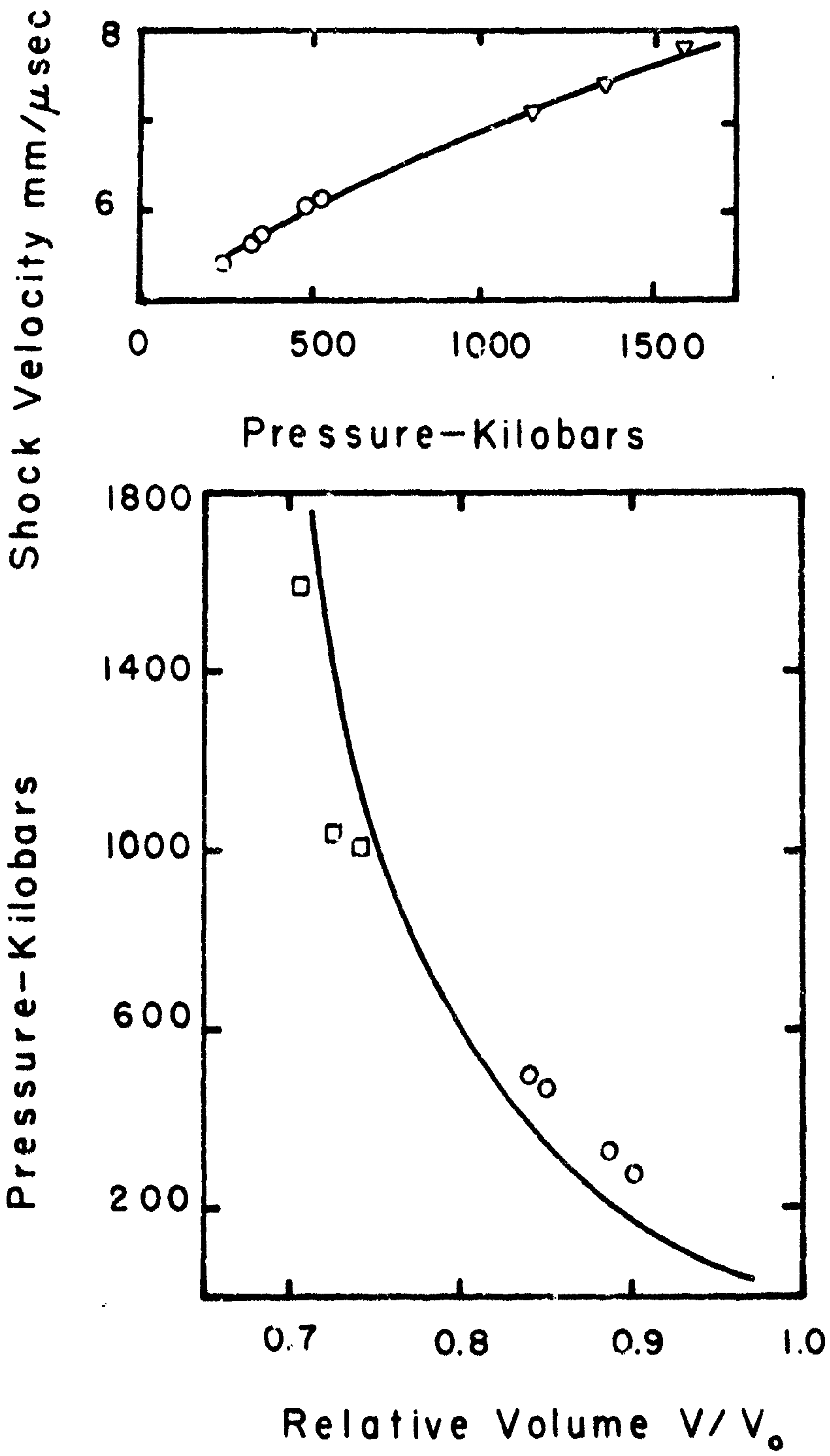
Source: McQueen and Marsh (1960)

COBALT

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.445	0.502	241.1	0.9078
5.696	0.683	343.2	0.8801
5.632	0.653	324.4	0.8841
6.019	0.901	478.1	0.8503
6.052	0.955	509.8	0.8422

ρ_o = 8.82

Source: Walsh, Rice, McQueen and Yarger (1957)


Shock Velocity mm/μsec
8
6
0
500
1000
1500
Pressure–Kilobars
1800
1400
1000
600
200
Pressure-Kilobars
0.7
0.8
0.9
1.0
Relative Volume V/ V_o

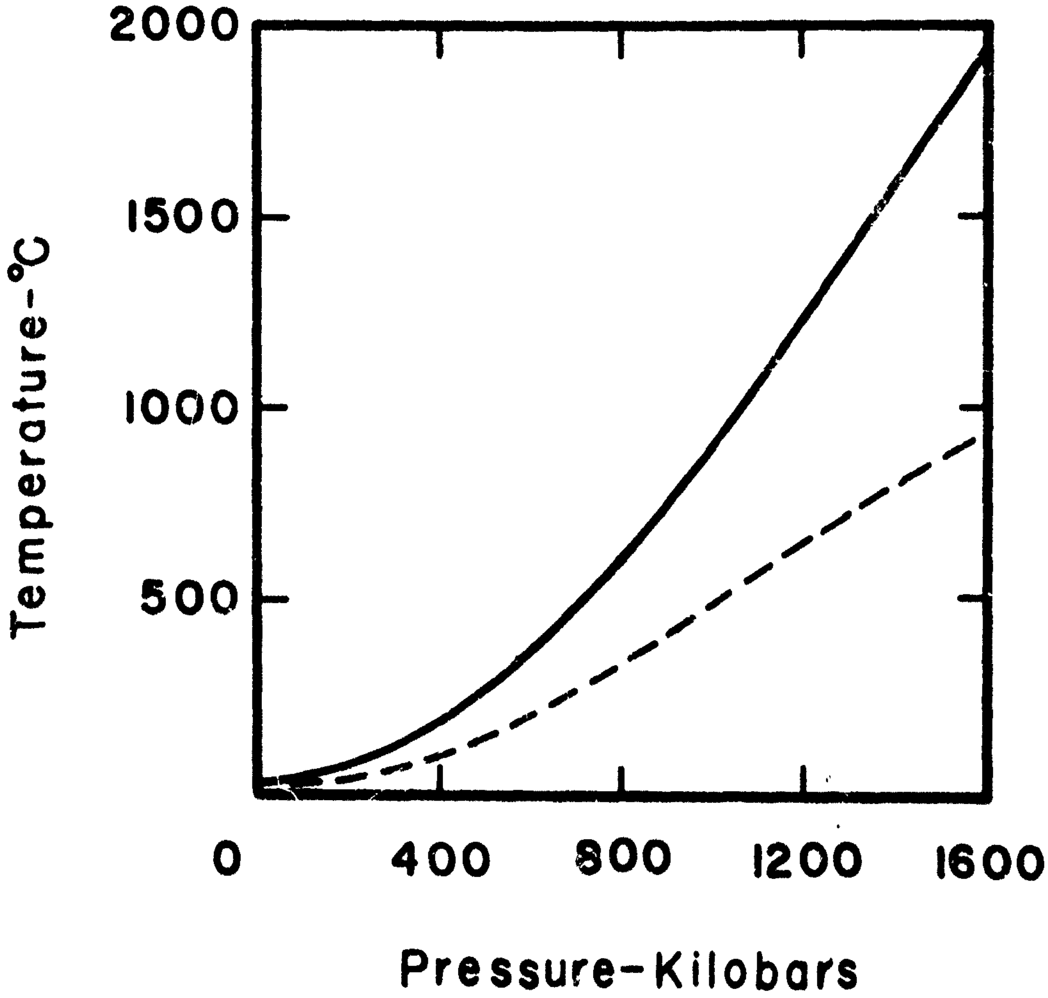
COBALT

Temperatures associated with shock

Cobalt

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	43	22
200	81	34
300	127	58
400	190	94
500	270	141
600	368	198
700	481	262
800	609	331
900	749	404
1000	900	480
1100	1059	557
1200	1223	635
1300	1396	711
1400	1571	786
1500	1748	860
1600	1926	930

Source: McQueen and March, 1960


2000
1500
1000
500
Temperature-°C
0
400
800
1200
1600
Pressure-Kilobars

COBALT

COPPER

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
6.33	1.57	883	0.752
6.23	1.58	875	0.746
6.26	1.57	877	0.749
7.26	2.20	1424	0.697
7.29	2.21	1430	0.698
7.32	2.22	1444	0.697

$\rho_0 = 8.90$

Source: McQueen and Marsh (1960)

COPPER

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.744	0.511	215.8	0.8923
4.768	0.570	241.9	0.8804
5.070	0.711	320.8	0.8598
5.015	0.731	326.3	0.8542
5.508	1.032	505.9	0.8126

$\rho_0 = 8.90$

Source: Walsh, Rice, McQueen and Yarger (1957)

COPPER

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.36	0.94	450	0.826
7.13	2.29	1460	0.681
10.16	4.19	3800	0.588

$\rho_0 = 8.93$

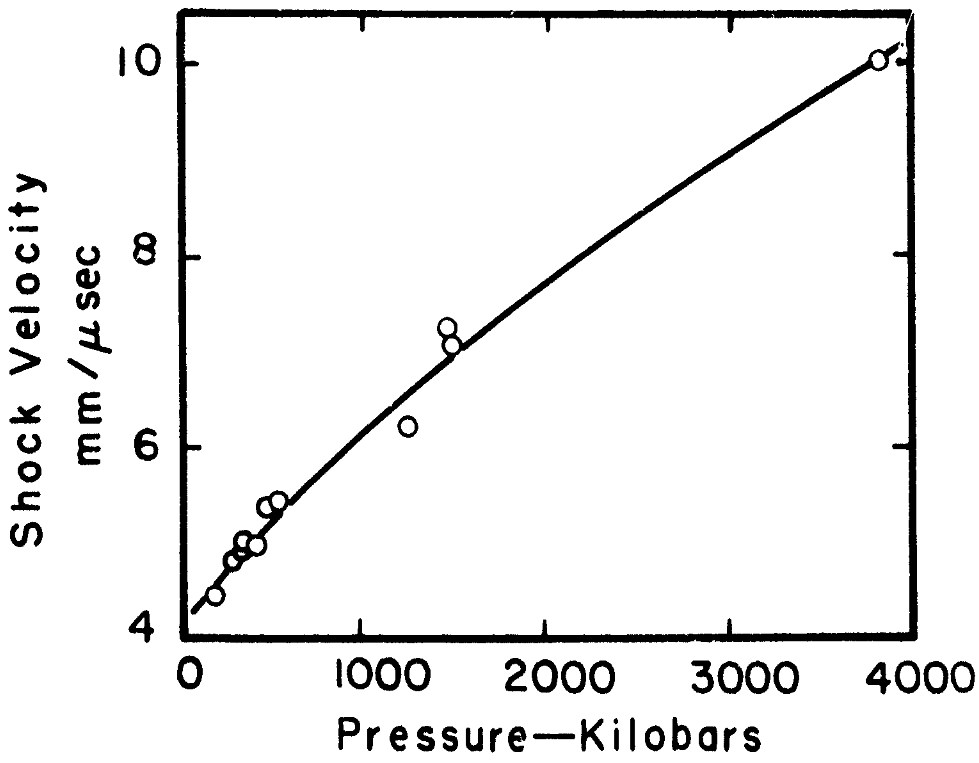
Source: Al'tshuler, Krupnikov and Brazhnik (1958)

COPPER

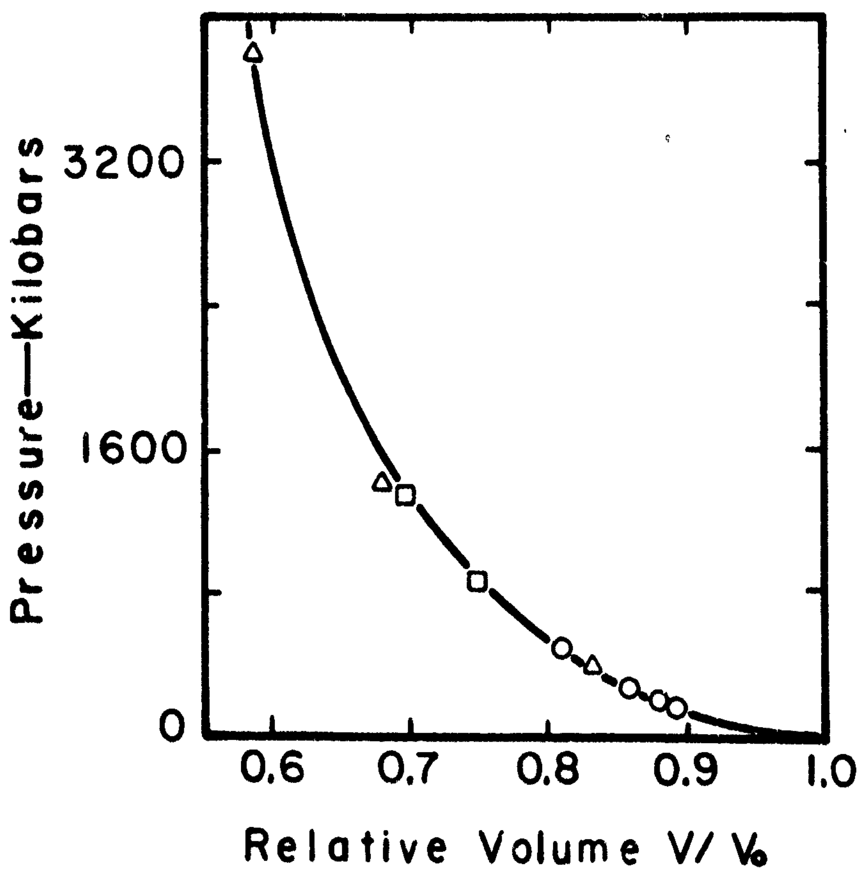
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.556	0.460	186.6	0.899
4.525	0.460	185.1	0.898
4.768	0.547	232.1	0.8853
4.769	0.550	233.4	0.8847
4.94	0.672	295.3	0.864
4.913	0.684	299.0	0.861
5.258	0.823	356.1	0.848
5.128	0.780	385.0	0.844
5.240	0.835	389.5	0.841
5.285	0.855	402.3	0.838
5.391	0.964	462.0	0.821
5.397	0.969	465.4	0.821

$\rho_0 = 8.903$

Source: Walsh and Christian (1955)



Shock Velocity mm/μsec
10
8
6
4
0
1000
2000
3000
4000
Pressure—Kilobars



Pressure—Kilobars
3200
1600
0
0.6
0.7
0.8
0.9
1.0
Relative Volume V/V₀

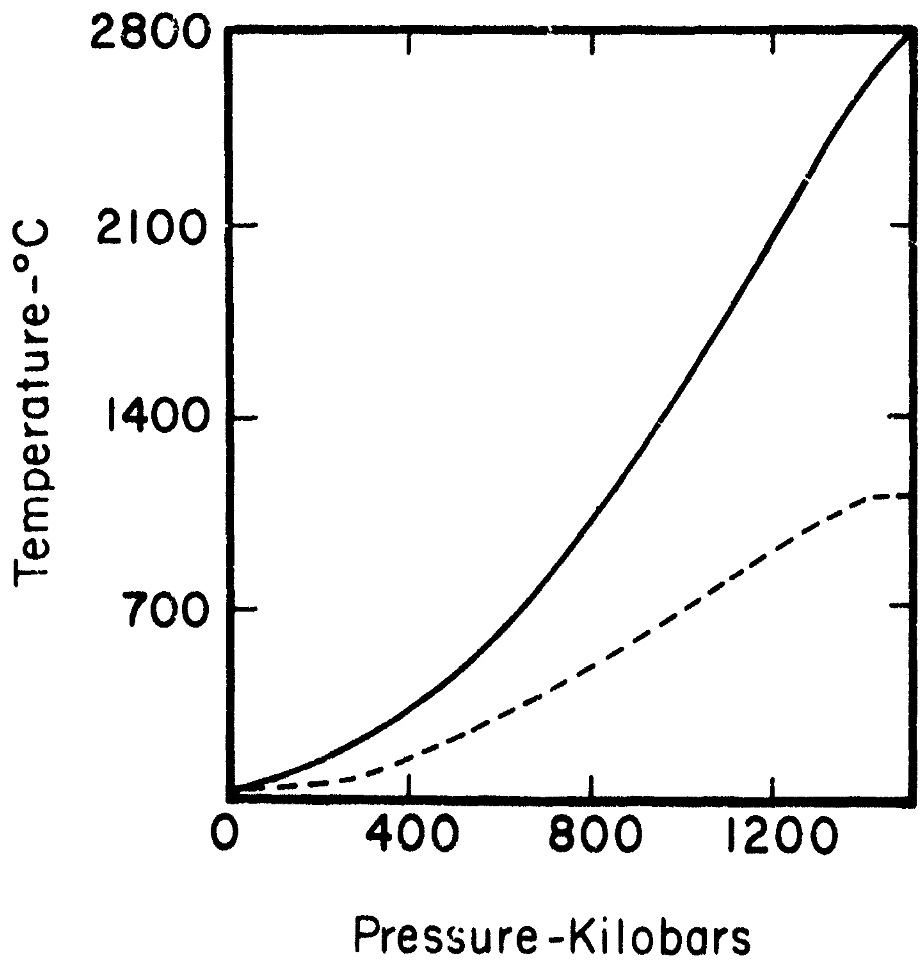
COPPER

Temperatures associated with shock

Copper

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	61	25
200	118	46
300	199	87
400	309	144
500	446	214
600	608	295
700	795	383
800	1004	478
900	1233	576
1000	1482	677
1100	1747	780
1200	2028	883
1300	2323	984
1400	2629	1083
1500	2769	1083

Source: McQueen and Marsh, 1960


2800
2100
1400
700
Temperature-°C
0
400
800
1200
Pressure-Kilobars

COPPER

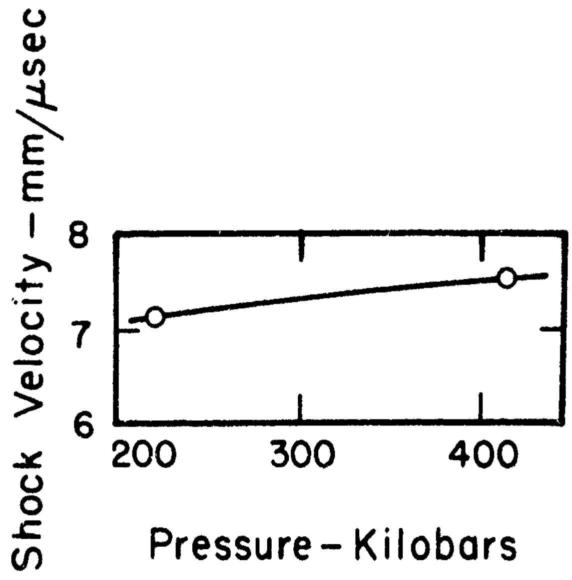
DOLOMITE*

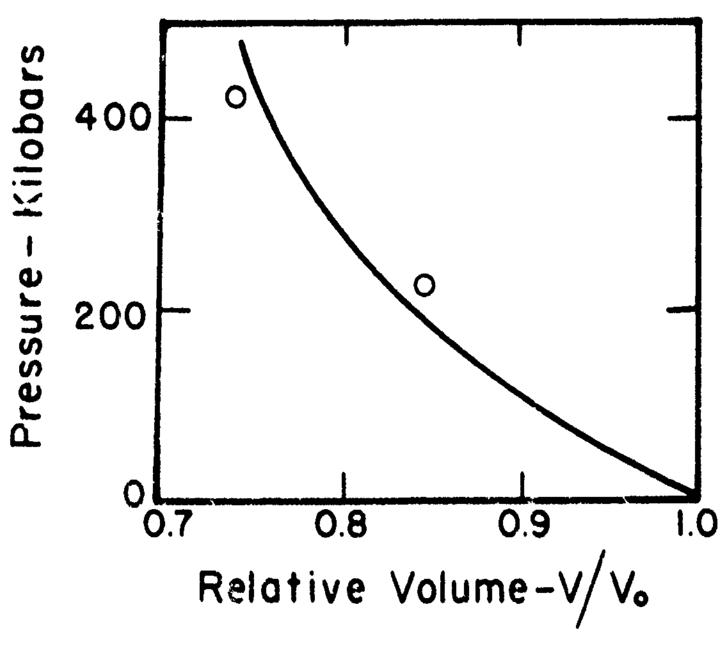
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
7.14	1.10	223	0.846
7.546	1.935	417	0.7436

$\rho_o = 2.84$

Source: Lombard (1961)

* from surface, Nevada Test Site 12


Shock Velocity – mm/μsec
8
7
6
200
300
400
Pressure – Kilobars


Pressure – Kilobars
400
200
0
0.7
0.8
0.9
1.0
Relative Volume – V/V₀

DOLOMITE

GOLD

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.679	0.380	269.0	0.3967
3.864	0.505	375.4	0.8693
4.130	0.666	529.2	0.8389

$\rho_0 = 19.24$

Source: Walsh, Rice, McQueen and Yarger (1957)

GOLD

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.27	0.71	590	0.834
5.70	1.78	1950	0.690
8.06	3.30	5130	0.592

$\rho_0 = 19.30$

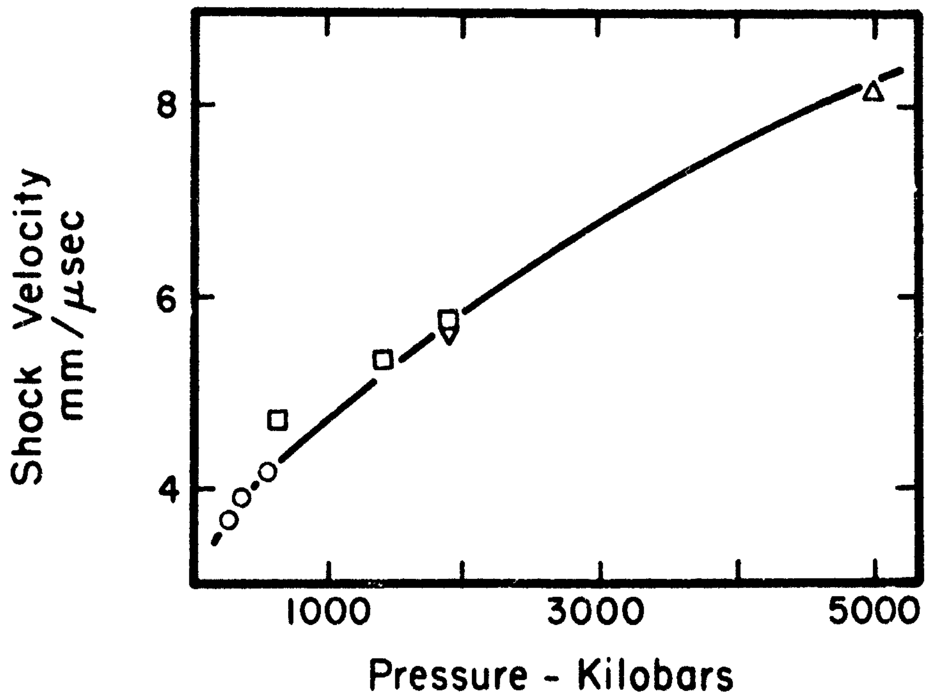
Source: Al'tshuler, Krupnikov and Brazhnik (1958)

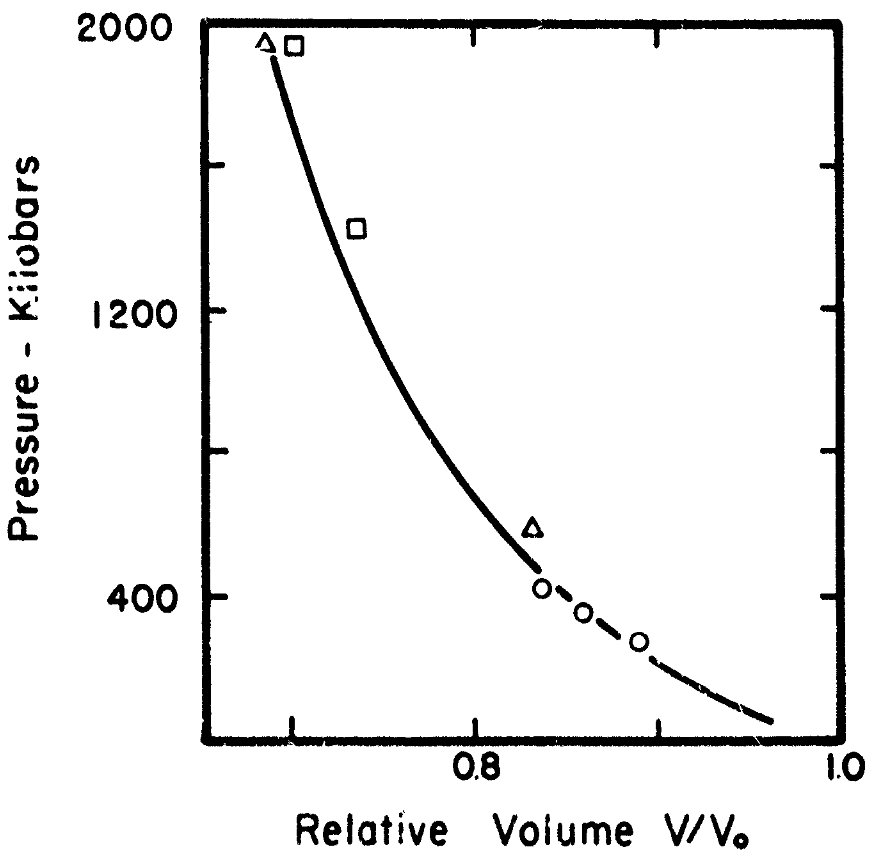
GOLD

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.25	1.37	1387	0.739
5.21	1.41	1410	0.730
5.80	1.73	1932	0.702
5.78	1.74	1931	0.700
5.78	1.74	1936	0.699
5.79	1.74	1942	0.699

$\rho_0 = 19.24$

Source: McQueen and Marsh (1960)


8
6
4
Shock Velocity mm/μsec
1000
3000
5000
Pressure - Kilobars


2000
1200
400
Pressure - Kilobars
0.8
1.0
Relative Volume V/V₀

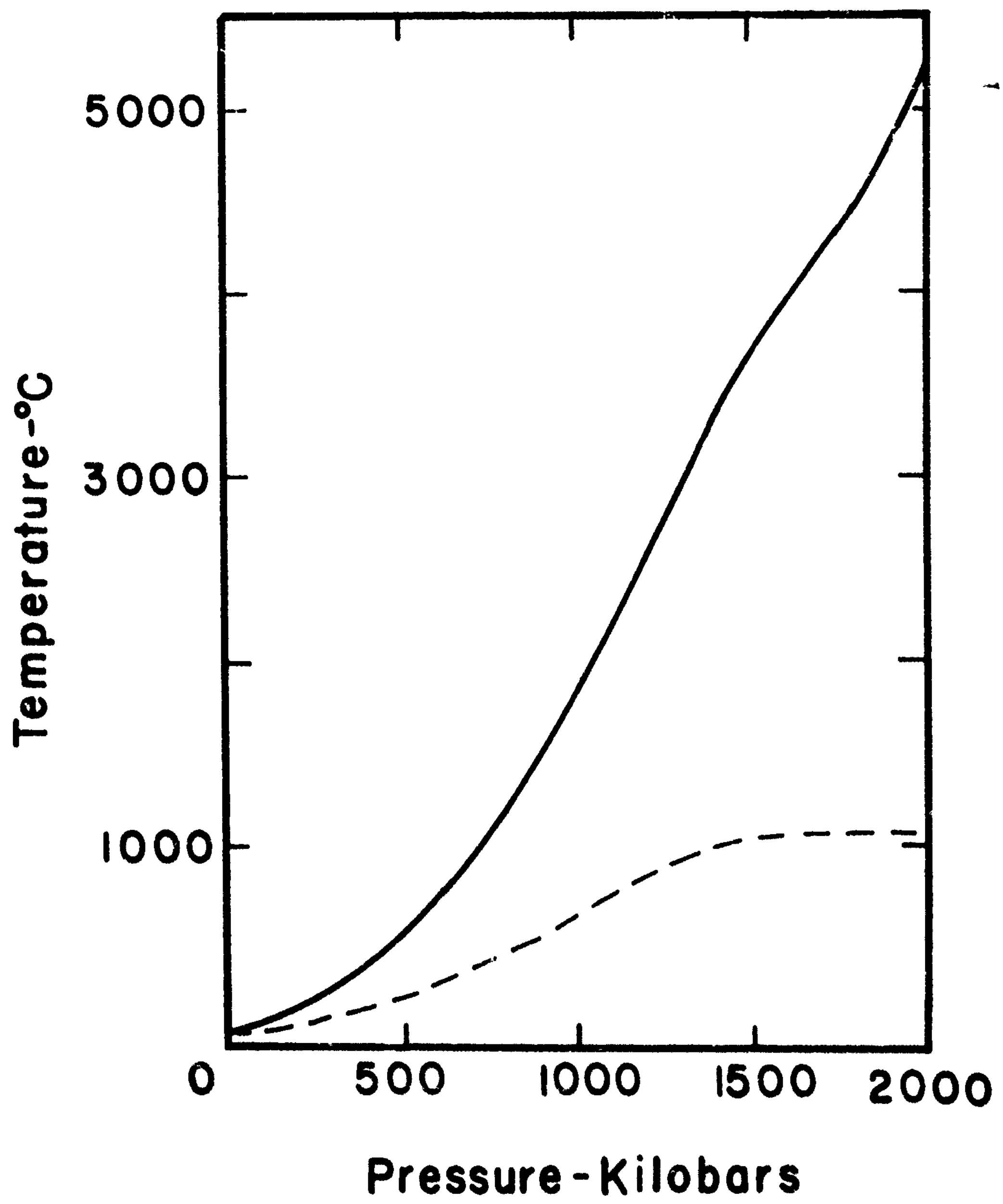
GOLD

Temperatures associated with shock

Gold

Pressure (kilobars)	Temperatures behind shock (C^o)	Residual temperature (C^o)
0	20	20
100	74	24
200	146	44
300	246	82
400	378	136
500	543	201
600	741	277
700	970	359
800	1230	447
900	1518	539
1000	1834	632
1100	2175	727
1200	2539	821
1300	2926	915
1400	3334	1007
1500	3693	1063
1600	3951	1063
1700	4216	1063
1800	4487	1063
1900	4764	1063
2000	5257	1131

Source: McQueen and Marsh, 1960


5000
3000
1000
Temperature-°C
0
500
1000
1500
2000
Pressure-Kilobars

GOLD

GRANITE

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.383	0.485	0.068	0.915 (1)
5.37	1.31	0.182	0.756 (1)
5.825	2.220	0.337	0.6189(1)
5.71	0.490	0.0743	0.914 (2)
5.58	0.822	0.123	0.853 (2)
5.48	0.960	0.143	0.826 (3)
5.506	1.15	0.148	0.791 (4)
5.658	1.63	0.246	(4)
5.64	1.625	0.247	0.712 (3)
5.61	1.715	0.2565	0.693 (4)
6.31	2.63	0.446	0.584 (3)
7.64	3.35	0.680	0.558 (4)
8.27	4.00	0.884	0.516 (2)

$\rho_o = 2.61$

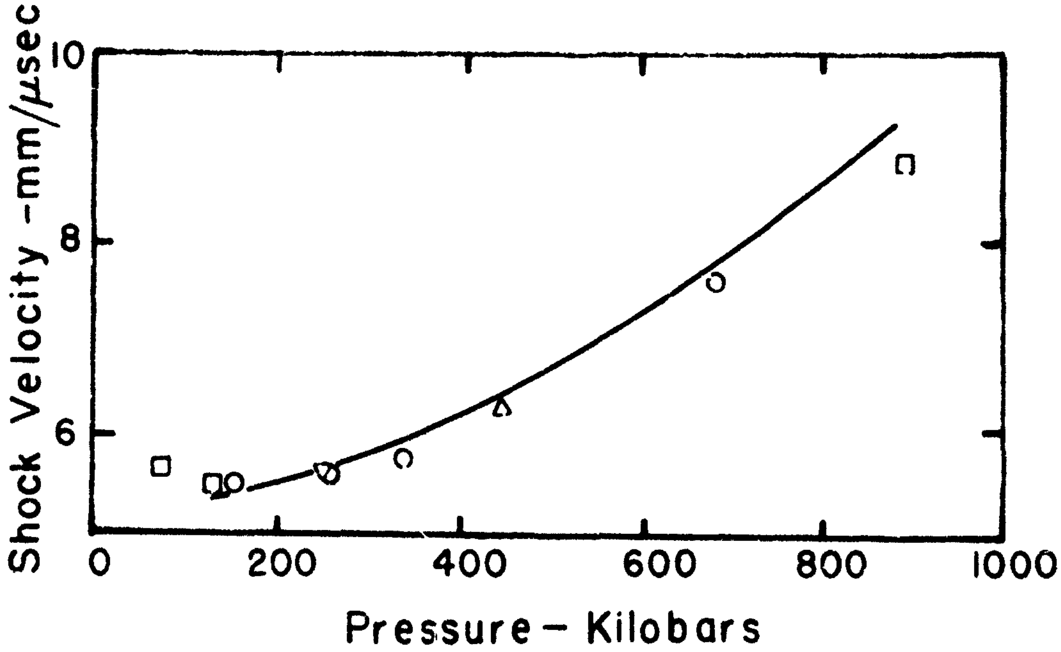
Source: Lombard (1961)

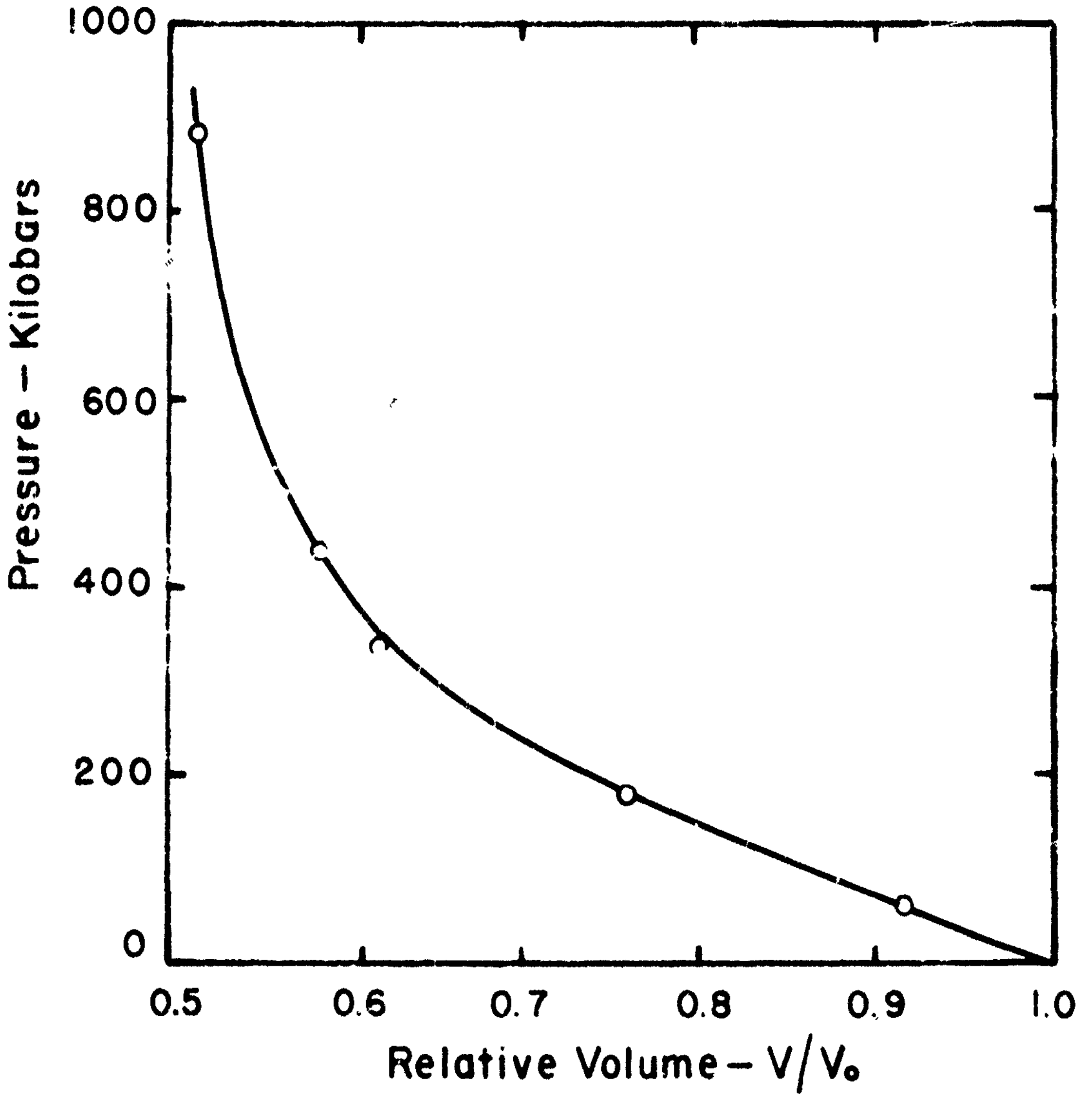
(1) Pink quartz monzonite, surface, Nevada Test Site Area 15

(2) Origin undetermined

(3) Stanford Research Institute exploratory core, 1005 ft, Nevada Test Site Area 15

(4) Gray grandiorite, surface, Nevada Test Site Area 15


Shock Velocity -mm/μsec
10
8
6
0
200
400
600
800
1000
Pressure — Kilobars


1000
800
600
400
200
0
Pressure — Kilobars
0.5
0.6
0.7
0.8
0.9
1.0
Relative Volume — V/V₀

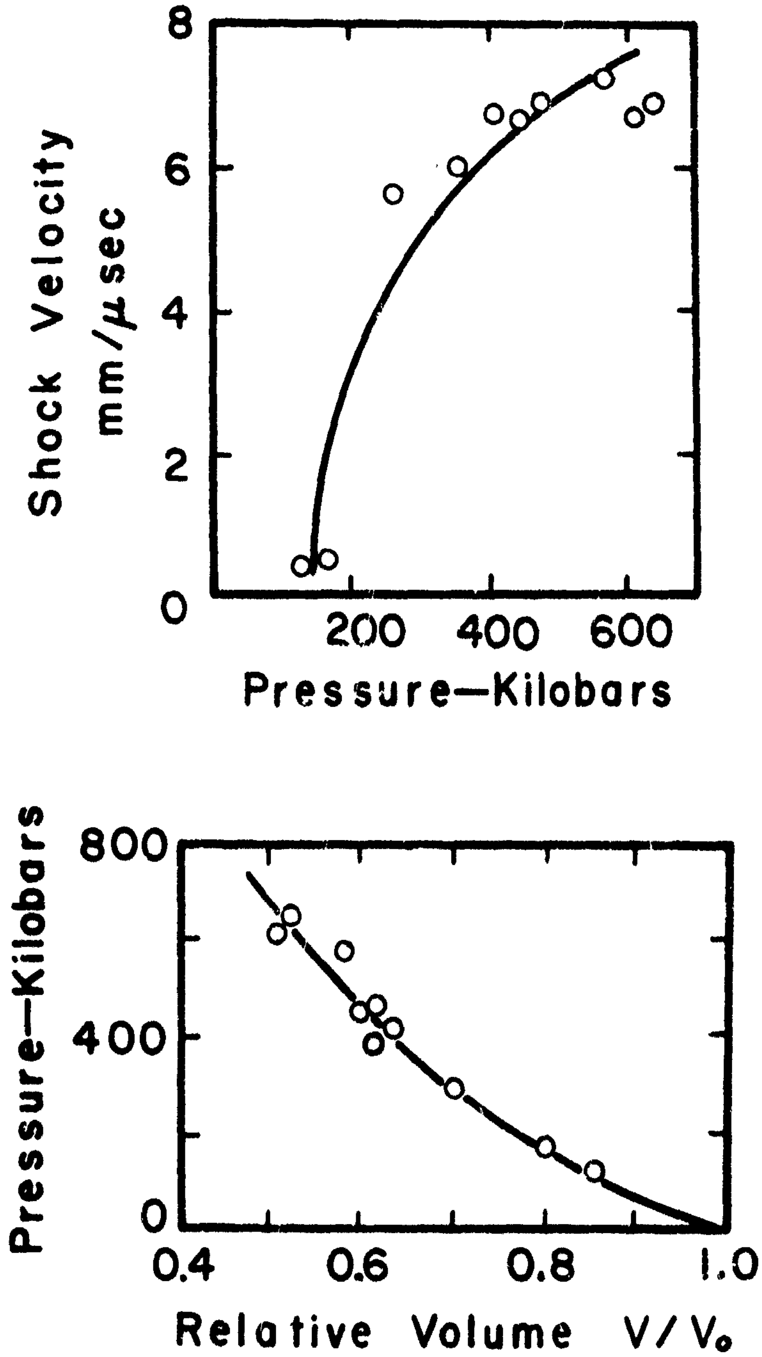
GRANITE

SHOAL GRANITE

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.98	1.80	285	0.699
6.15	2.36	386	0.616
6.60	2.38	416	0.639
6.57	2.60	453	0.604
6.81	2.58	466	0.621
7.16	3.02	573	0.578
6.86	3.42	622	0.501
7.04	3.45	644	0.510
0.493	0.98	128	0.859
0.500	1.22	160	0.800

$\rho_0 = 2.65$

Source: Bass, Hawk and Chabai (1963)



SHOAL GRANITE

PYROLYTIC GRAPHITE

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.93	0.461	50.1	0.929
5.88	0.663	85.8	0.904
6.20	0.852	116	0.883

ρ_0 = 2.20

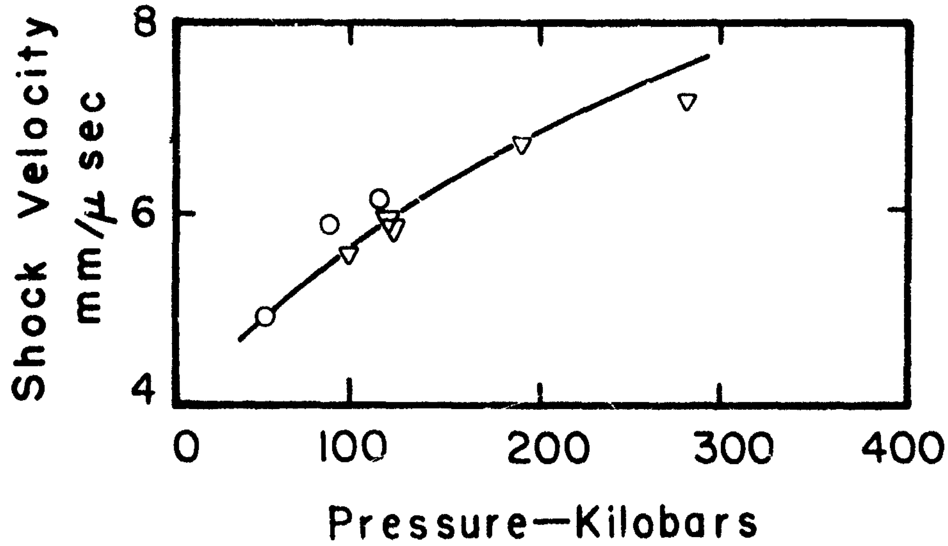
Source: Wagner, Waldorf and Louie (1962)

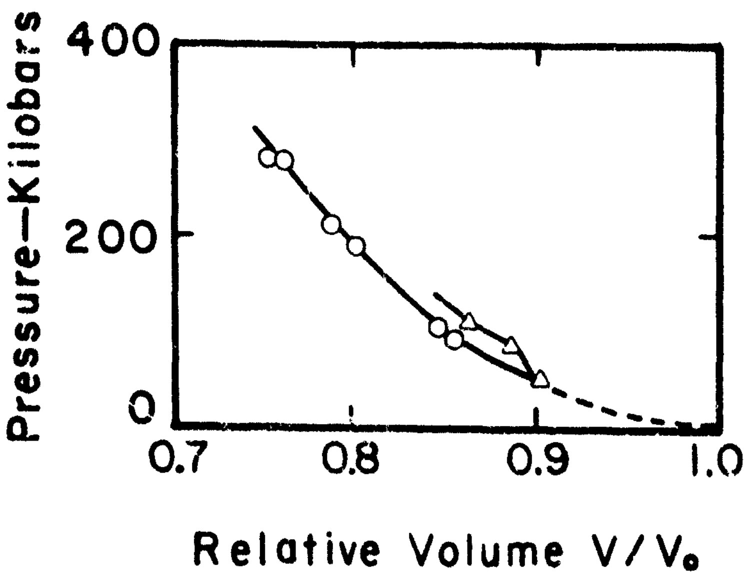
PYROLYTIC GRAPHITE

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.59	0.807	98	0.858
5.91	0.963	123	0.842
5.98	0.961	117	0.851
5.95	0.967	122	0.844
6.65	1.33	193	0.802
7.19	1.78	281	0.752

ρ_0 = 2.20

Source: Doran (1963)





PYROLYTIC GRAPHITE

HALIDES

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Cesium Bromide (single crystal)			
3.41	0.97	146	0.716
3.33	1.25	213	0.672
4.15	1.52	280	0.632
4.38	1.69	328	0.614

$\rho_0 = 4.414$

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Cesium Chloride			
2.92	0.51	60	0.825
3.75	1.04	154	0.723
3.350	1.13	17[illegible]	0.707
4.47	1.23	270	0.658
4.70	1.7[illegible]	316	0.636

$\rho_0 = 3.960$

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Cesium Iodide (single crystal)			
3.12	1.00	140	0.680
3.51	1.23	195	0.649
3.94	1.55	274	0.608
4.19	1.71	324	0.590

$\rho_0 = 4.481$

HALIDES (cont)

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Lithium Bromide			
4.12	1.02	136	0.752
4.51	1.36	194	0.712
4.96	1.63	267	0.672
4.97	1.805	300	0.637
$\rho_0 = 3.30$			
Lithium Chloride			
5.49	1.087	121	0.802
5.80	1.415	170	0.756
6.32	1.780	230	0.720
6.57	1.941	263	0.704
$\rho_0 = 2.06$			
Lithium Fluoride (single crystal)			
6.40	0.927	155	0.855
6.61	1.071	185	0.838
7.28	1.487	282	0.796
7.47	1.680	328	0.775
$\rho_0 = 2.614$			
Lithium Iodide (single crystal)			
4.01	1.270	205	0.683
4.24	1.575	268	0.628
4.47	1.780	320	0.602
$\rho_0 = 4.016$			

HALIDES (cont)

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Potassium Bromide (single crystal)			
3.52	1.16	112	0.670
4.06	1.46	161	0.641
4.58	1.74	218	0.618
4.88	1.97	264	0.596

$\rho_0 = 2.73$

Potassium Chloride

2.30	0.67	40	0.77
4.04*	1.21	97	0.698
4.64	1.57	144	0.661
5.19*	1.88	194	0.636
5.51	2.13	232	0.613
5.54*	2.08	229	0.624

$\rho_0 = 1.950$

* Single crystal

Potassium Fluoride

4.23	1.11	117	0.738
4.69	1.43	168	0.695
5.24	1.78	232	0.661
5.54	1.94	266	0.650

$\rho_0 = 2.485$

Potassium Iodide

3.28	1.10	110	0.668
3.70	1.40	161	0.624
4.22	1.72	227	0.594
4.47	1.99	278	0.555

$\rho_0 = 3.10$

HALIDES (cont)

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Rubidium Bromide			
3.16	1.08	112	0.659
3.62	1.38	163	0.621
4.16	1.73	237	0.585
4.44	1.96	286	0.559

$\rho_0 = 3.285$

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Rubidium Chloride			
3.43	1.16	109	0.663
3.91	1.44	151	0.632
4.48	1.82	222	0.594
4.87	2.04	268	0.581

$\rho_0 = 2.752$

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Rubidium Iodide			
3.01	1.11	117	0.633
3.44	1.37	163	0.601
3.95	1.73	235	0.554
4.24	1.91	279	0.522

$\rho_0 = 3.50$

HALIDES (cont)

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Sodium Bromide			
3.38	0.55	58	0.838
3.34	0.54	57	0.839
4.00	1.06	133	0.736
4.29	1.30	177	0.697
4.38	1.36	189	0.689
4.79	1.63	247	0.659
5.10	1.83	293	0.641
5.06	1.35	295	0.635
5.10	1.89	305	0.630

$\rho_0 = 3.165$

Sodium Chloride (see separate tables)

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Sodium Iodide (single crystal)			
3.58	1.02	134.	0.714
4.03	1.35	202	0.657
4.39	1.61	259	0.634
4.58	1.86	312	0.593

$\rho_0 = 3.64$

Source: Christian (1957)

ROCK SALT

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.652	0.891	89	0.809 (1)
5.018	1.170	126	0.767 (2)
5.382	1.392	161	0.741 (2)
5.325	1.377	162	0.755 (2)
5.511	1.400	166	0.746 (2)
5.874	1.747	220	0.7026(2)
5.870	1.79	226	0.695 (1)
6.07	1.99	258	0.672 (2)
6.122	1.98	260	0.677 (2)
6.088	1.996	262	0.672 (2)
7.07	2.87	437	0.594 (2)
7.10	2.85	436	0.599 (2)
7.17	2.96	457	0.587 (2)
7.465	2.98	479	0.601 (2)
8.24	3.49	620	0.577 (1)
8.425	3.90	709	0.537 (1)
8.73	3.92	735	0.551 (2)
9.118	4.445	856	0.5089(2)
9.157	4.596	865	0.498 (3)
9.025	4.54	882	0.497 (3)

$\rho_0 = 2.15$

Source: Lombard (1961)

(1) Louisiana dome salt: Carey Mine

(2) Origin undetermined

(3) New Mexico red potash ore

SODIUM CHLORIDE (SINGLE CRYSTALS)

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.19	0.59	53	0.863
4.73	0.98	100	0.794
5.29	1.33	152	0.736
5.41	1.55	182	0.719
5.59	1.59	193	0.714
5.66	1.71	209	0.699
5.96	1.85	236	0.689
6.13	2.07	276	0.666
7.85	3.24	547	0.588
8.91	4.10	790	0.541

$\rho_o = 2.16$

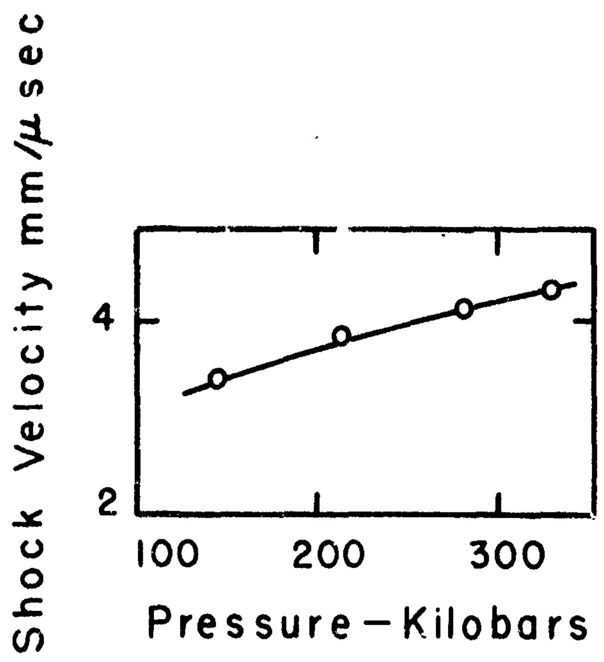
Source: Al'tshuler, Kuleshova and Pavlovskii (1960)

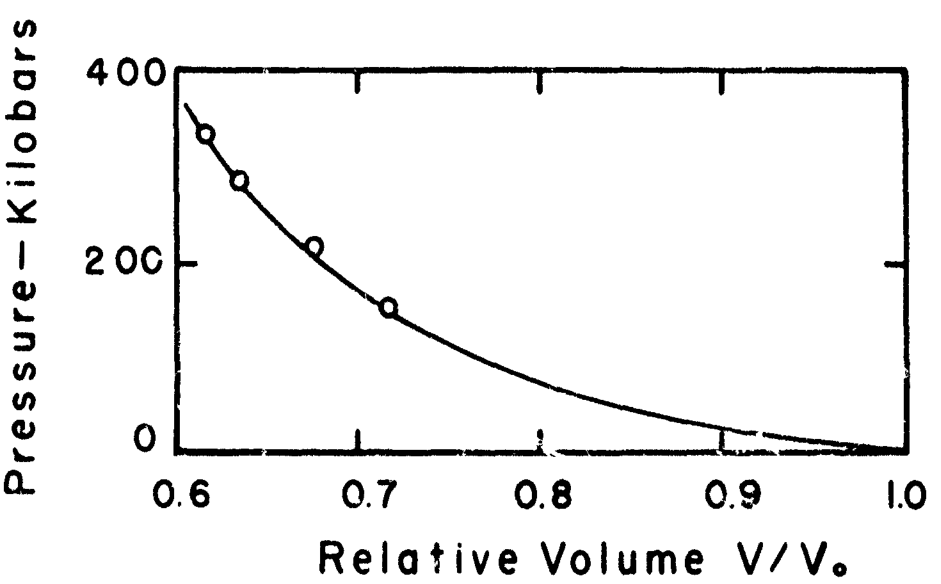
SODIUM CHLORIDE (SINGLE CRYSTALS)

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Crystal orientation to shock front: 100			
5.066	1.099	120	0.783
5.860	1.76	223	0.700
5.937	1.73	224	0.710
6.064	1.860	243	0.693
6.237	1.963	2655	0.6853
6.24	2.05	277	0.671
6.34	2.28	313	C.640
6.36	2.35	321	0.613
6.45	2.537	352	0.607
7.22	3.00	473	0.585
7.72	3.32	550	0.570
7.83	3.27	548	0.582
8.624	3.90	725	0.547
8.47	3.98	747	0.530
Crystal orientation to shock front: 111			
5.875	1.88	238	0.680
5.980	2.012	260	0.664
5.999	2.029	2645	0.6618
6.04	2.09	272	0.656
6.25	2.27	308	0.637
8.66	3.92	730	0.547

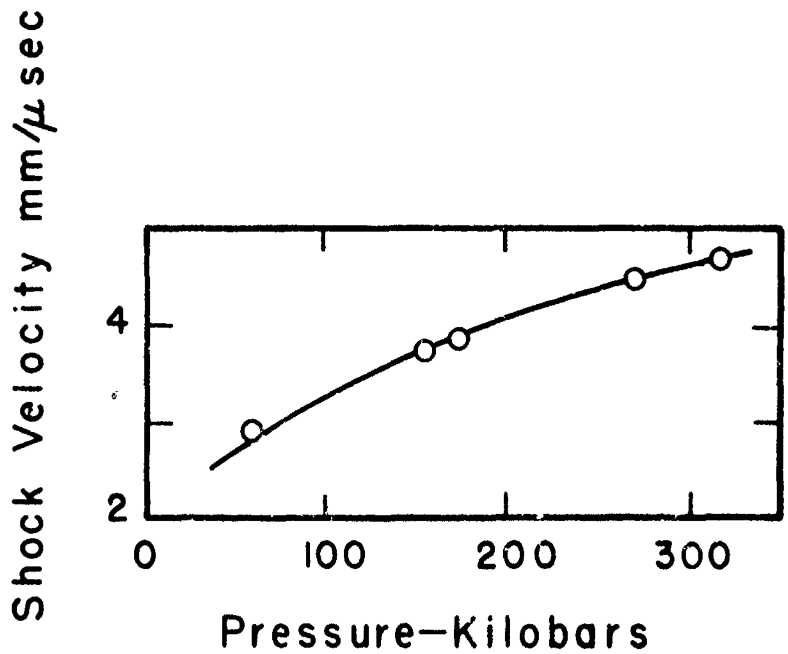
$\rho_0 = 2.15$

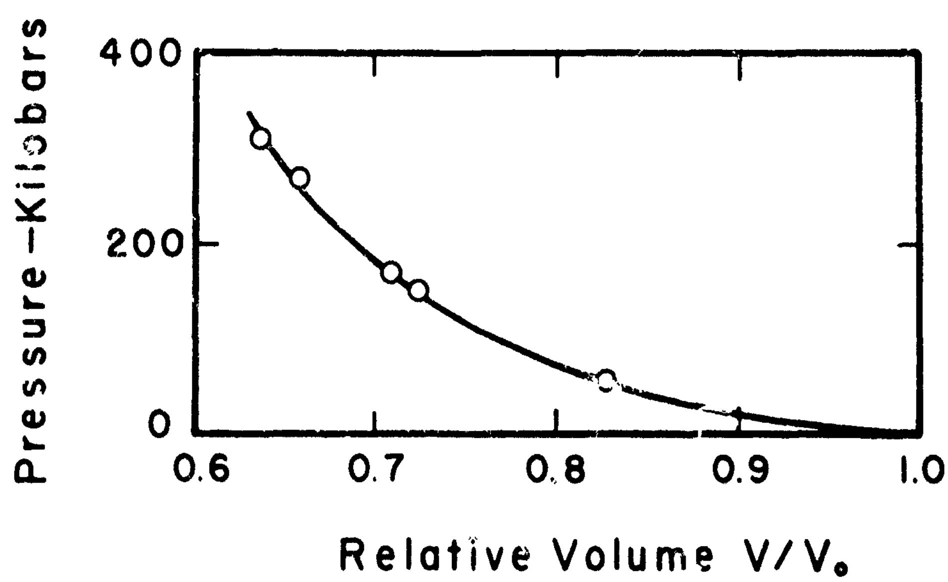
Source: Unpublished data: LRL



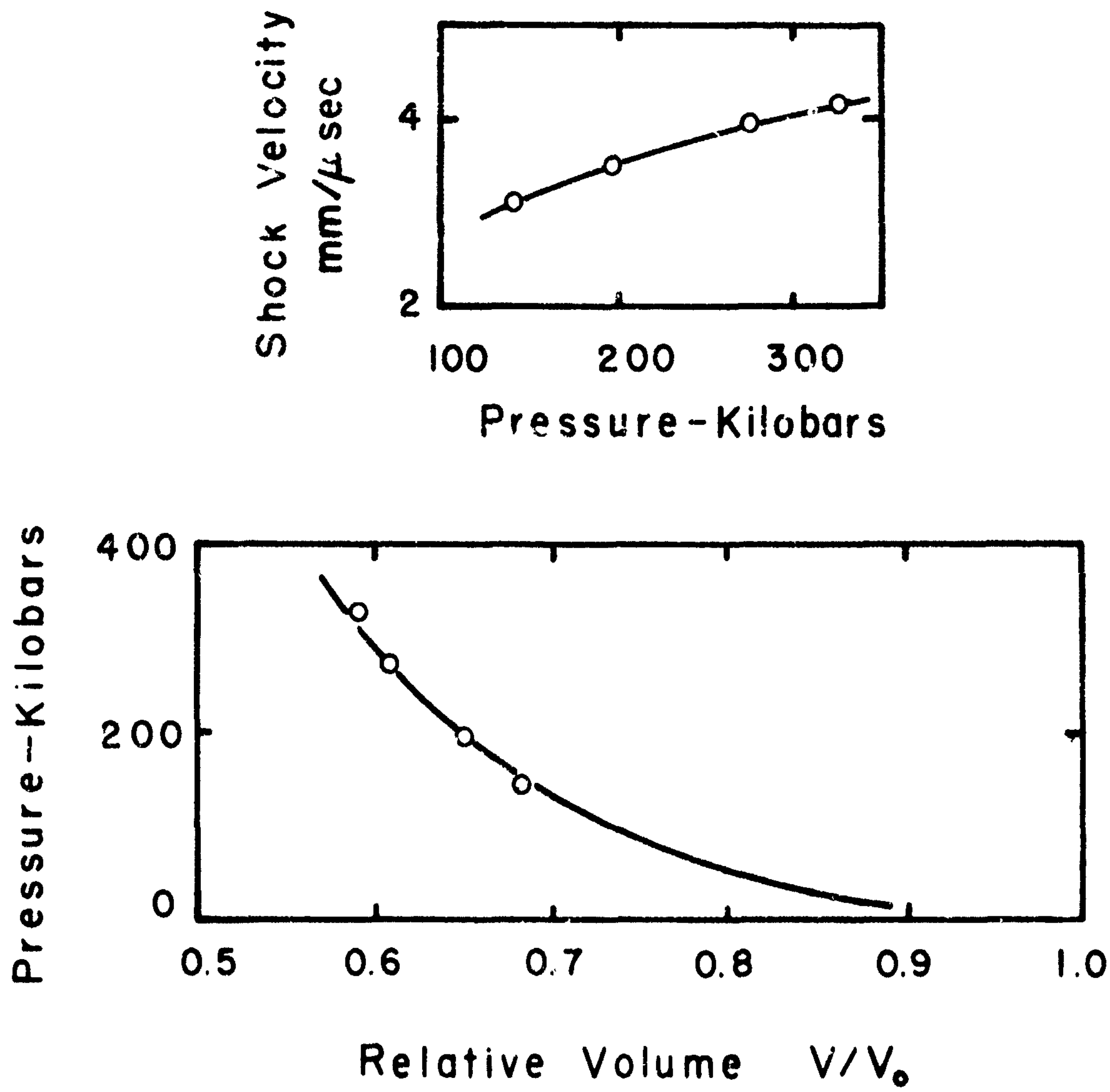


CESIUM BROMIDE





CESIUM CHLORIDE



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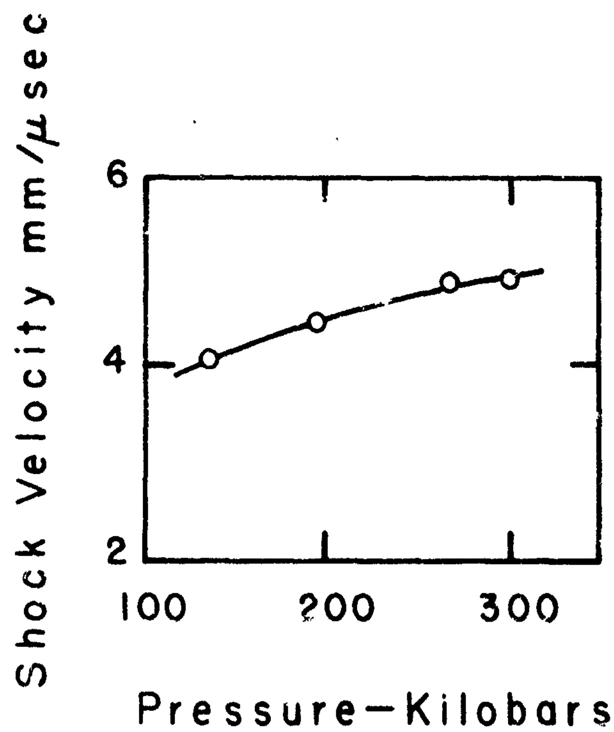
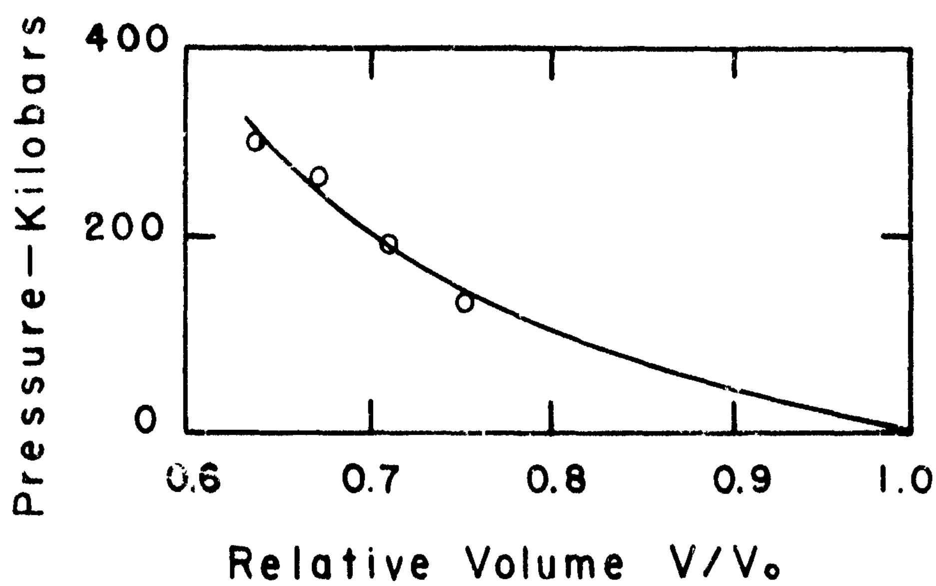
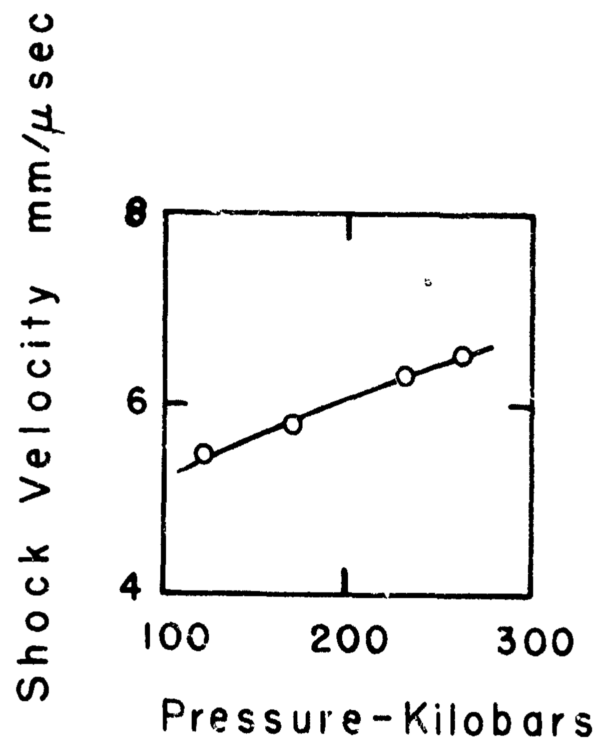
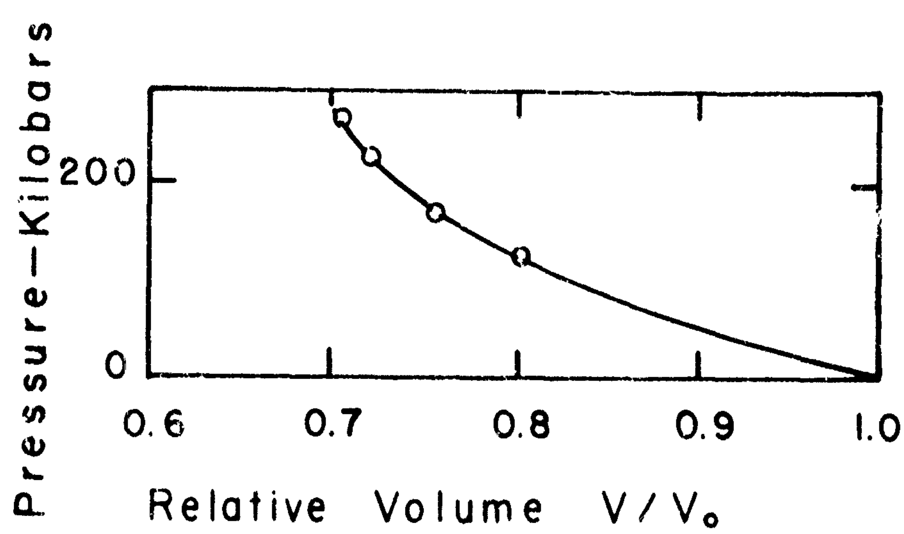




LITHIUM BROMIDE





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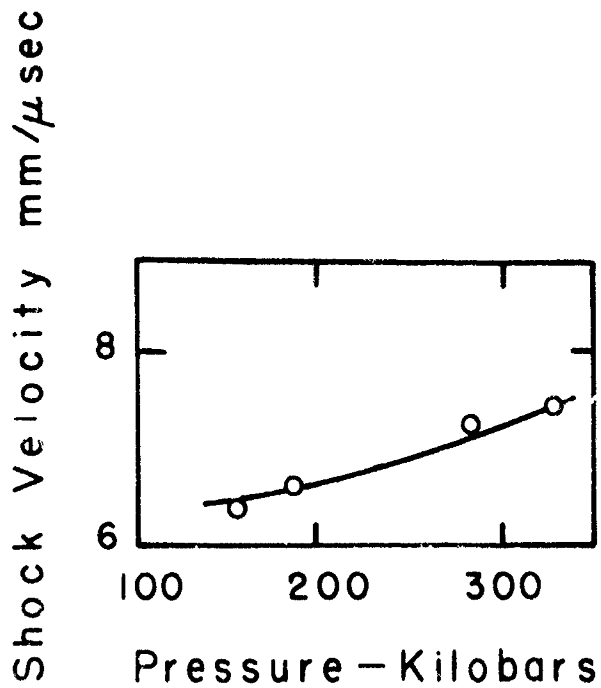

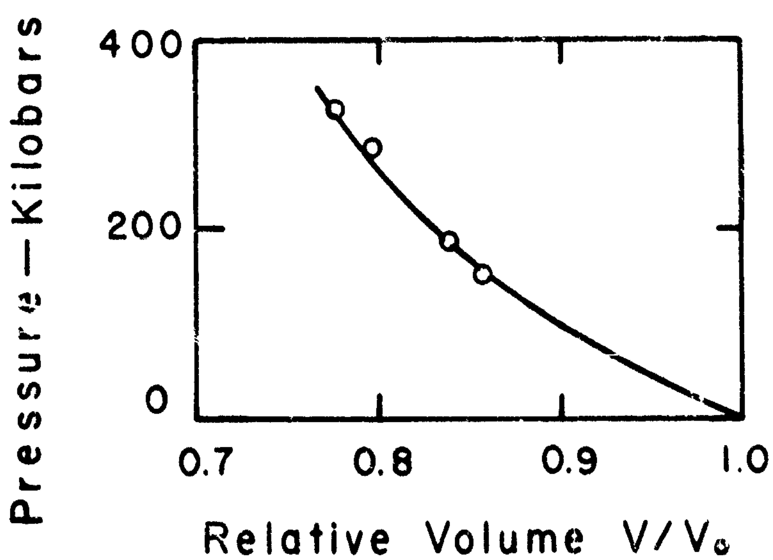

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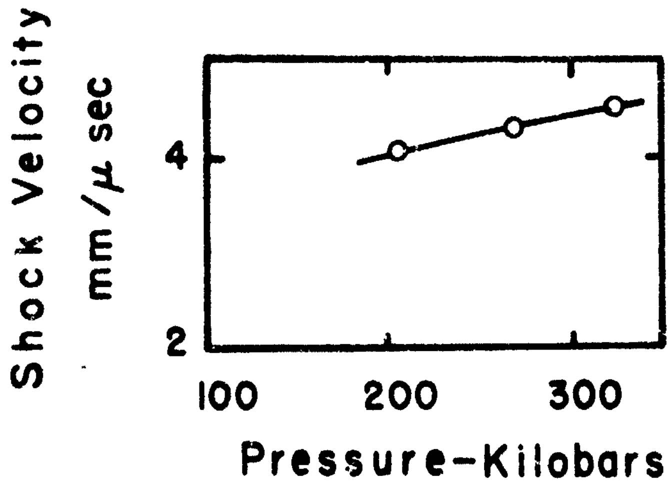

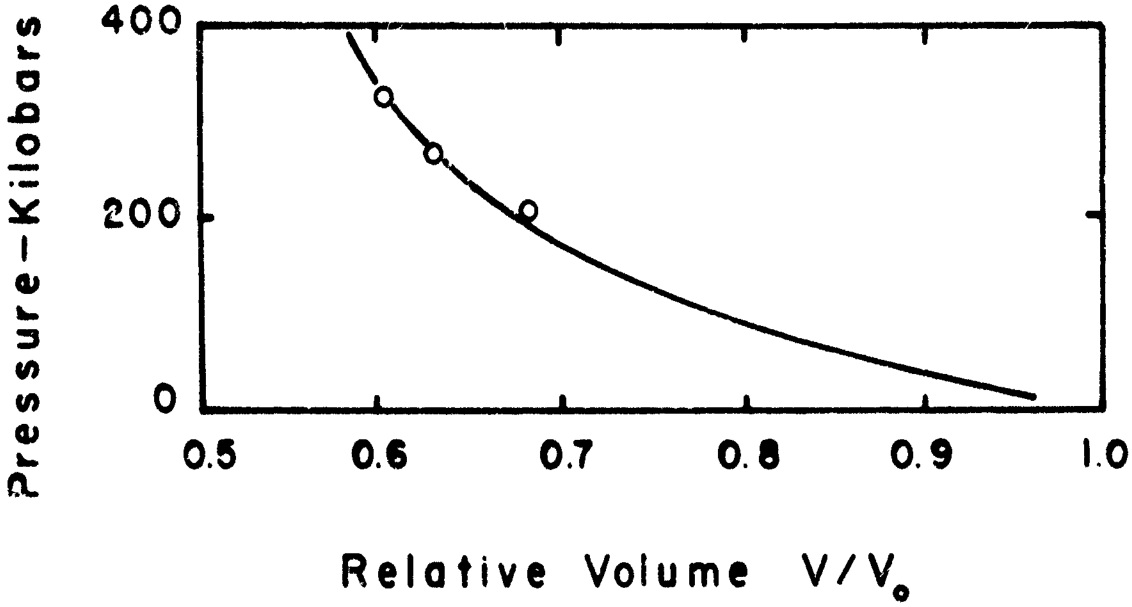

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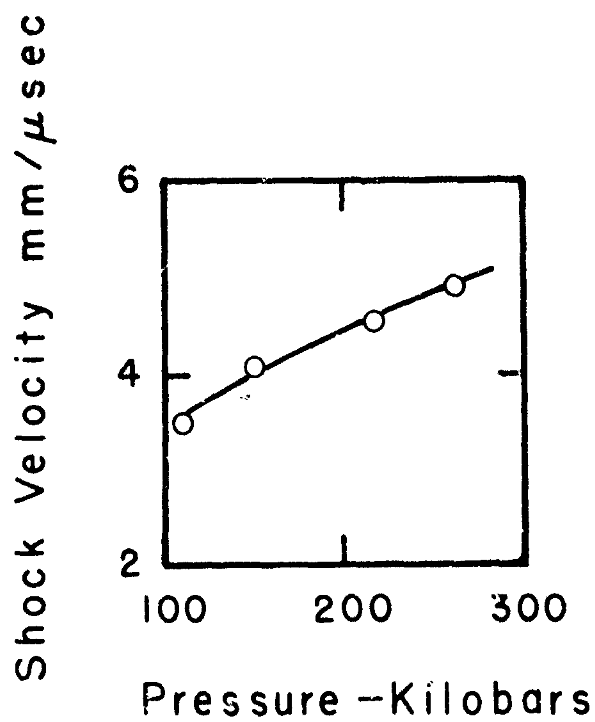

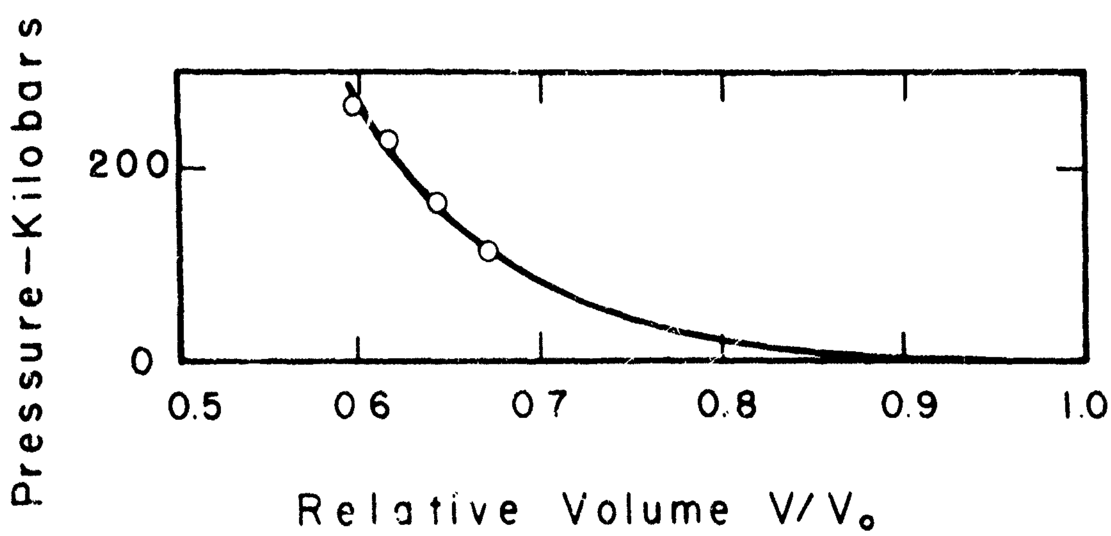

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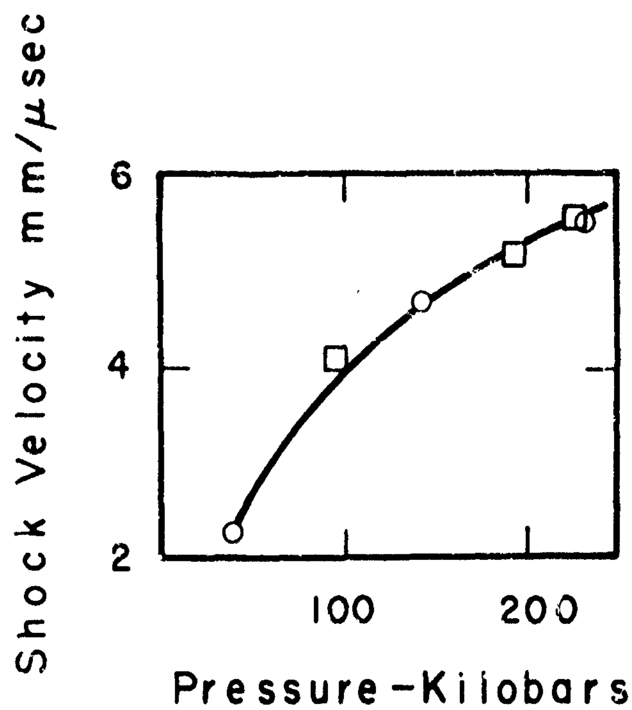

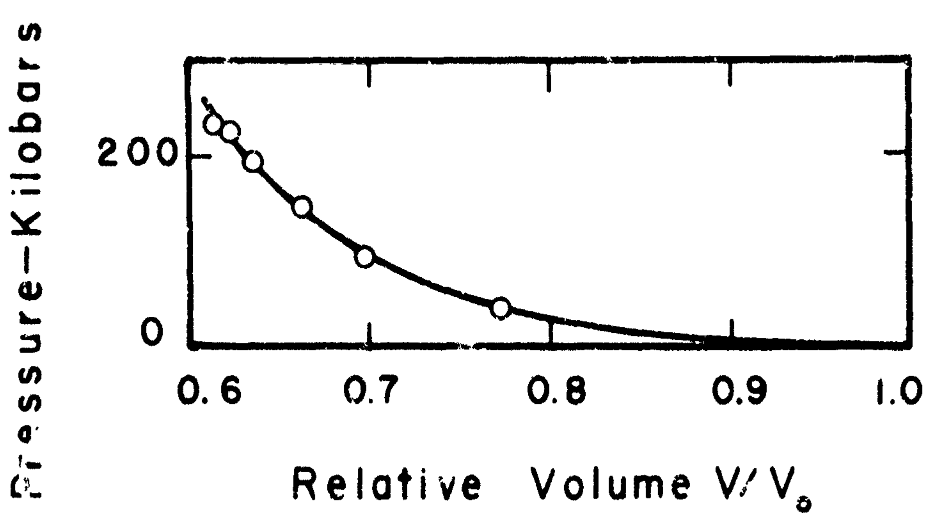

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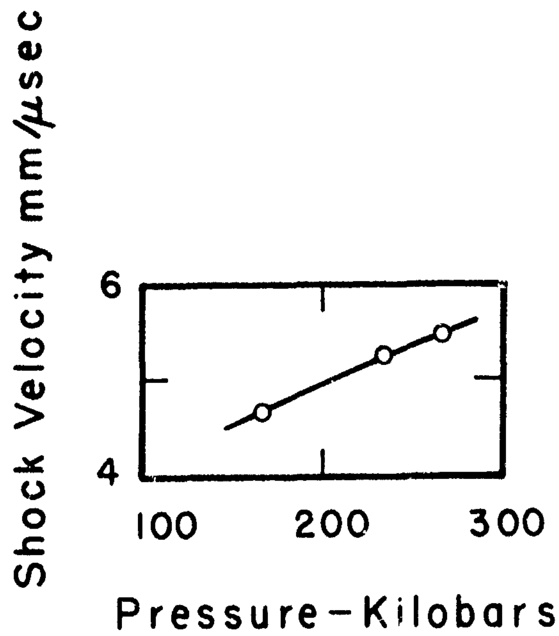

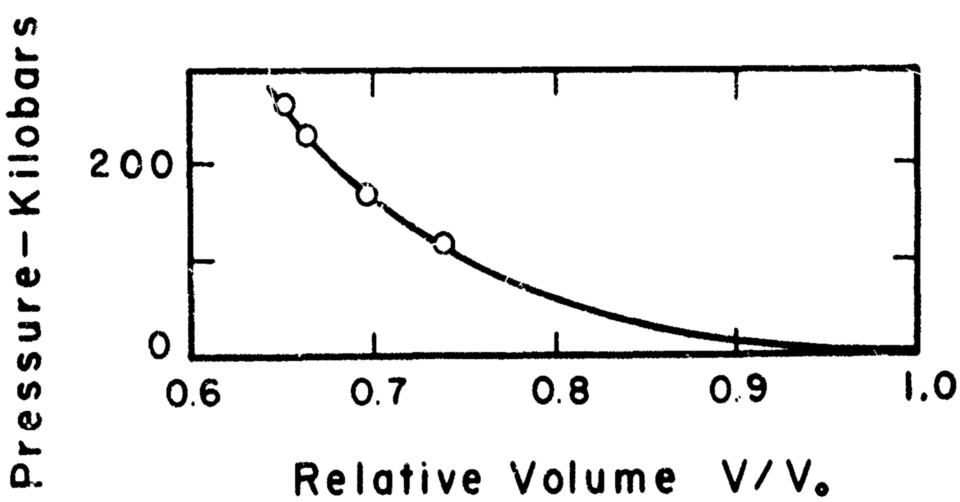

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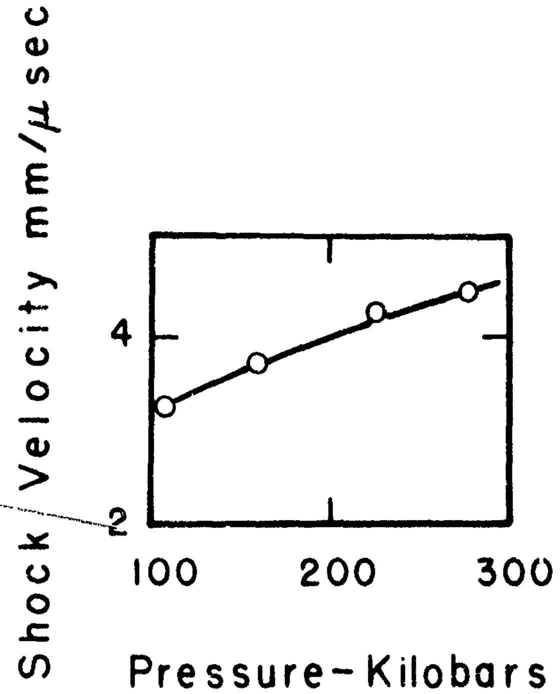

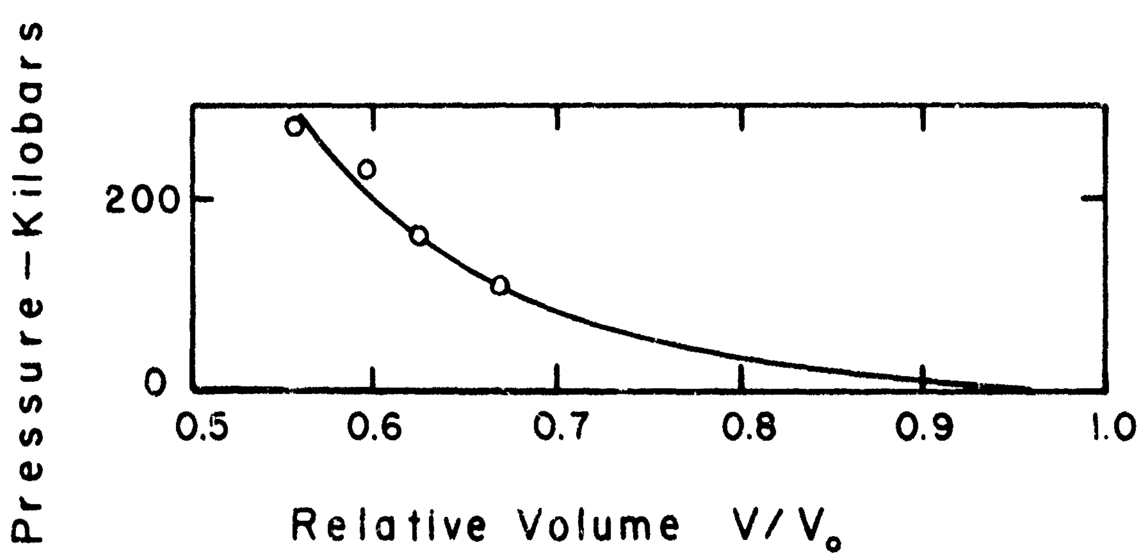

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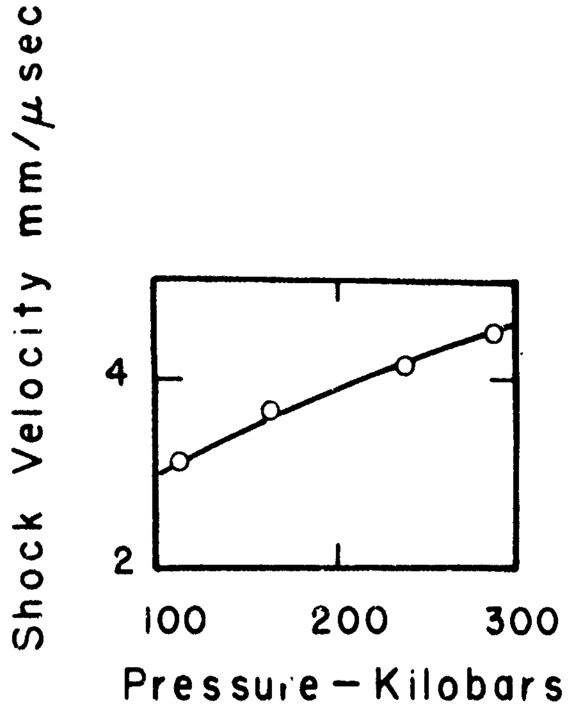
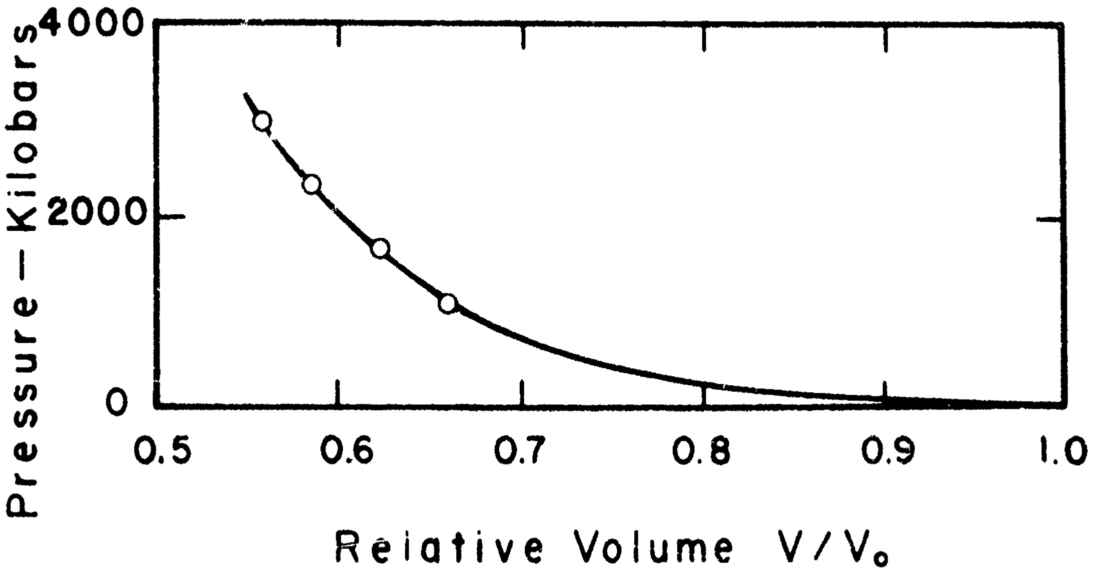
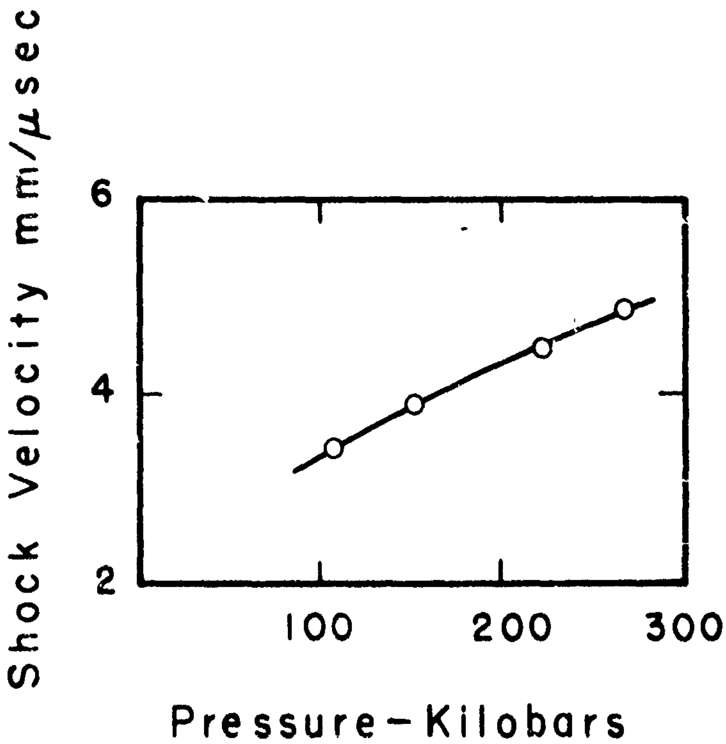
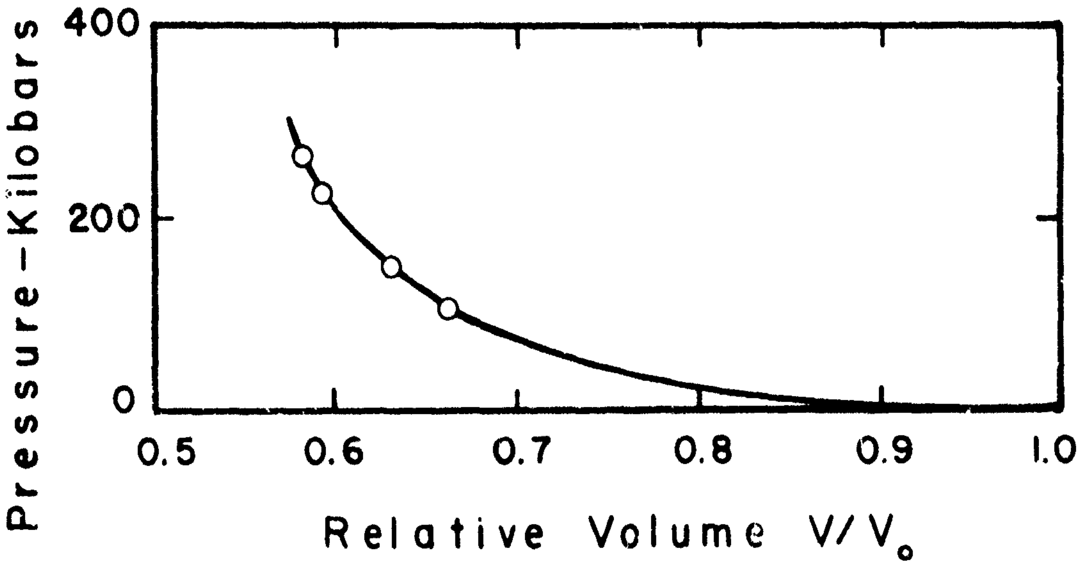




RUBIDIUM BROMIDE





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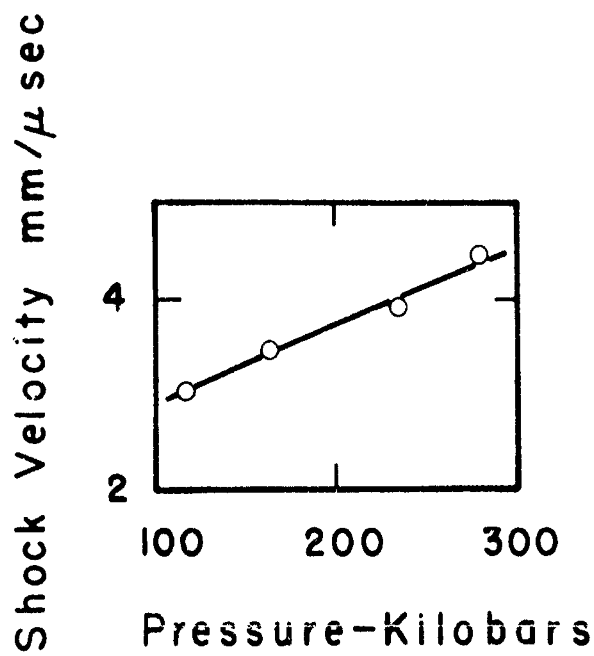

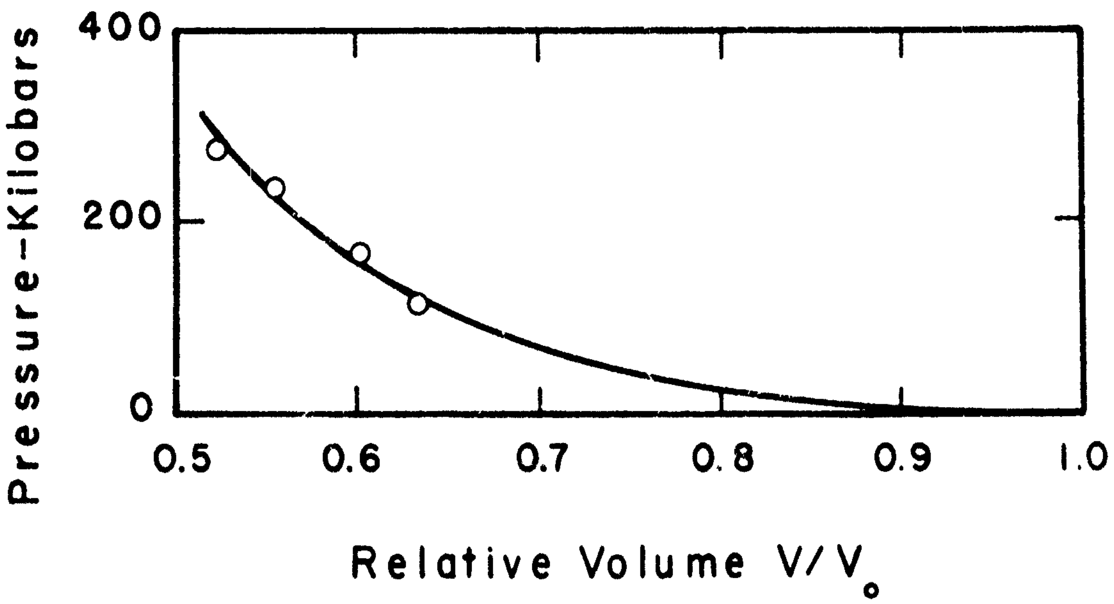

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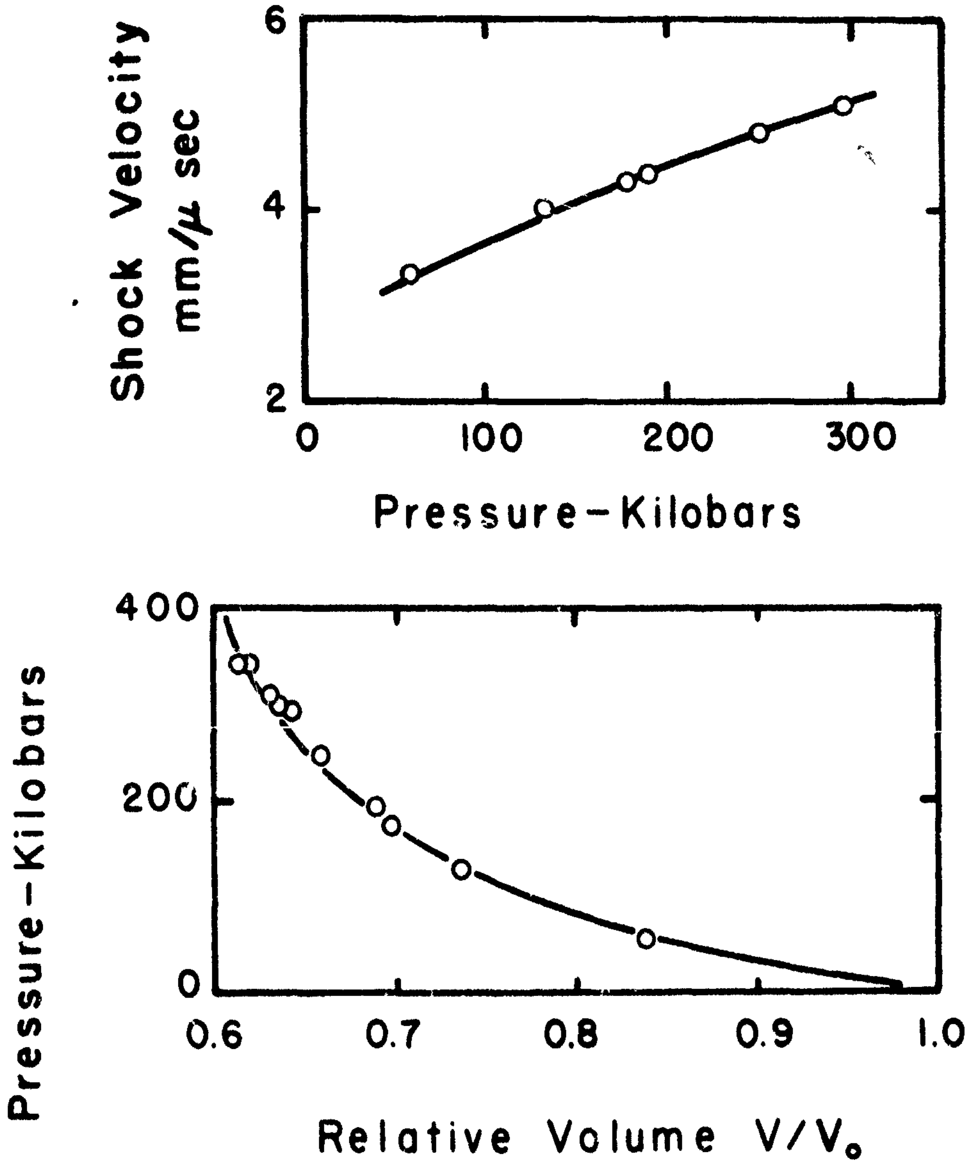
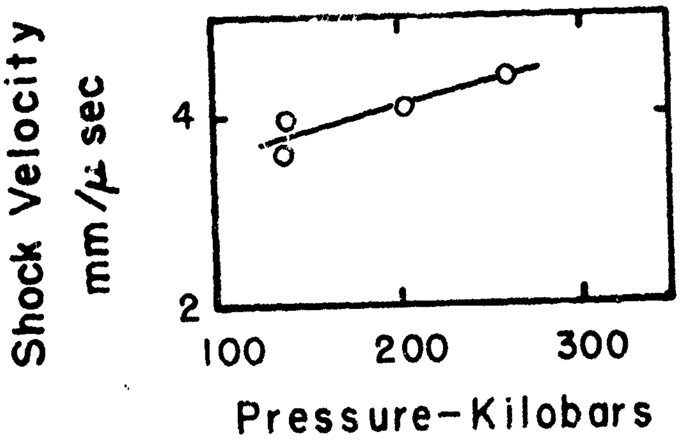
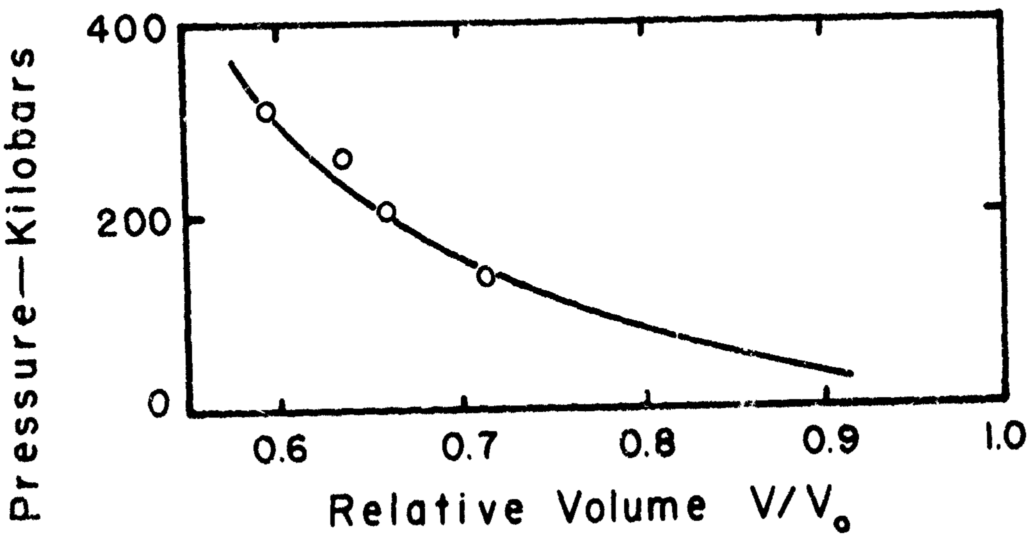
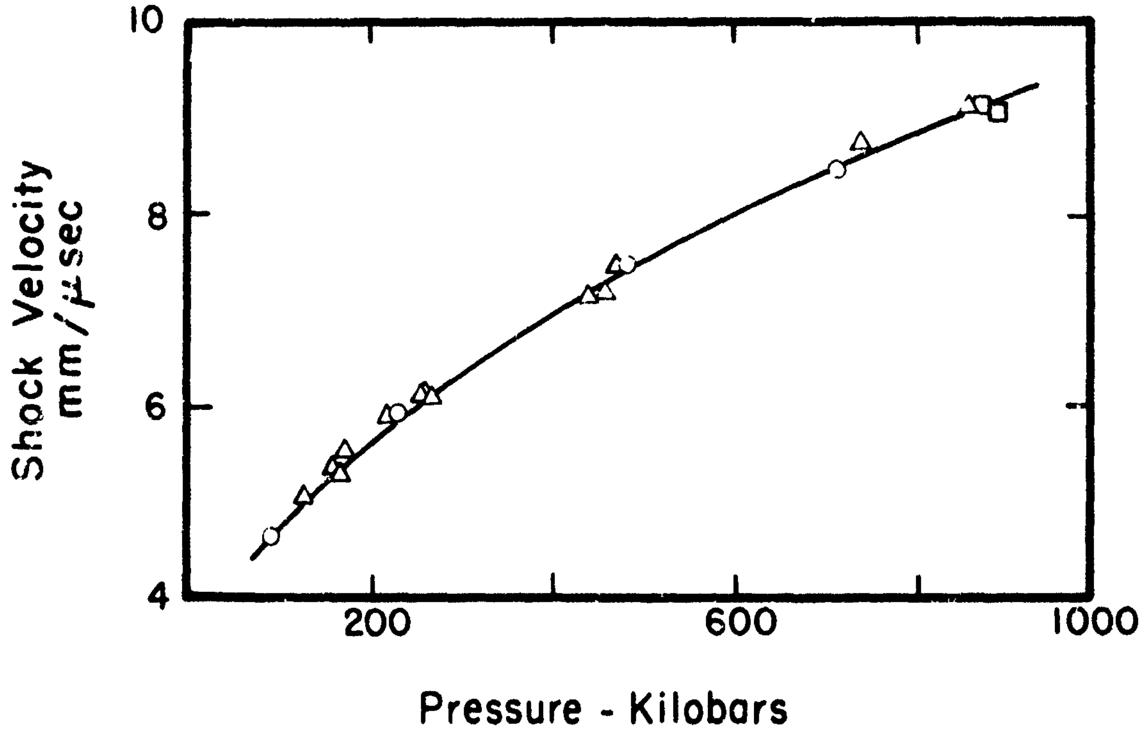


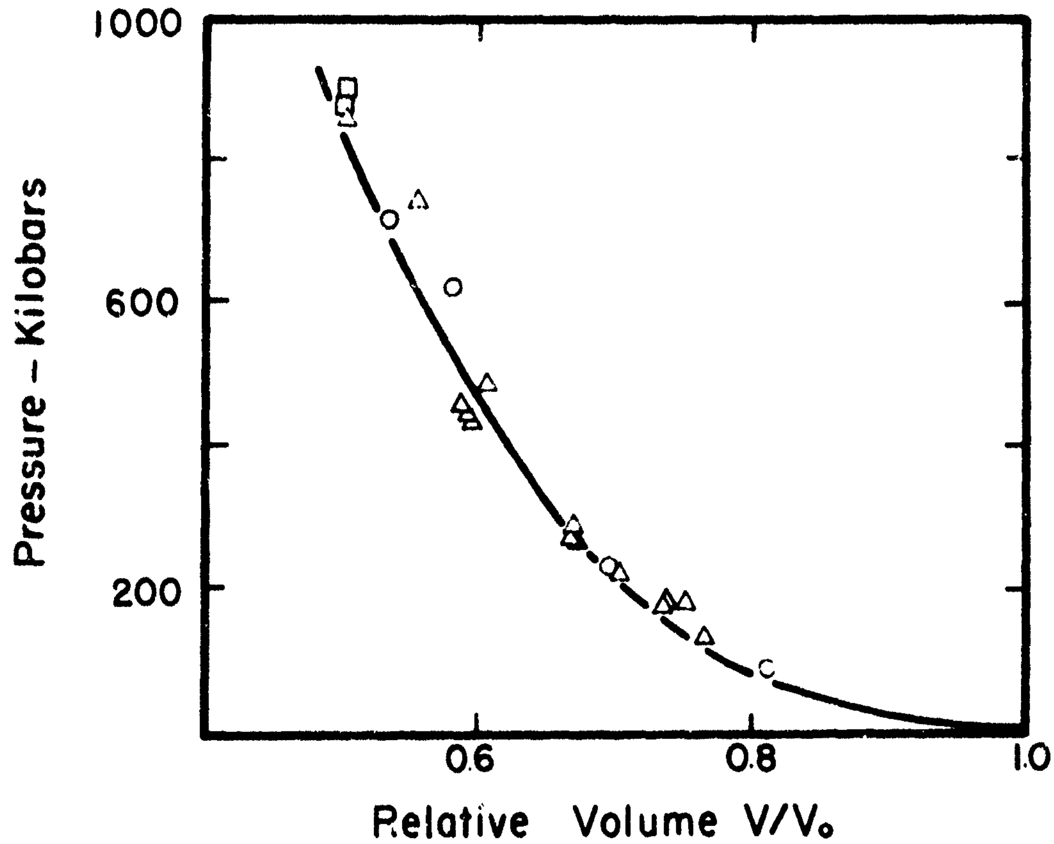
SODIUM BROMIDE



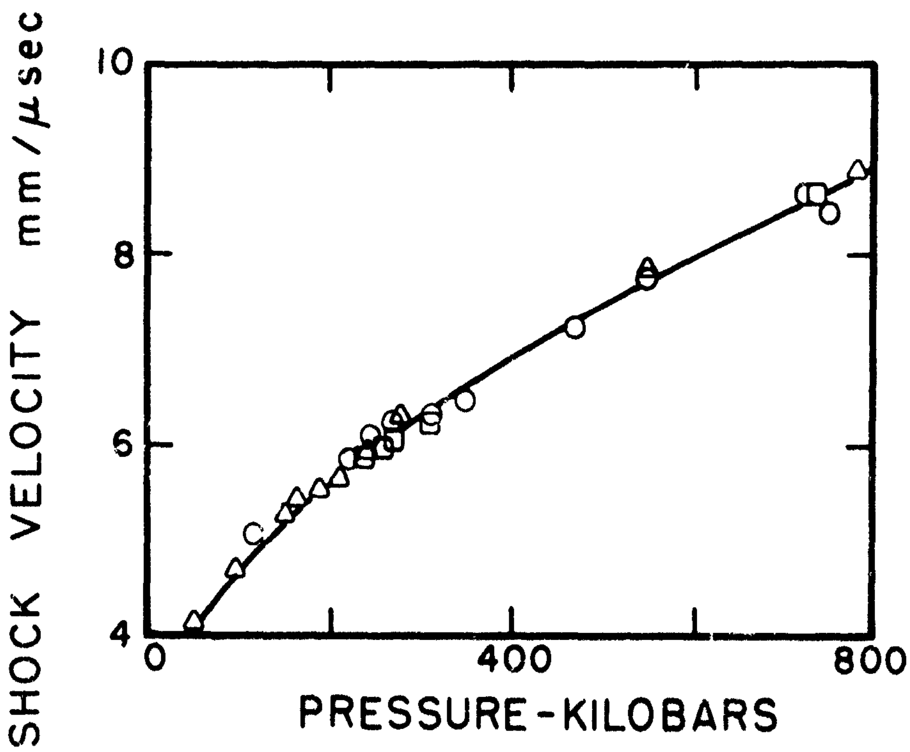


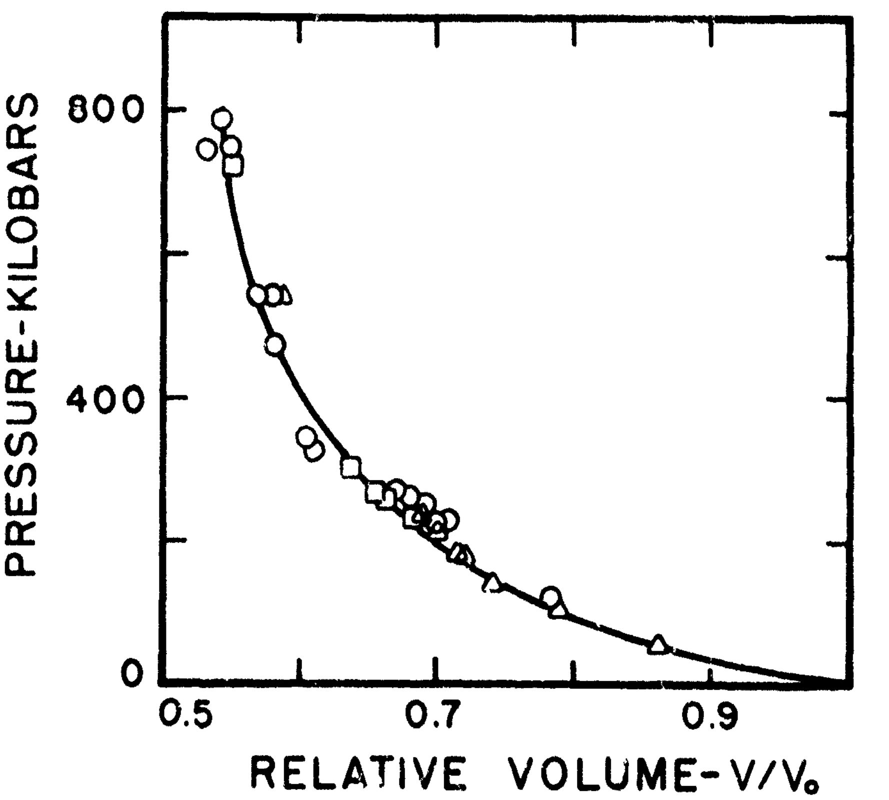
SODIUM IODIDE


10
8
6
4
Shock Velocity
mm/μsec
200
600
1000
Pressure - Kilobars


1000
600
200
Pressure – Kilobars
0.6
0.8
1.0
Relative Volume V/Vo

ROCK SALT





SODIUM CHLORIDE

Temperatures associated with shock

Halides

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
Cesium bromide		
0	20	20
146	950	425
213	1620	645 (M-2%)
280	2600	645 (M-80%)
328	3200	850 (L)
Cesium chloride		
0	20	20
60	265	100
154	910	340
172	1075	390
270	2100	560 (T)
318	2700	650 (T, M-50%)
Cesium iodide		
0	20	20
140	1400	490
195	2300	630 (M-30%)
274	3800	750 (L)
324	4700	900 (L)

Source: Christian, 1957

(M- %) indicates the final state is at the "melting point" with % liquid

(L) indicates the liquid state

(T) indicates a transition is assumed to occur in the rarefaction only

Temperatures associated with shock

Halides

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
Lithium bromide		
0	20	20
136	425	170
194	695	290
267	1080	435
300	1645	520
Lithium chloride		
0	20	20
121	235	74
170	425	170
230	635	290
263	805	400
Lithium fluoride		
0	20	20
155	134	62
185	175	80
282	315	155
328	410	200

Source: Christian, 1957

Temperatures associated with shock

Halides

Pressure (kilobars)	Temperature behind shock (C^o)	Residual temperature (C^o)
Potassium bromide		
0	20	20
112	1000	540
161	1600	630
218	2400	750 (L)
264	3100	900 (L)
Potassium chloride		
0	20	20
40	160	50
97	600	320
144	1060	620
194	1640	750 (M-45%)
232	2110	750 (M-70%)
229	2080	750 (M-70%)
Potassium fluoride		
0	20	20
117	400	235
168	600	335
232	1100	630
266	1400	750
Potassium iodide		
0	20	20
110	1100	400
161	1950	600
227	3200	900 (L)
278	4400	1000 (L)

Source: Christian, 1957

(M- %) indicates the final state is at the "melting point" with % liquid

(L) indicates the liquid phase

Temperatures associated with shock

Halides

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
Rubidium bromide		
0	20	20
112	1240	695 (M-40%)
163	2040	810 (L)
237	3200	1200 (L)
286	4100	1400 (L)
Rubidium chloride		
0	20	20
109	1080	700
151	1600	725 (M-75%)
222	2700	1050 (L)
268	3400	1100 (L)
Rubidium iodide		
0	20	20
117	1500	670 (L)
163	2600	1050 (L)
235	4200	1450 (L)
279	5150	1850 (L)

Source: Christian, 1957

(M- %) indicates the final state is at the "melting point" with % liquid

(L) indicates the liquid state

Temperatures associated with shock

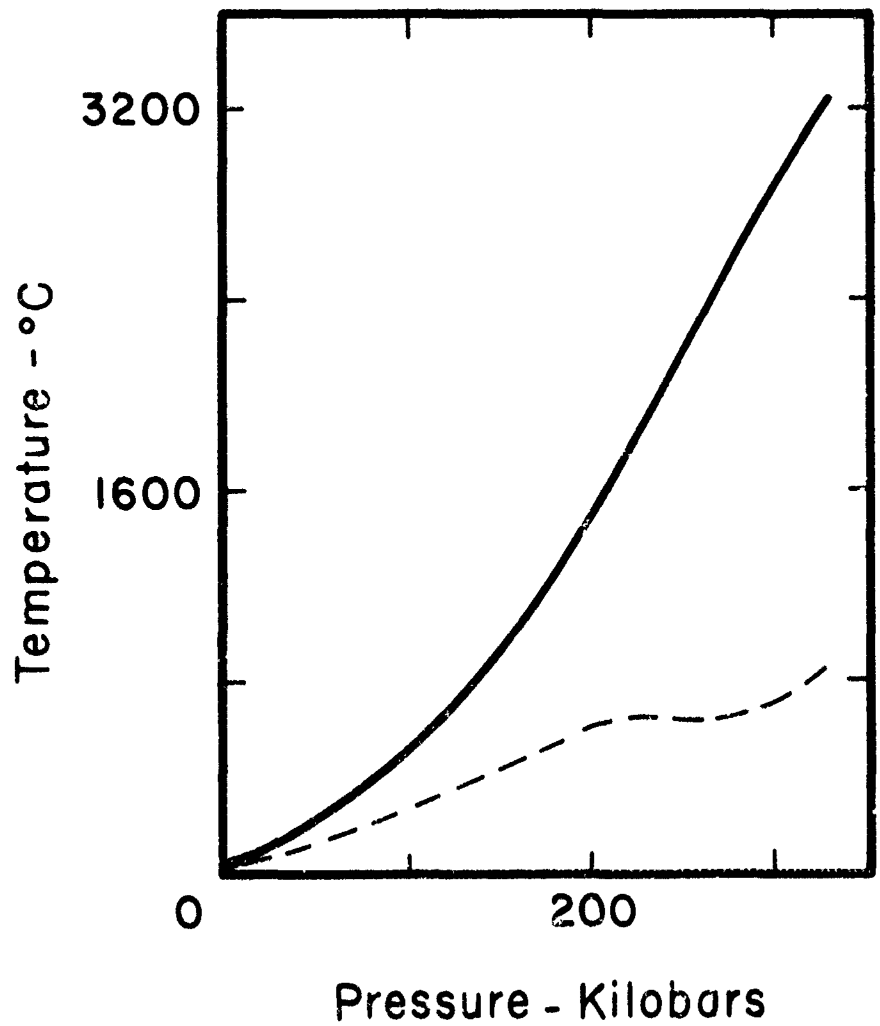
Halides

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
Sodium bromide		
0	20	20
58	150	95
57	145	95
133	475	215
177	750	330
189	830	365
247	1290	550
293	1725	725
295	1725	735
305	1825	775
Sodium chloride		
0	20	20
52	120	60
118	345	155
120	320	130
119	345	155
120	340	150
120	330	140
126	395	180
161	520	240
223	745	345
224	720	320
237	960	410
243	880	370
238	960	410
260	1100	470
259	1000	435
264	1060	450
270	980	410
264	1100	470

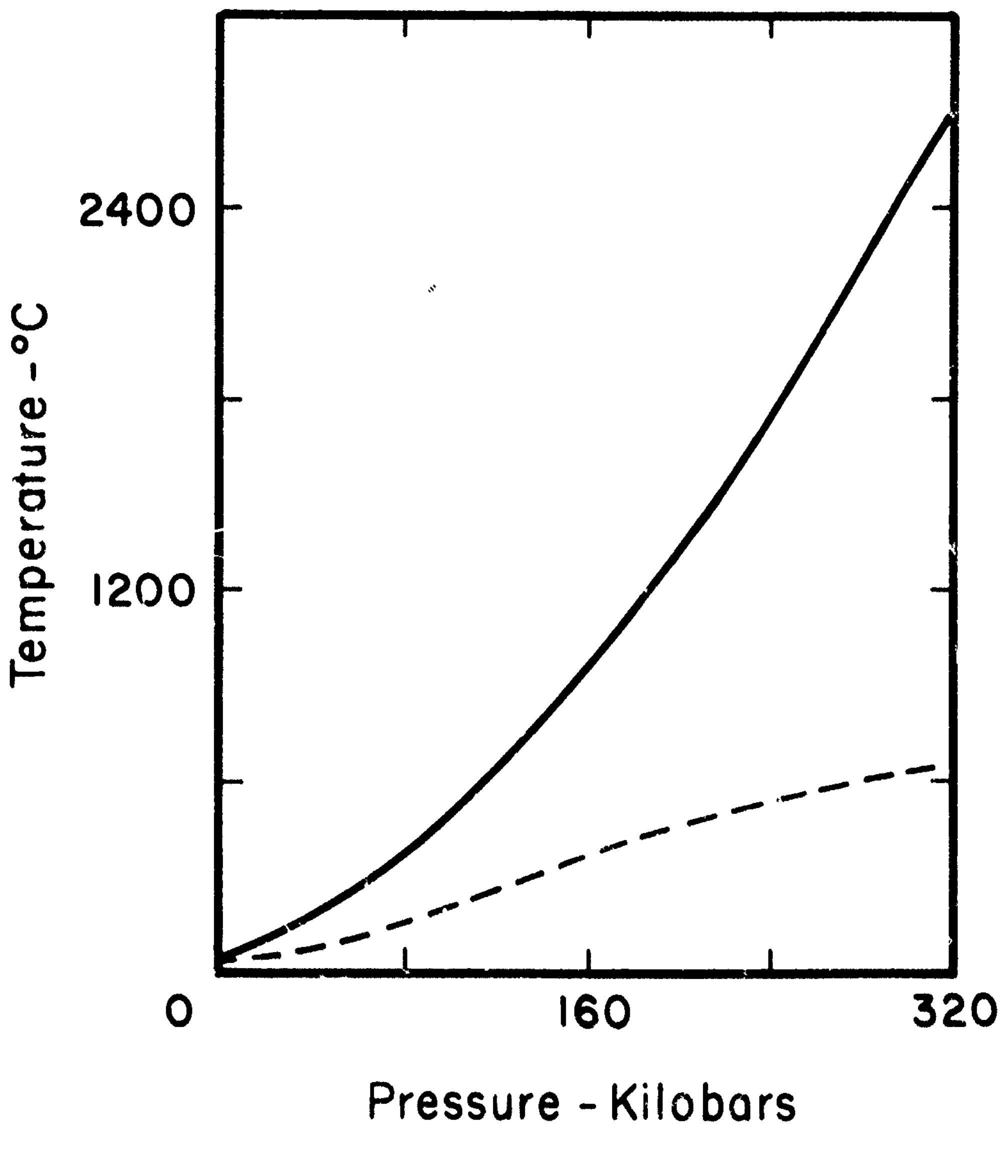
Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
Sodium iodide		
0	20	20
134	750	340
202	1350	650
259	2000	665 (M-30%)
312	2675	665 (M-85%)

Source: Christian, 1957

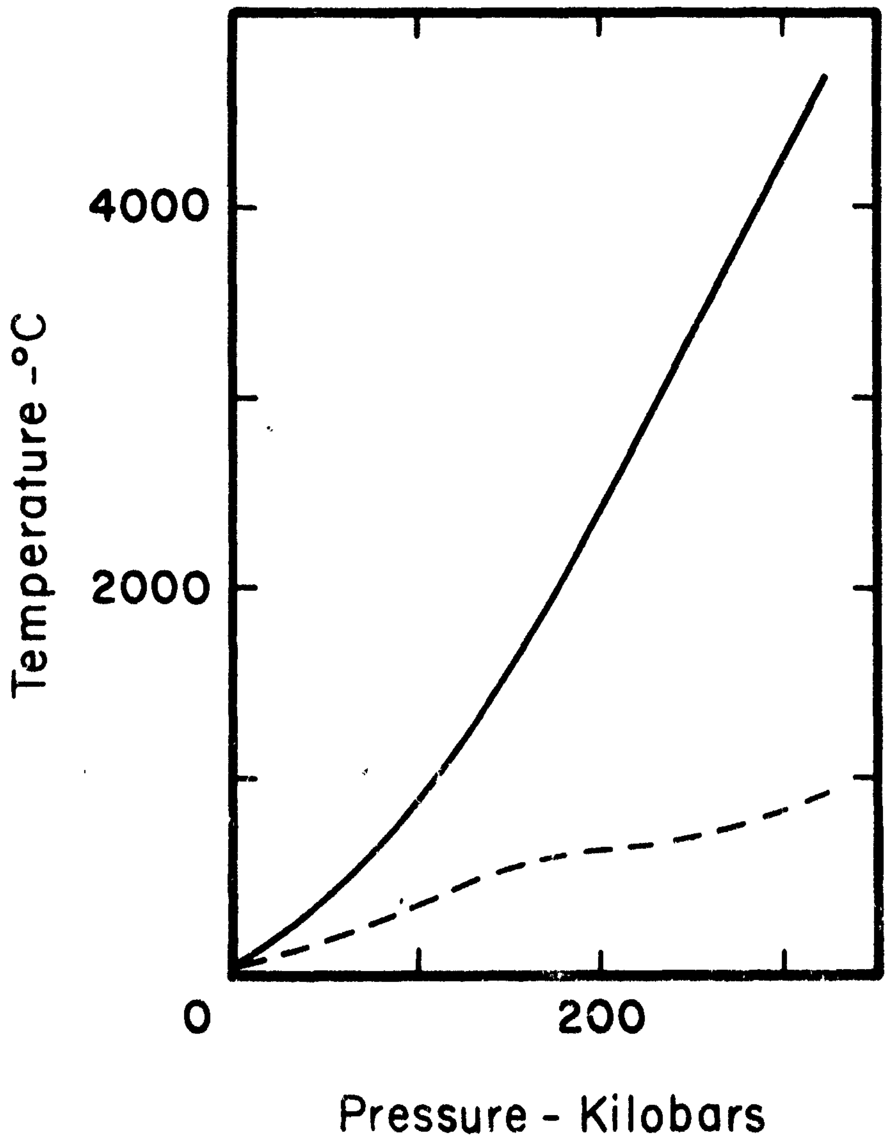
(M- %) indicates the final state is at the "melting point" with % liquid



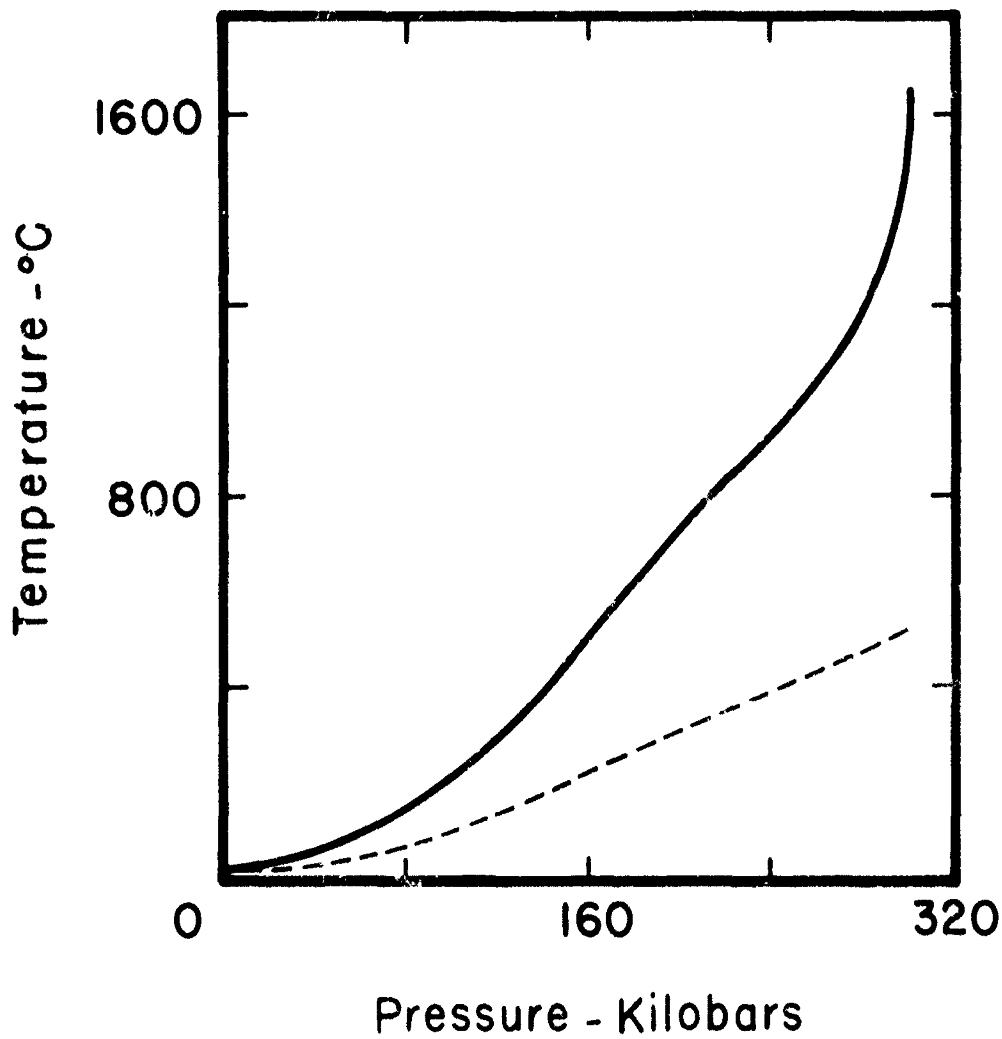
CESIUM BROMIDE



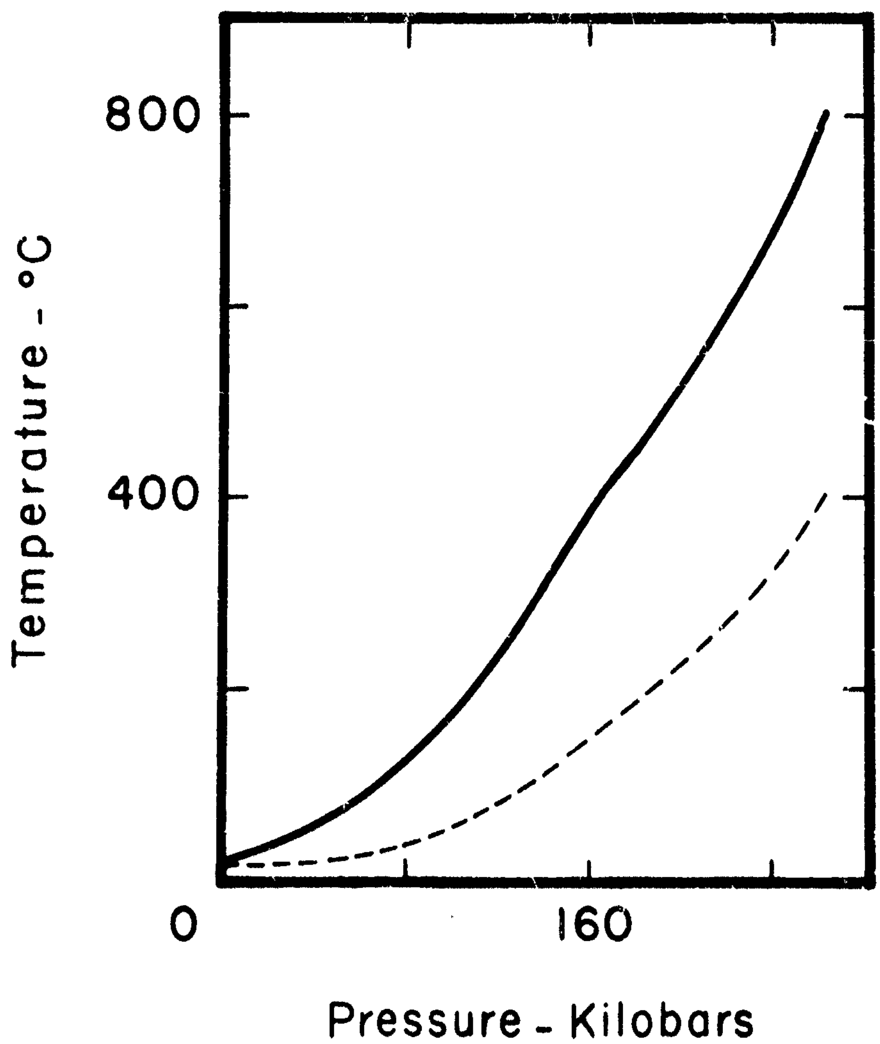
CESIUM CHLORIDE



CESIUM IODIDE



LITHIUM BROMIDE



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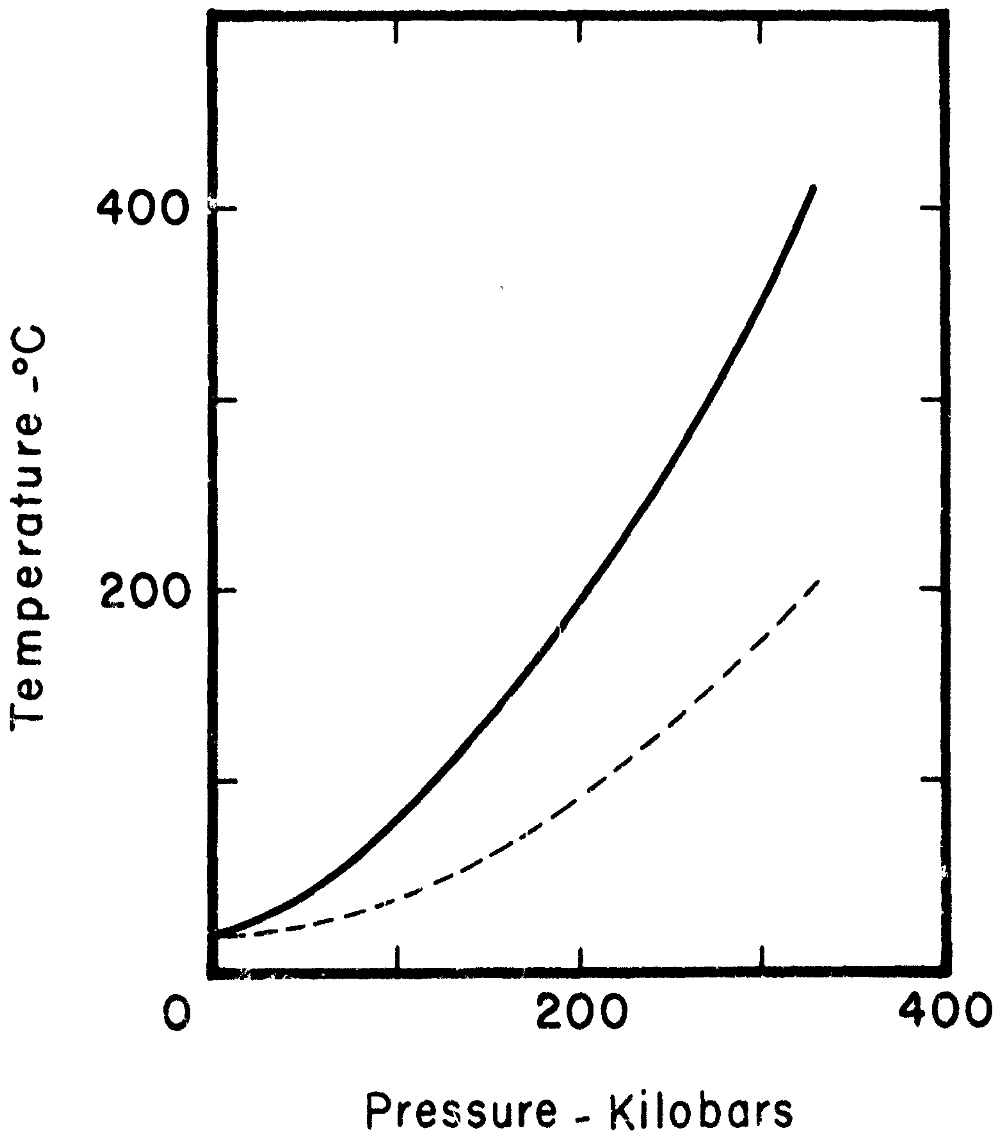
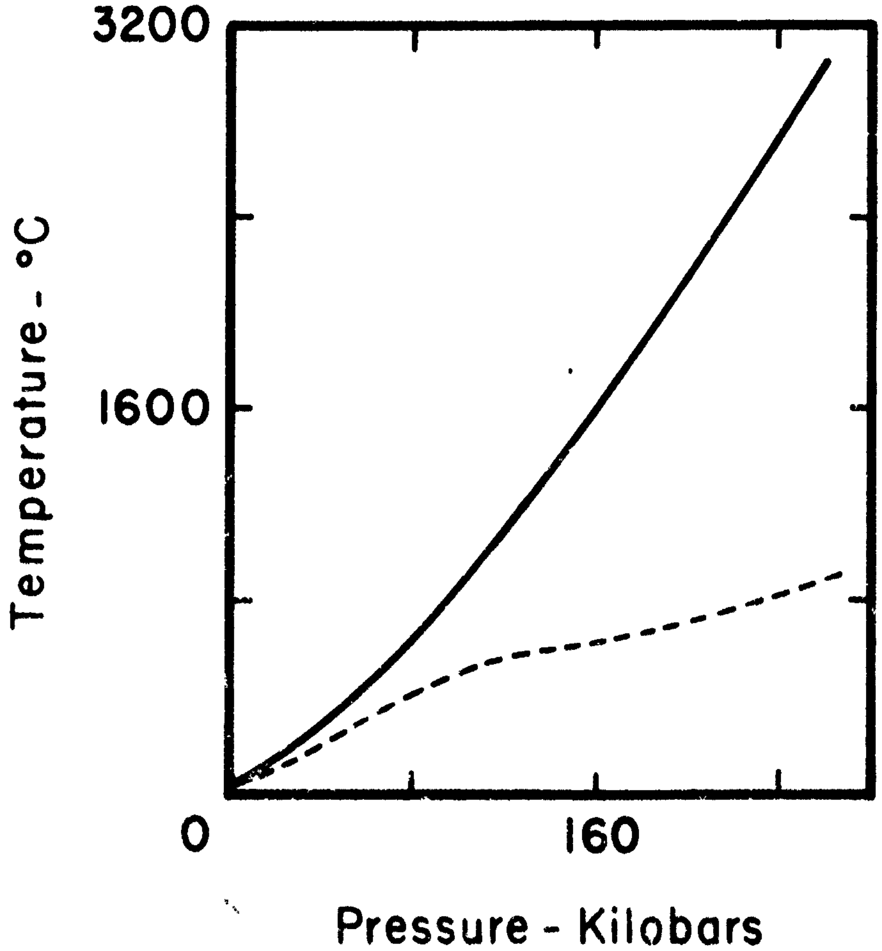
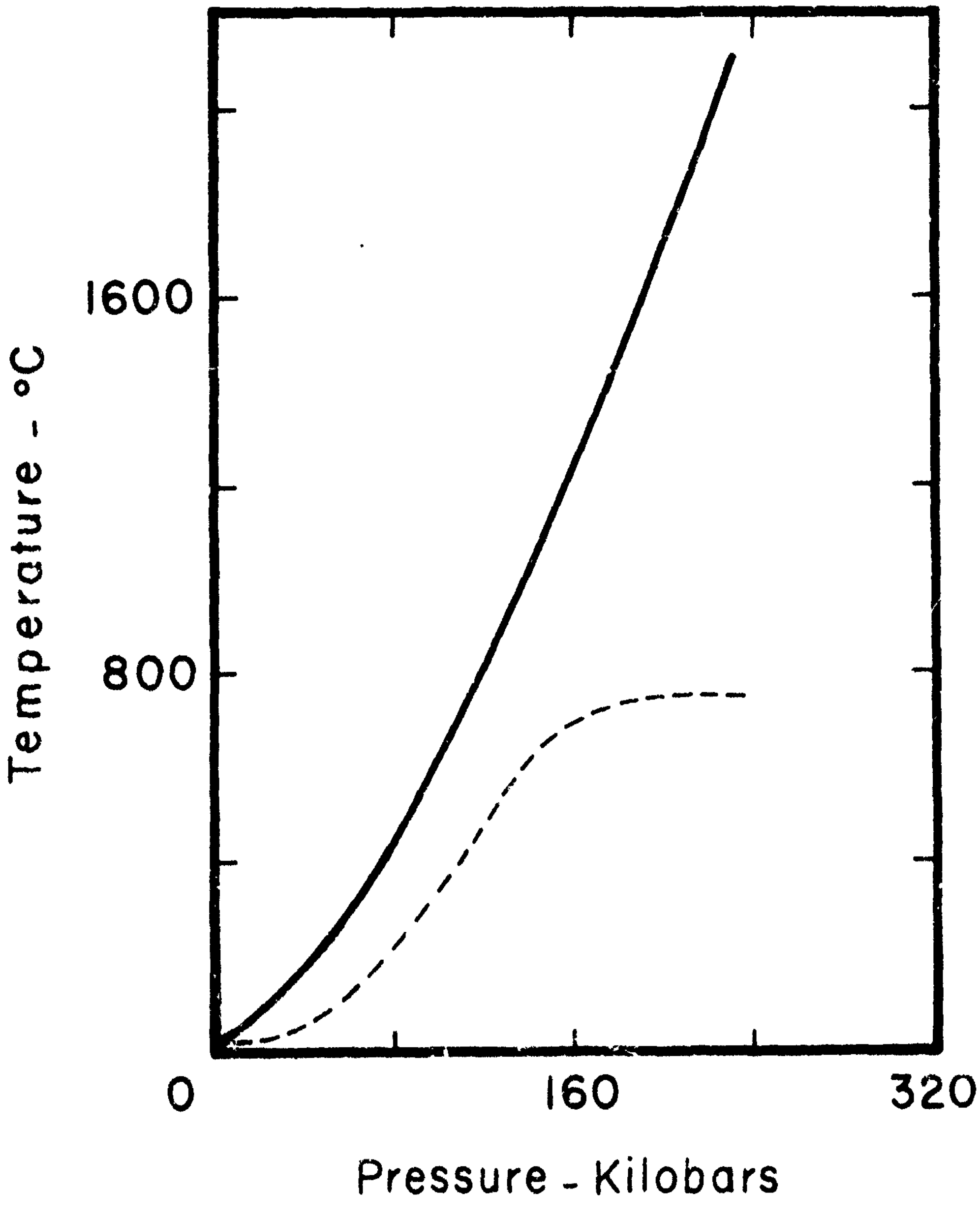


LITHIUM FLUORIDE



POTASSIUM BROMIDE



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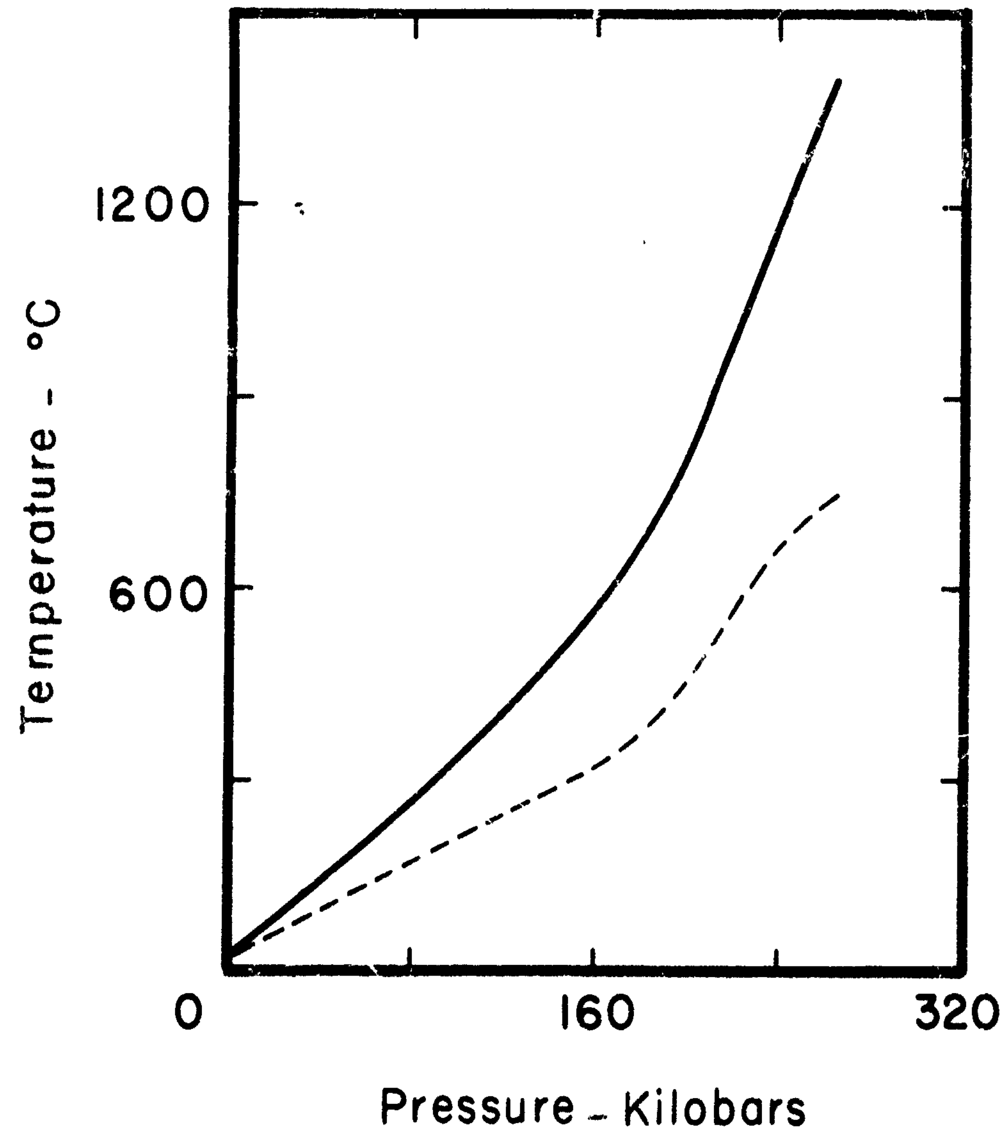

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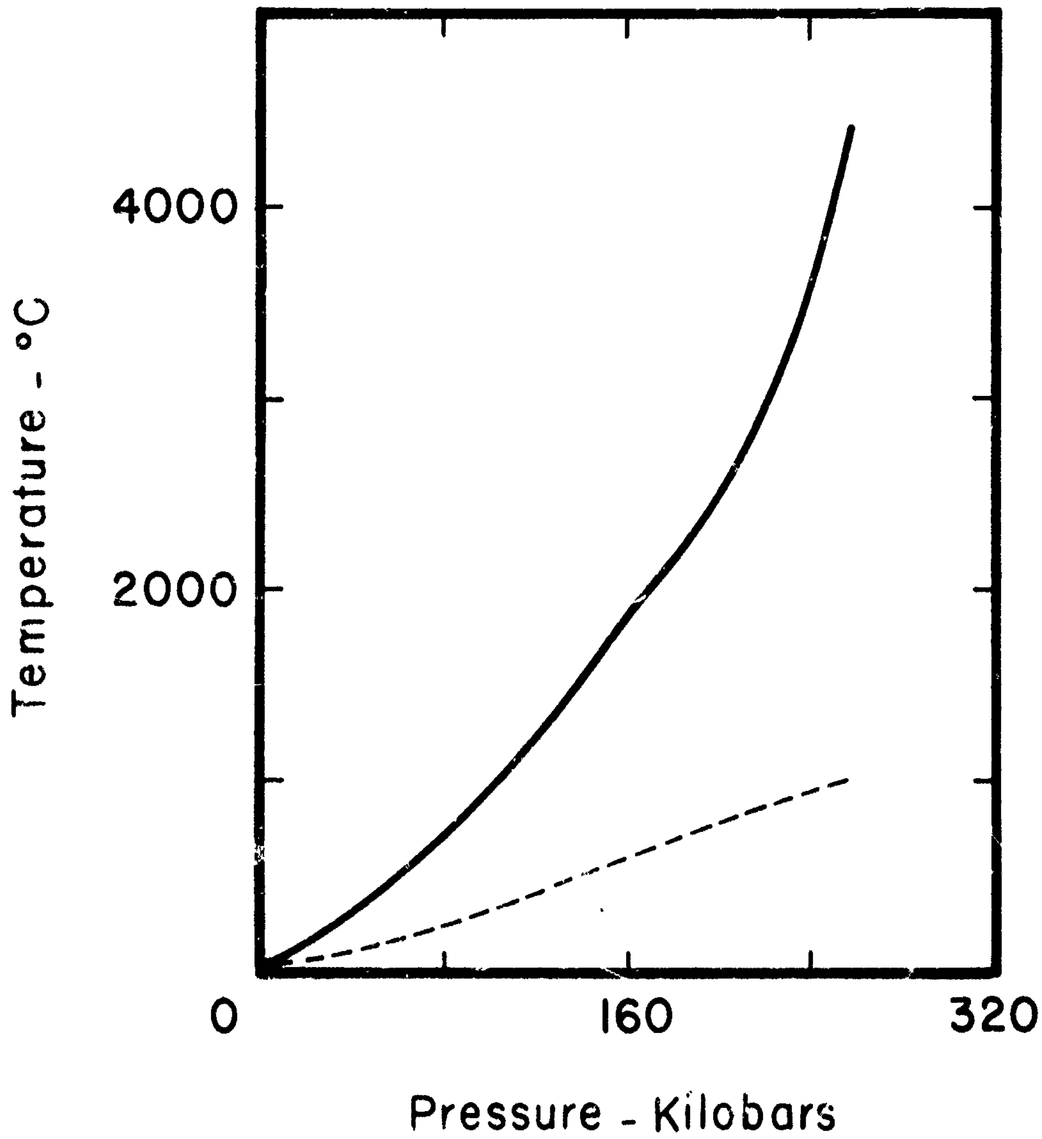

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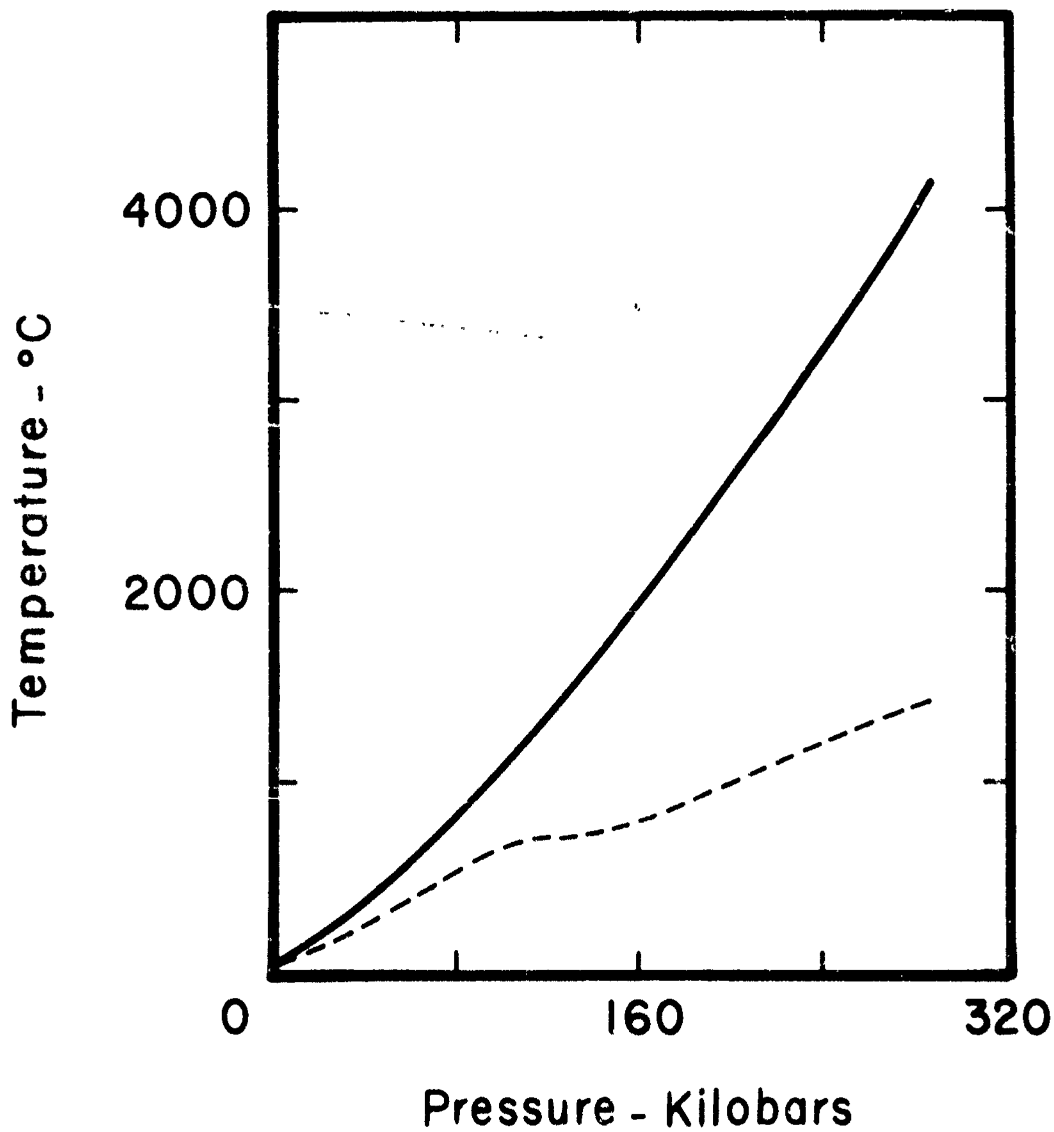
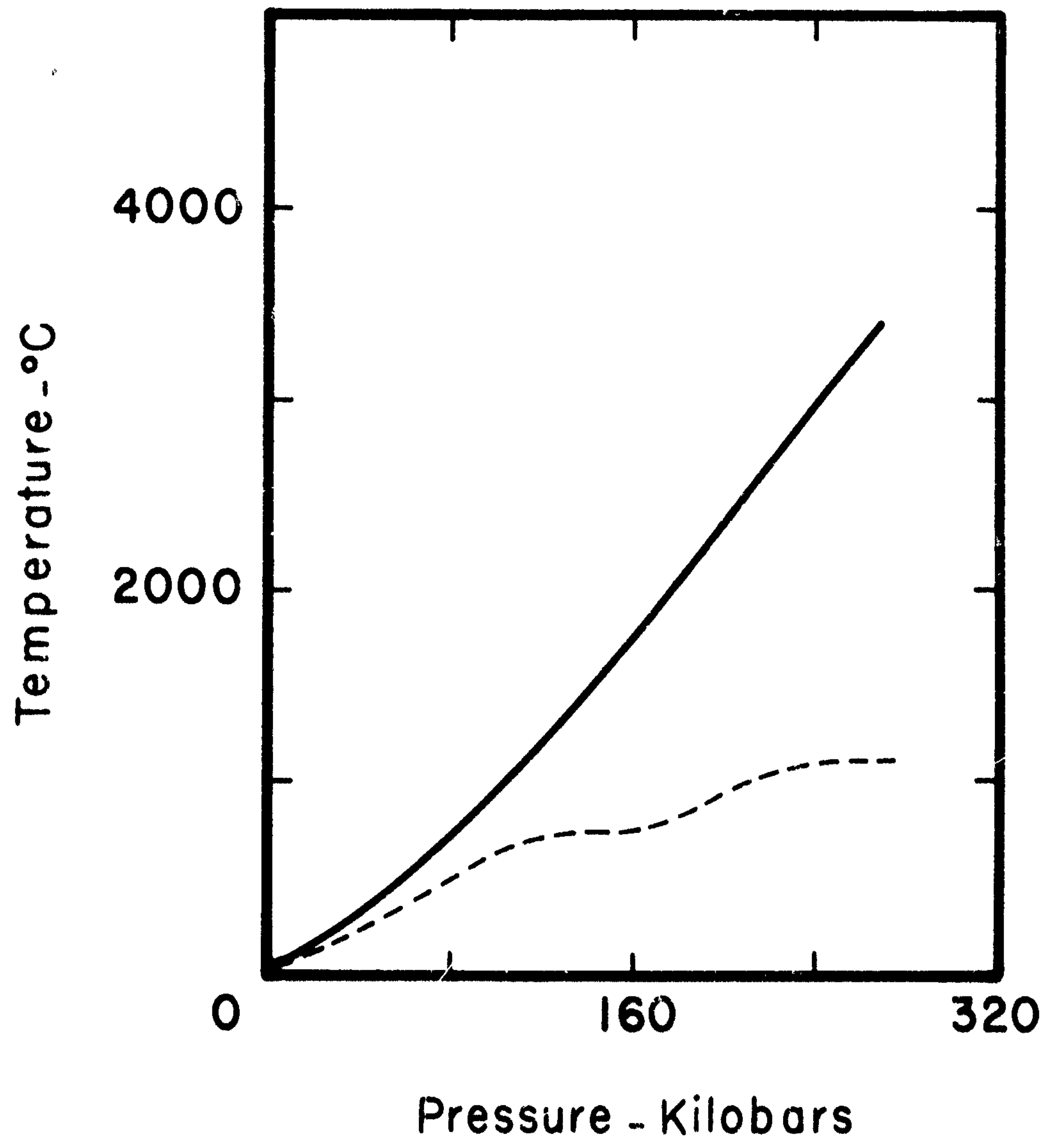
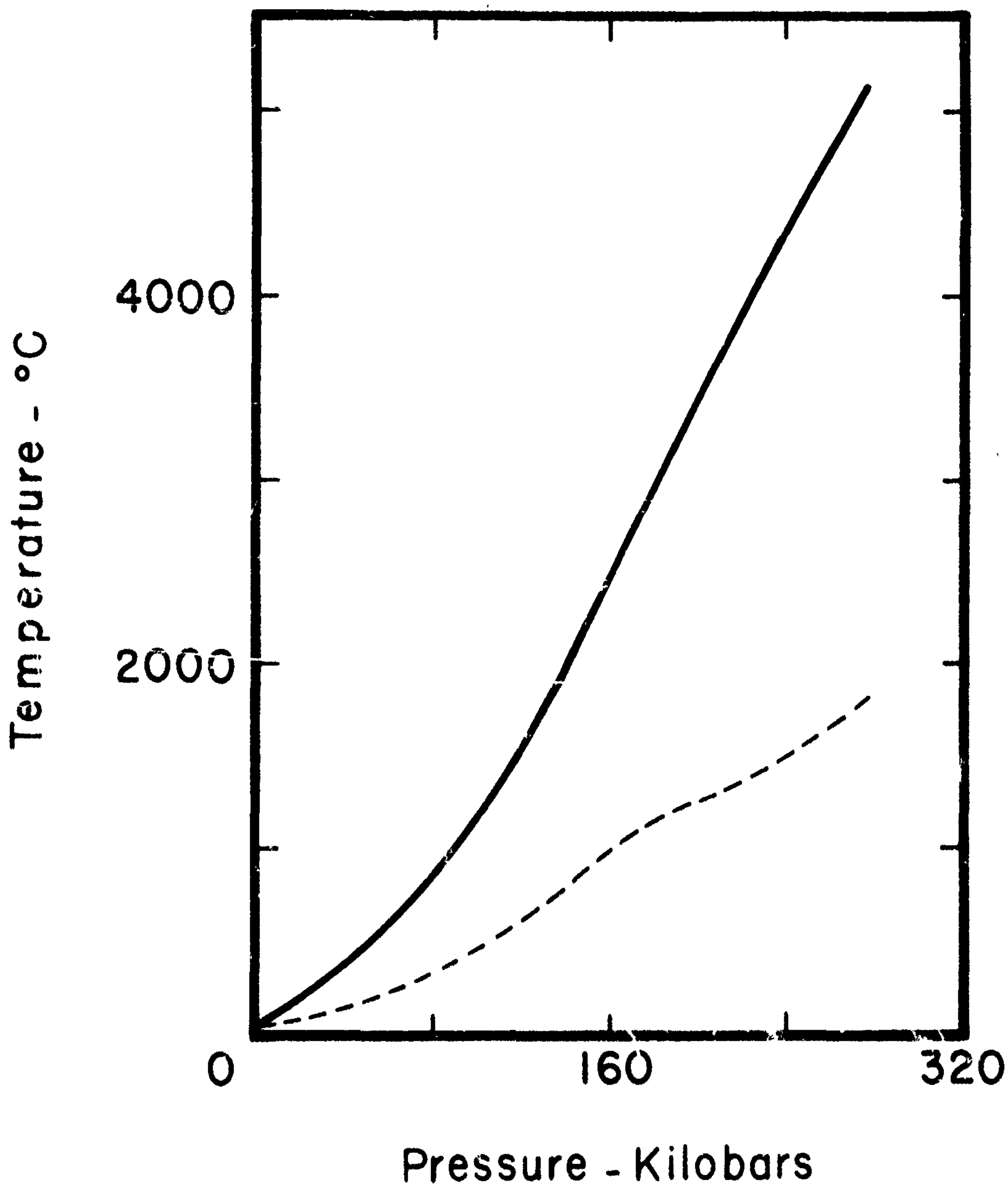


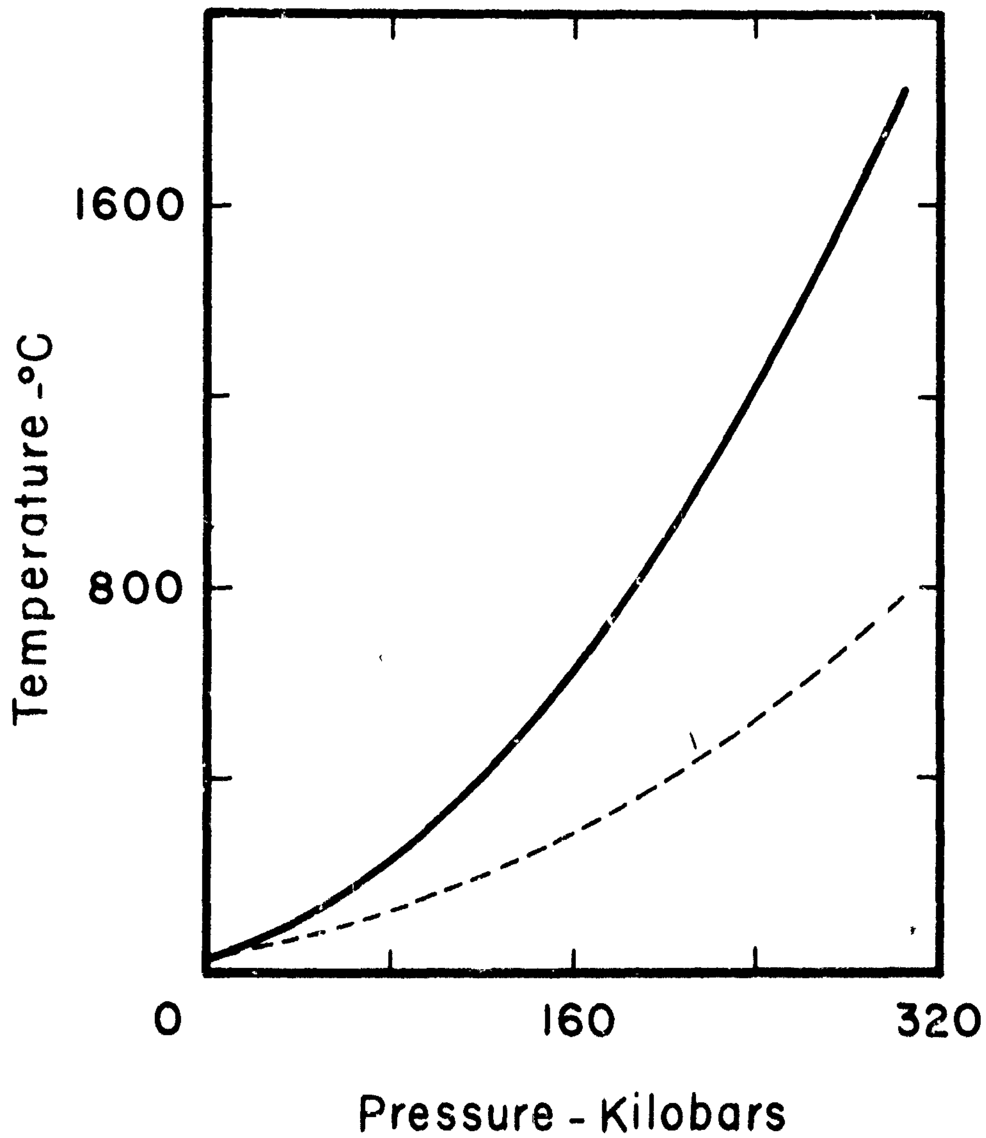
RUBIDIUM BROMIDE



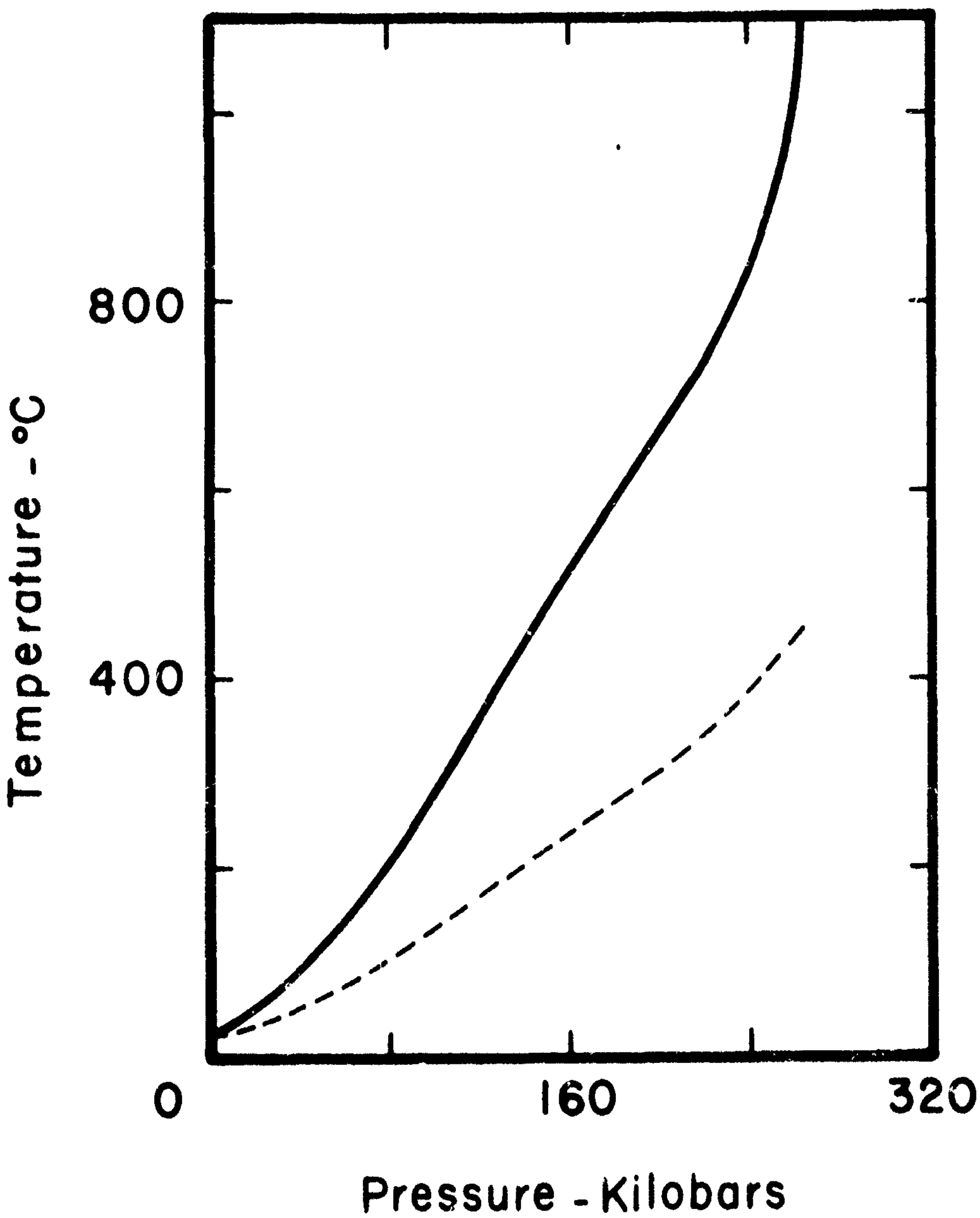
RUBIDIUM CHLORIDE



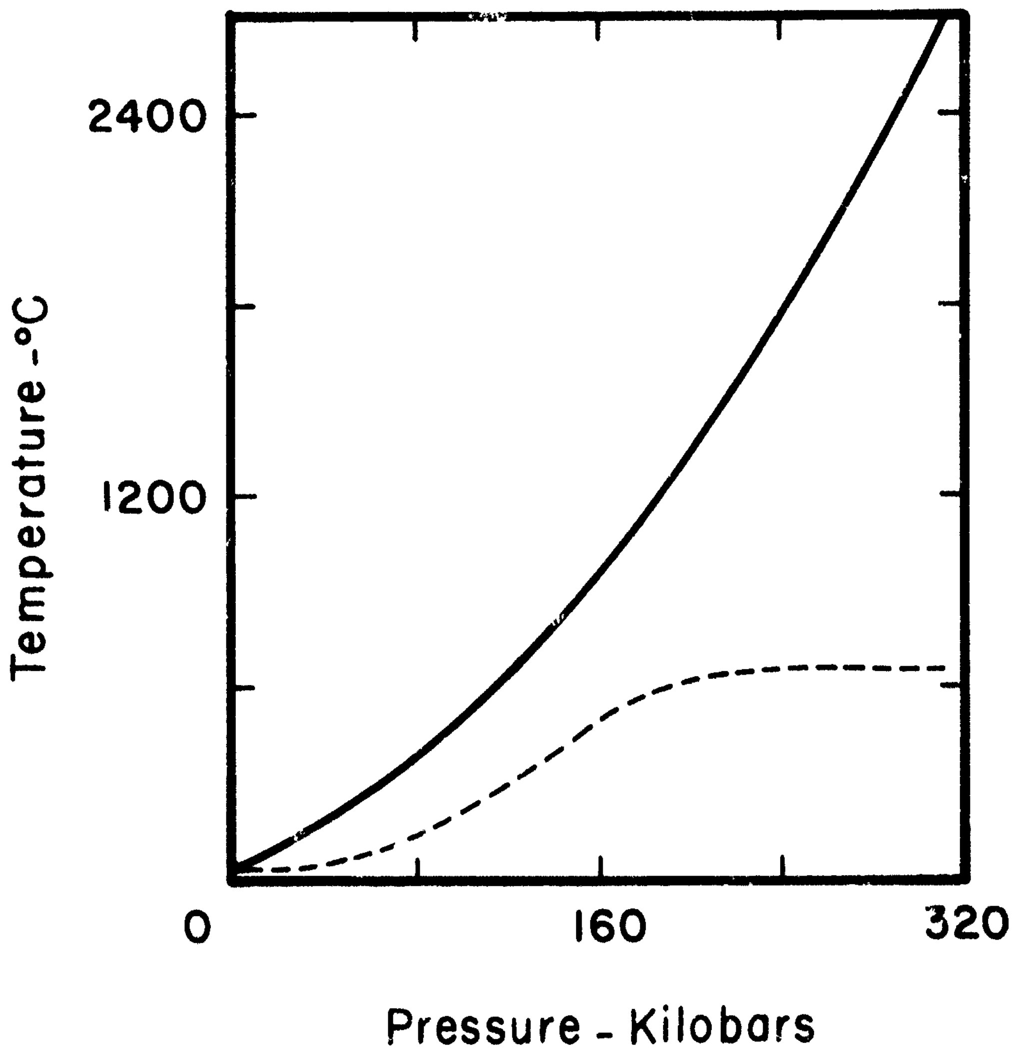
RUBIDIUM IODIDE



SODIUM BROMIDE



SODIUM CHLORIDE



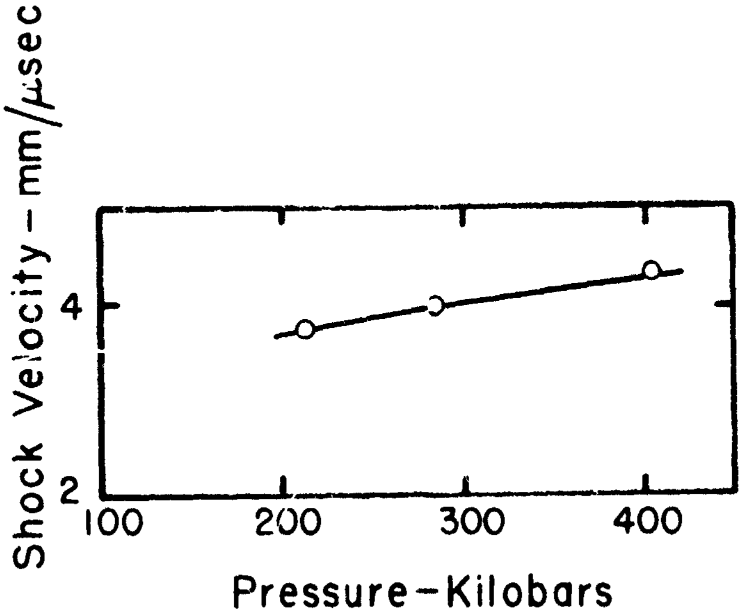
SODIUM IODIDE

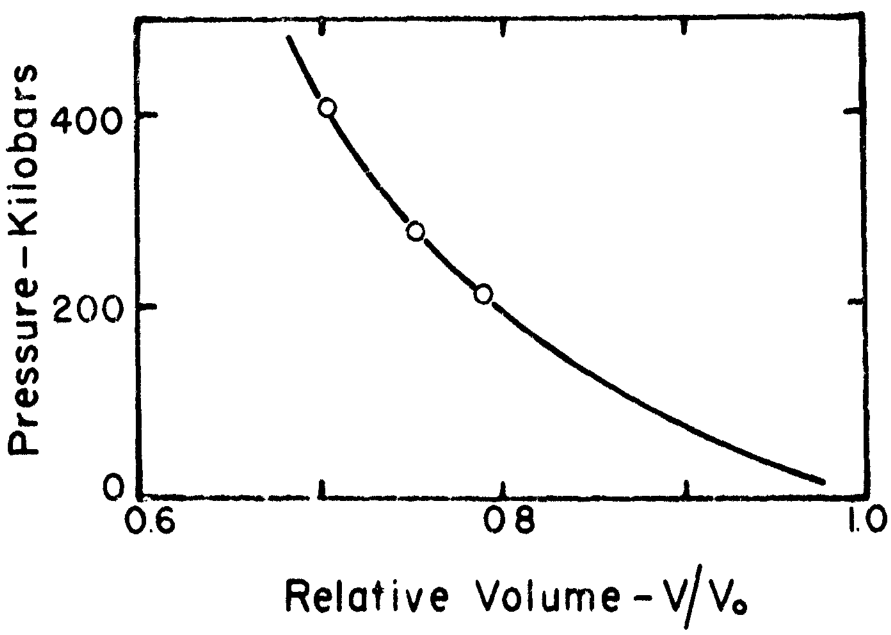
INDIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.745	0.7837	213.5	0.7907
3.965	0.9812	283	0.7525
4.348	1.281	405	0.7054

$\rho_0 = 7.27$

Source: Walsh, Rice, McQueen and Yarger (1957)


Shock Velocity - mm/μsec
4
2
100
200
300
400
Pressure-Kilobars


Pressure-Kilobars
400
200
0
0.6
0.8
1.0
Relative Volume - V/Vo

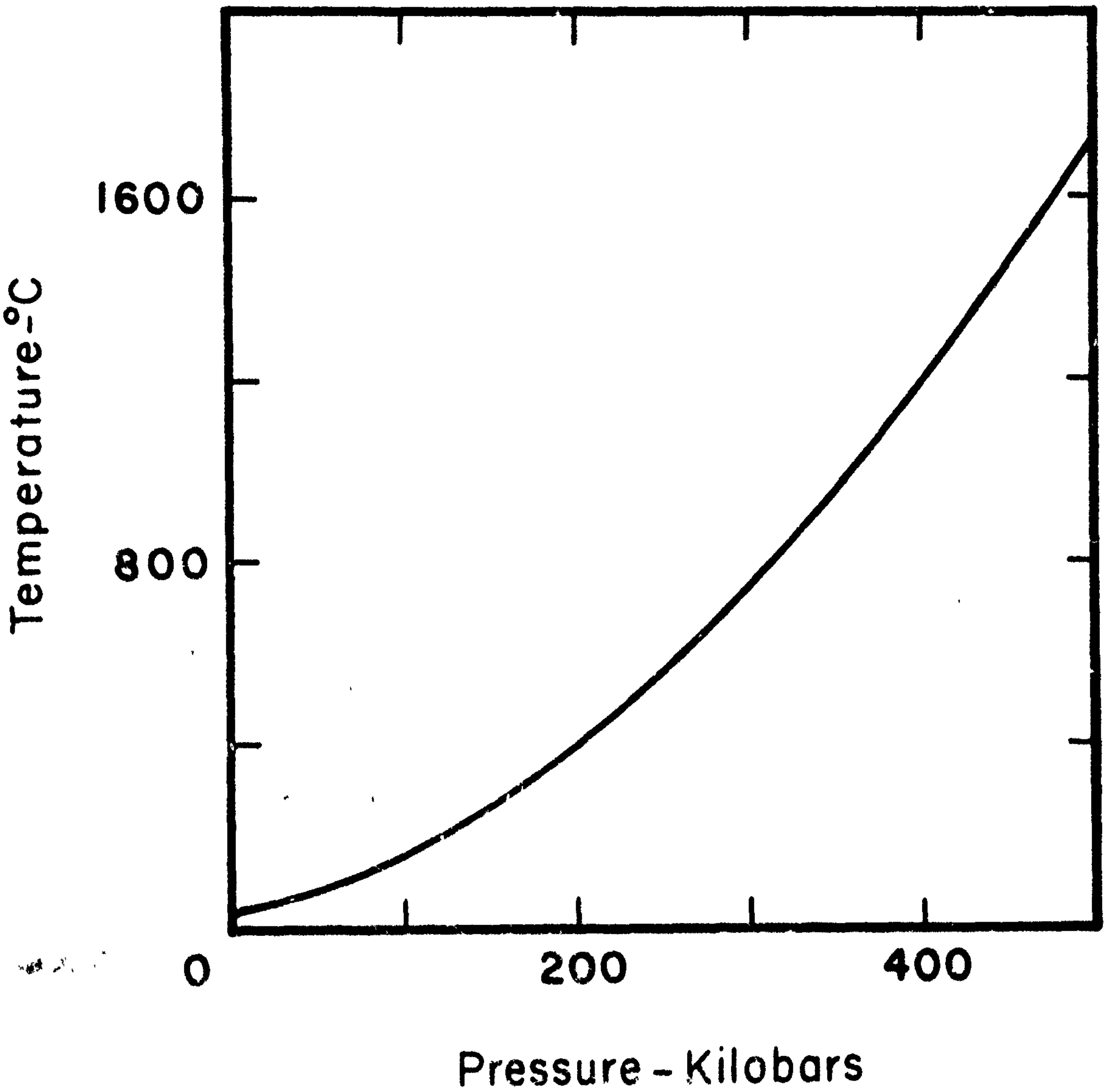
INDIUM

Temperatures associated with shock

Indium

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	
100	153	
150	260	
200	397	
250	561	
300	745	
350	950	
400	1179	
450	1439	
500	1710	

Source: Rice, McQueen and Walsh, 1958



INDIUM

IRON

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.30	0.97	400	
5.38	1.00	422	
5.54	1.14	500	
7.27	2.26	1290	
7.54	2.38	1410	
8.89	3.25	2270	
9.36	3.56	2620	
9.98	3.83	3000	
10.45	4.20	3440	
10.67	4.32	3620	
11.10	4.59	4000	
11.32	4.83	4290	
12.00	5.17	4870	

$\rho_0 = 7.85$

Source: Al'tshuler, Krupnikov and Brazhnik (1958)

IRON

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.438	0.994	423.8	0.8172
5.458	0.993	424.9	0.8181
5.474	1.013	434.7	0.8149
5.652	1.083	480.8	0.8080

$\rho_0 = 7.84$

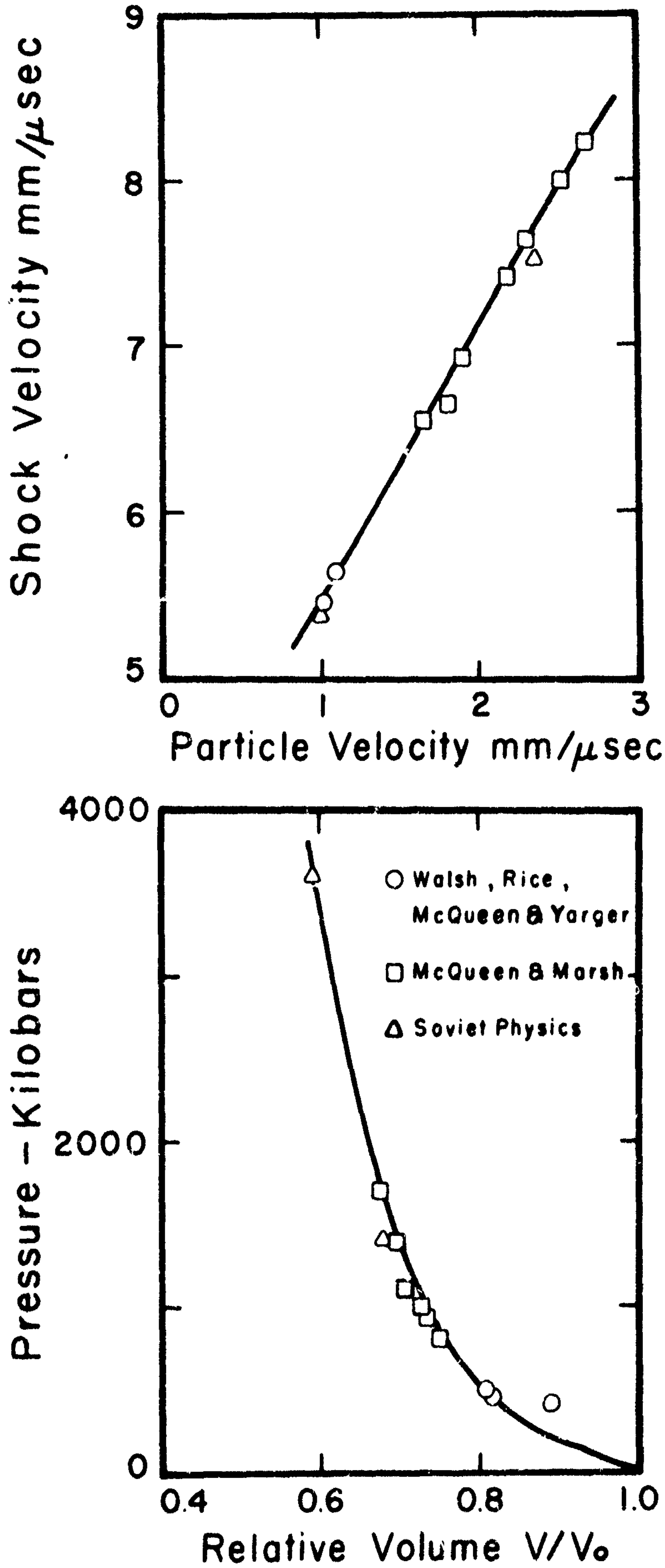
Source: Walsh, Rice, McQueen and Yarger (1957)

IRON

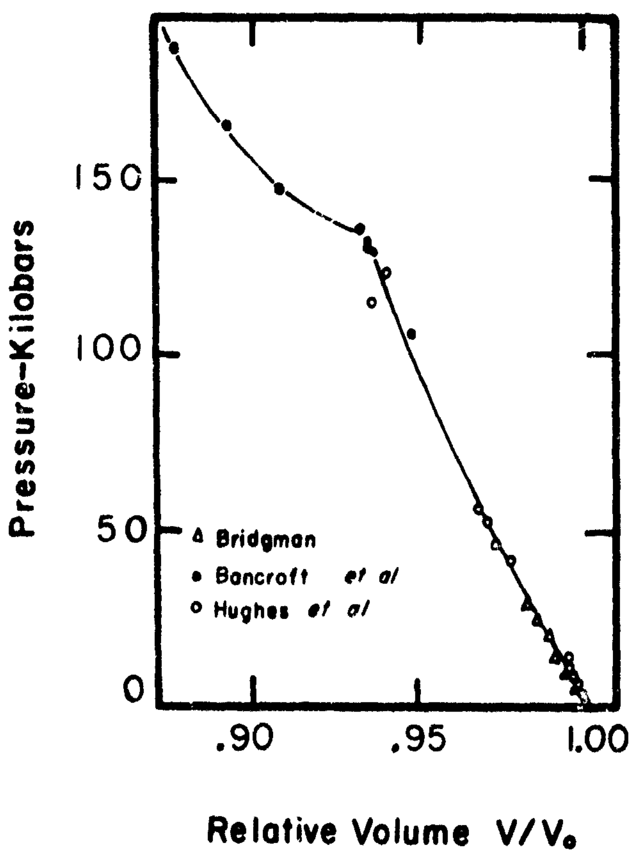
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.57	1.09	477	0.804
6.54	1.64	843	0.749
6.57	1.66	857	0.748
6.65	1.74	911	0.738
6.71	1.79	943	0.733
6.63	1.86	968	0.720
6.89	1.89	1024	0.726
6.95	1.89	1033	0.728
7.42	2.17	1267	0.707
7.42	2.19	1276	0.705
7.66	2.32	1397	0.697
7.58	2.34	1393	0.692
8.00	2.57	1618	0.679
8.22	2.68	1728	0.675
8.20	2.68	1730	0.673

$\rho_o = 7.8$

Source: McQueen and Marsh (1960)


Shock Velocity mm/μsec
9
8
7
6
5
0
1
2
3
Particle Velocity mm/μsec
Pressure – Kilobars
4000
2000
0
0.4
0.6
0.8
1.0
Relative Volume V/Vo
Walsh, Rice, McQueen & Yarger
McQueen & Marsh
Soviet Physics

IRON


150
100
50
0
Pressure-Kilobars
Δ Bridgman
• Bancroft et al
○ Hughes et al
.90
.95
1.00
Relative Volume V/V₀

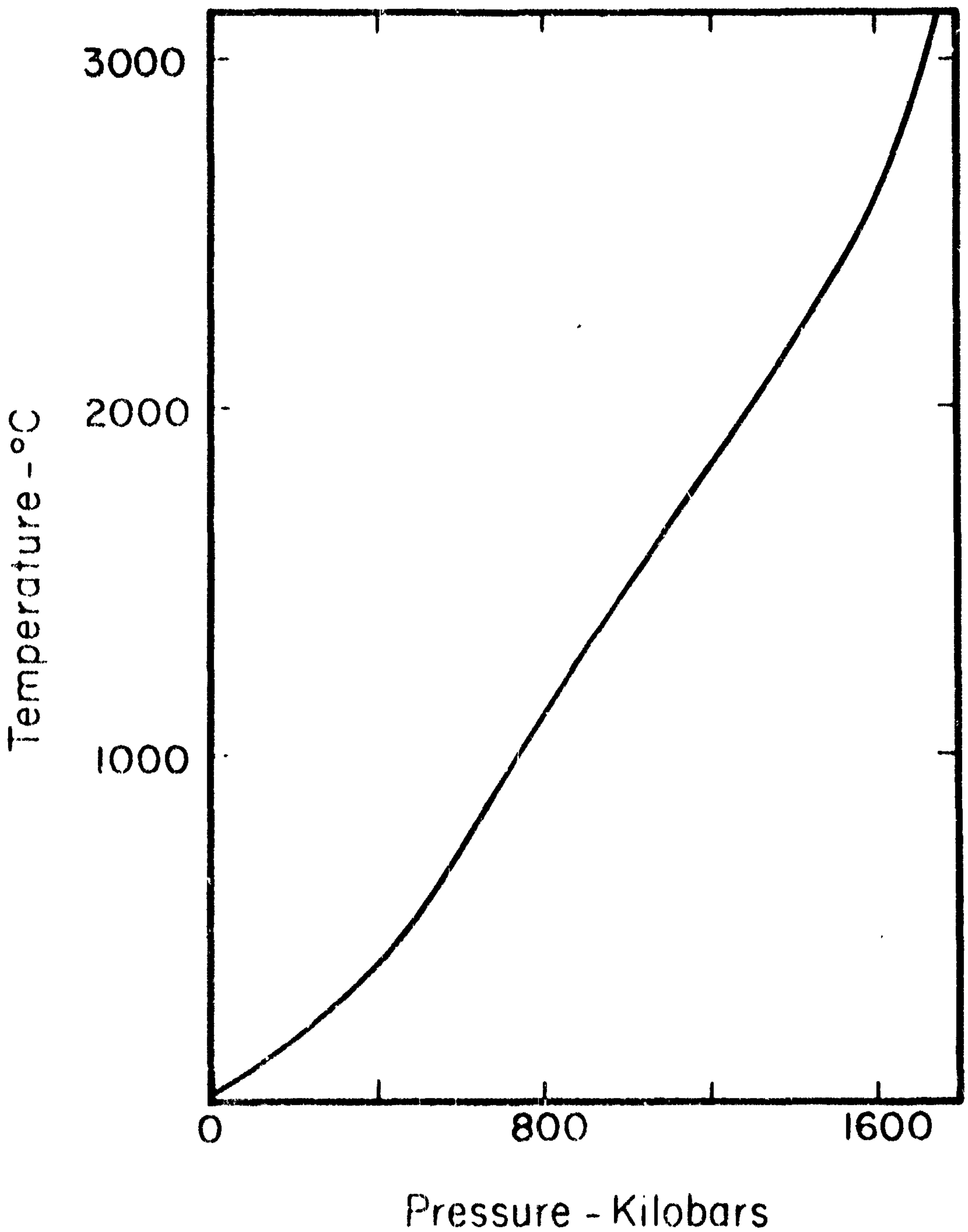
IRON

Temperatures associated with shock

Iron

Pressure (kilobars)	Temperature behind shock (C^0)	Residual temperature (C^0)
0	20	
250	227	
500	527	
750	1027	
1000	1477	
1250	1927	
1500	2377	
1750	3127	

Source: McQueen and Marsh, 1960



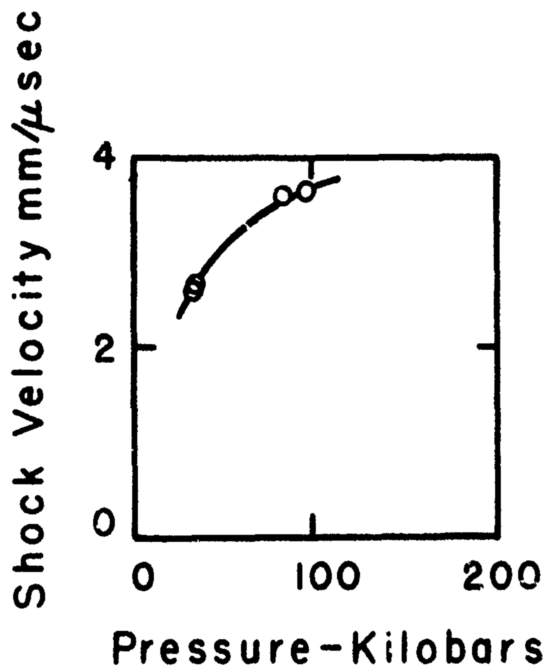
IRON

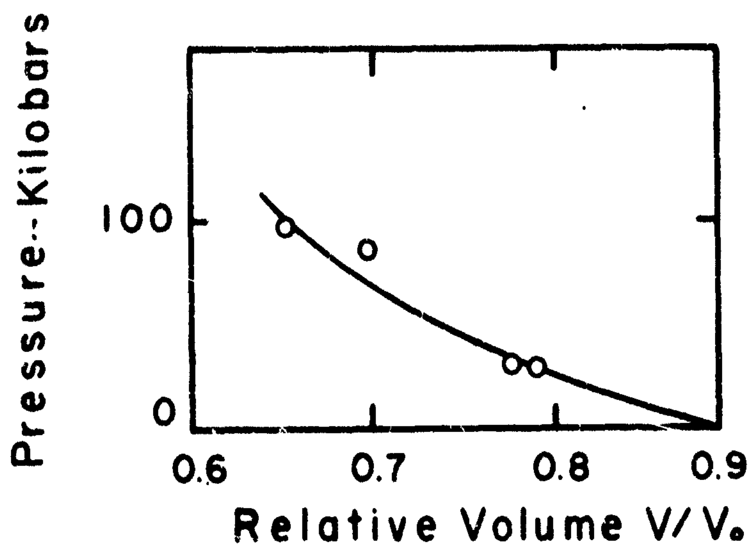
KEL-F

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
2.60	0.580	31.7	0.776
2.68	0.565	31.8	0.790
3.61	1.10	83.0	0.697
3.64	1.27	96.8	0.651

$\rho_o = 2.1$

Source: Wagner, Waldorf and Louie (1962)


Shock Velocity mm/μsec
4
2
0
0
100
200
Pressure-Kilobars


Pressure--Kilobars
100
0
0.6
0.7
0.8
0.9
Relative Volume V/V₀

KEL-F

LEAD

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
2.914	0.590	194.8	0.7975
3.266	0.819	303.2	0.7494
3.250	0.802	295.3	0.7532
3.724	1.118	471.7	0.6998

$\rho_o = 11.34$

Source: Walsh, Rice, McQueen and Yarger (1957)

LEAD

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.52	0.97	390	0.724
5.33	2.34	1410	0.563
7.65	4.26	3700	0.443

$\rho_o = 11.34$

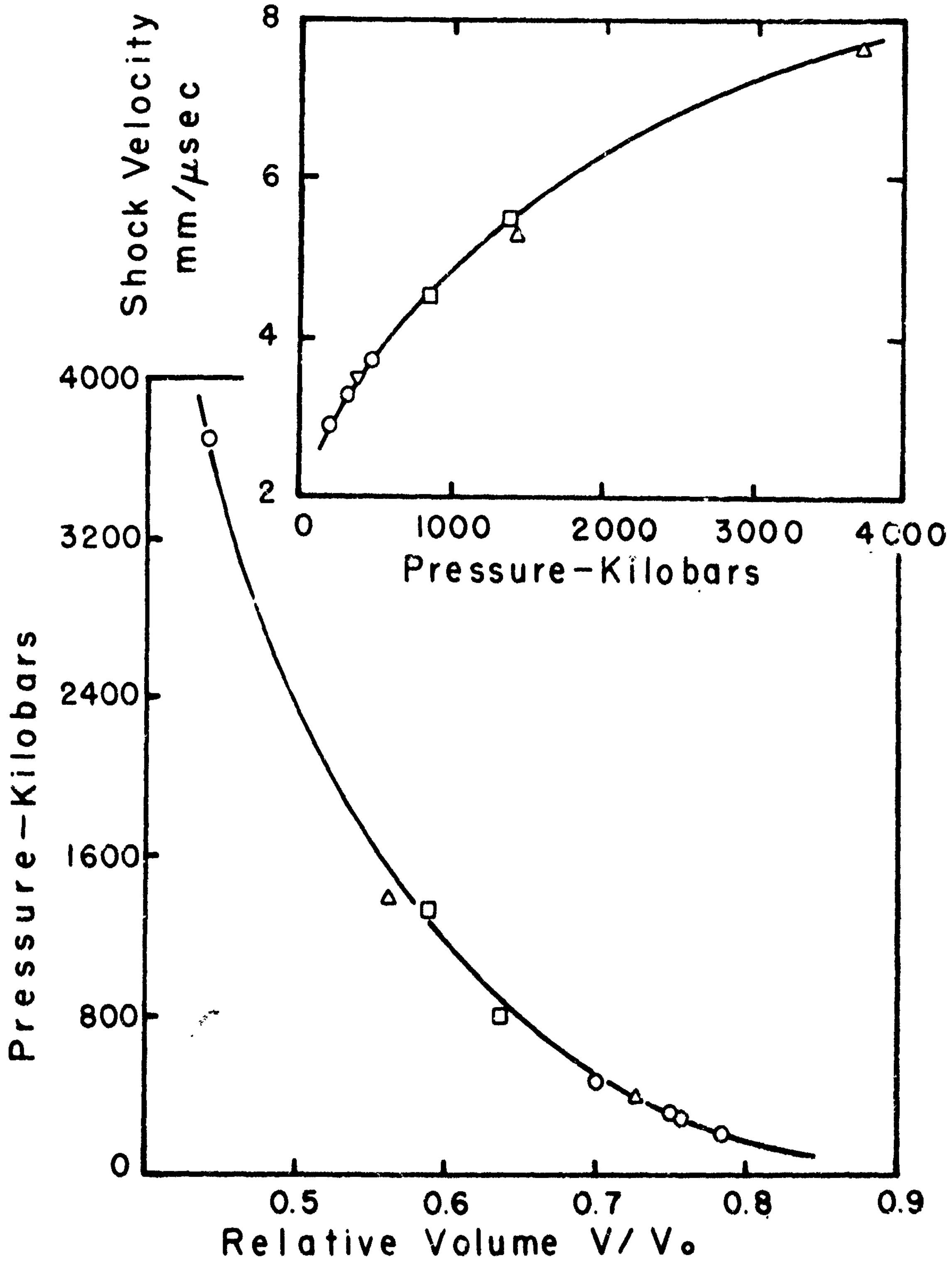
Source: Al'tshuler, Krupnikov and Brazhnik (1958)

LEAD

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.52	1.64	838	0.638
4.52	1.64	837	0.638
5.44	2.25	1388	0.587
5.42	2.25	1383	0.585

$\rho_o = 11.34$

Source: McQueen and Marsh (1960)


Shock Velocity mm/μsec
8
6
4
2
0
1000
2000
3000
4000
Pressure-Kilobars
Pressure-Kilobars
4000
3200
2400
1600
800
0
0.5
0.6
0.7
0.8
0.9
Relative Volume V/ Vo

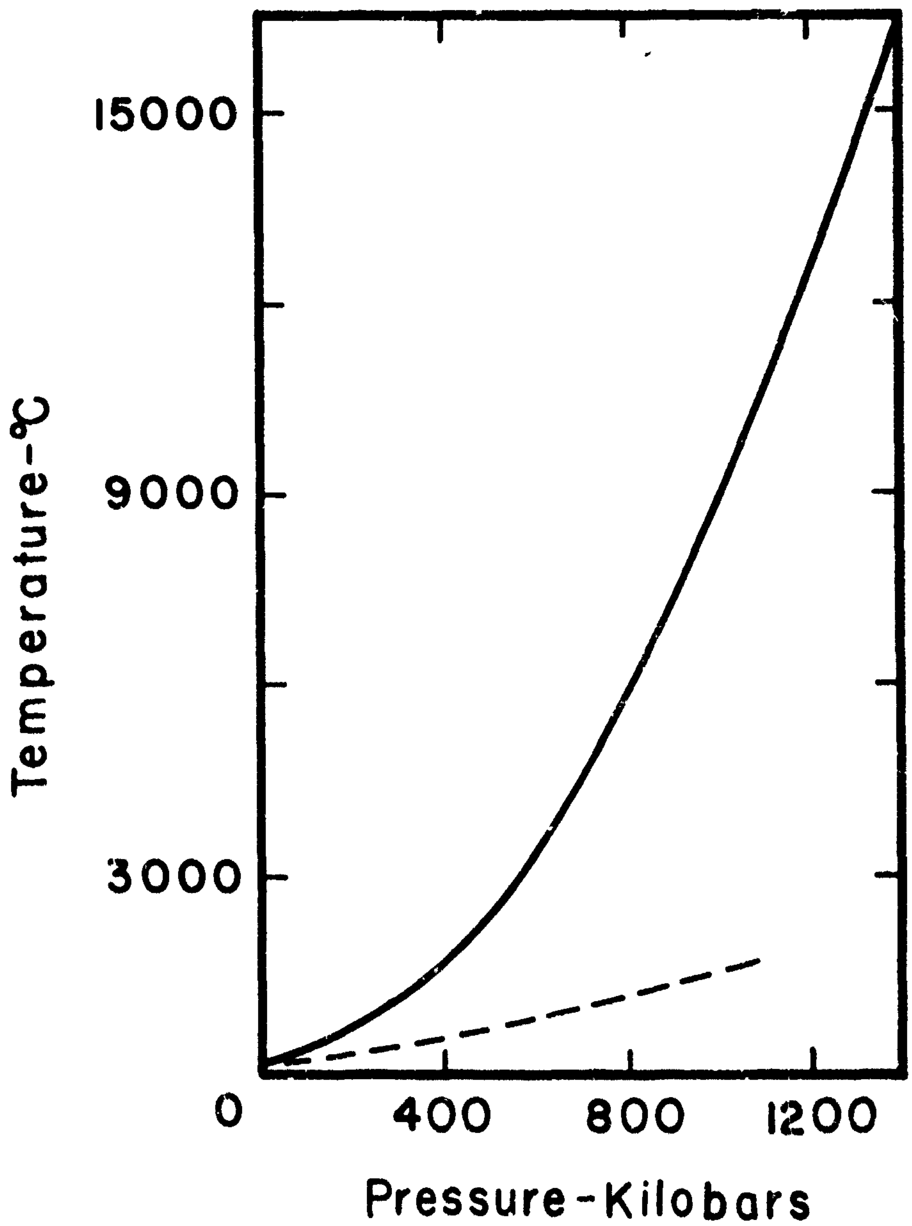
LEAD

Temperatures associated with shock

Lead

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	131	69
200	628	214
300	1070	327
400	1589	429
500	2449	624
600	3466	818
700	4631	1007
800	5937	1192
900	7378	1369
1000	8945	1540
1100	10637	1703
1200	12447	-
1300	14367	-
1400	16397	-

Source: McQueen and Marsh, 1960


15000
9000
3000
Temperature-°C
0
400
800
1200
Pressure-Kilobars

LEAD

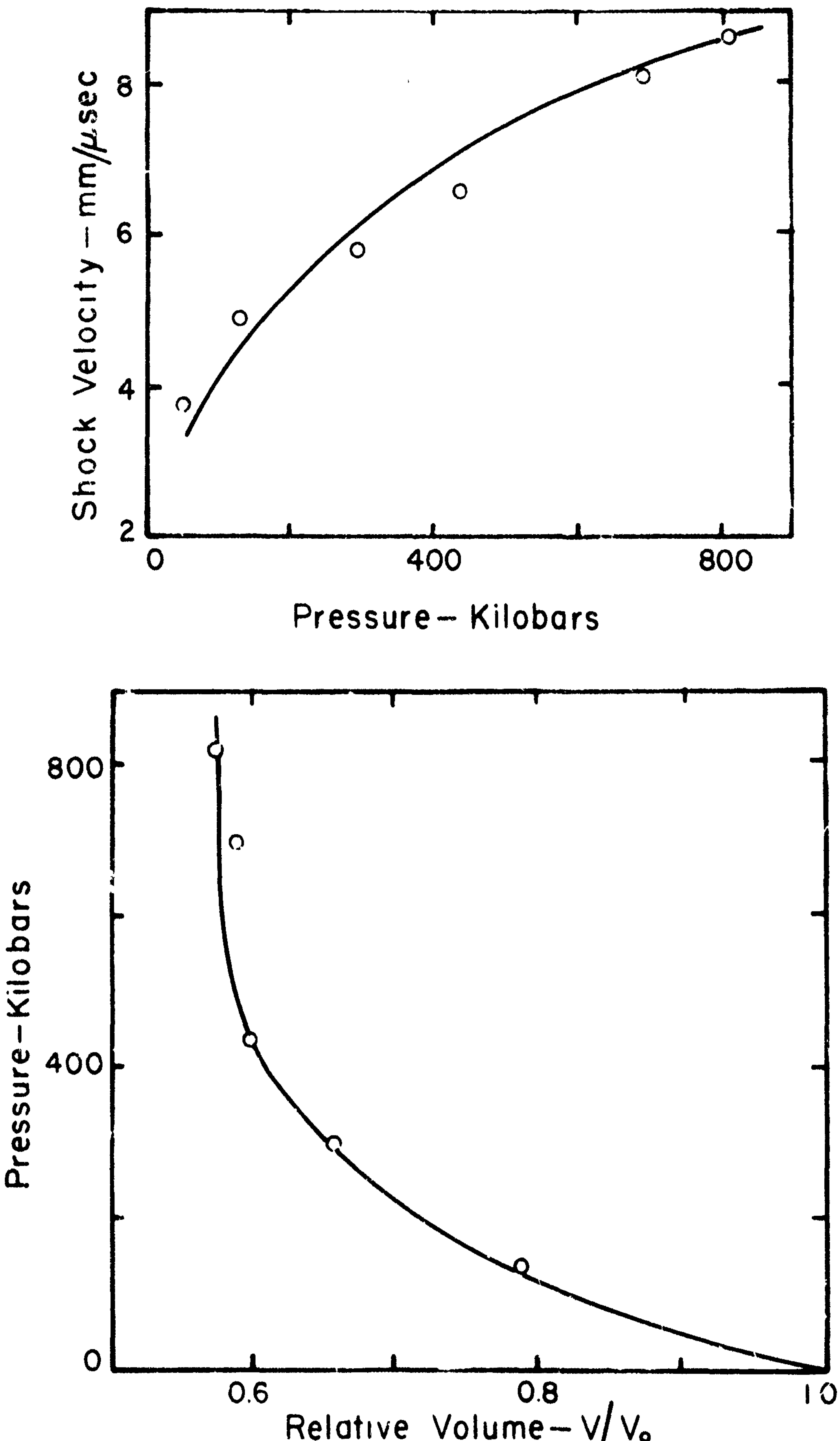
LIMESTONE*

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.707	0.570	53	0.846
4.927	1.055	130	0.786
5.83	2.01	294	0.655
6.56	2.64	439	0.598
8.05	3.31	692	0.589
8.60	3.67	817	0.573

$\rho_o = 2.50 - 2.59$

Source: Lombard (1961)

* From third fragmented formation, Pony Creek No. 2 core, Richfield Oil Co., Alberta, Canada


Shock Velocity — mm/μsec
2
4
6
8
0
400
800
Pressure — Kilobars
Pressure-Kilobars
0
400
800
0.6
0.8
1.0
Relative Volume — V/V₀

LIMESTONE

LIQUIDS

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Acetone			
5.37	2.510	105.8	0.533
3.97	1.495	46.4	0.623
$\rho_o = 0.78$			
Benzene			
5.66	2.470	121.0	0.564
4.10	1.448	52.4	0.647
$\rho_o = 0.87$			
Bromoethane			
4.68	2.300	157.1	0.508
3.40	1.363	68.0	0.599
$\rho_o = 1.46$			
Carbon Disulfide			
4.32	2.412	129.5	0.441
3.37	1.415	58.5	0.580
$\rho_o = 1.23$			
Carbon Tetrachloride			
4.85	2.235	171.0	0.539
3.51	1.325	73.9	0.622
$\rho_o = 1.58$			
Ethyl Ether			
5.40	2.550	96.1	0.528
3.88	1.517	41.8	0.609
$\rho_o = 0.70$			

LIQUIDS (cont)

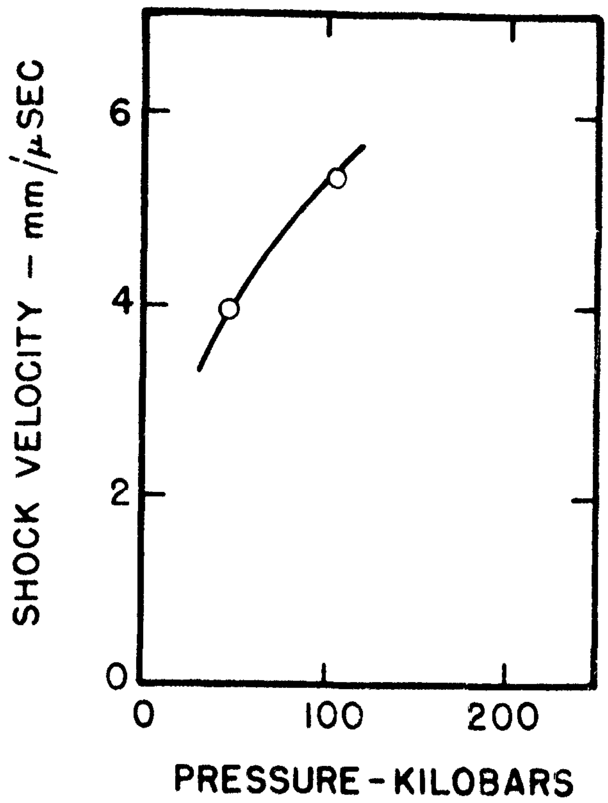
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Ethyl Alcohol			
5.63	2.500	110.4	0.556
4.03	1.487	47.3	0.631
$\rho_0 = 0.79$			
Glycerine			
6.07	2.240	170.3	0.631
4.58	1.328	76.6	0.710
$\rho_0 = 1.25$			
Hexane			
5.54	2.590	95.7	0.533
4.02	1.517	41.5	0.622
$\rho_0 = 0.68$			
Mercury			
2.752	0.608	226.4	0.779
3.101	0.772	324.0	0.751
3.504	0.978	463.7	0.721
$\rho_0 = 13.5$			
Methanol			
5.51	2.525	109.5	0.542
3.95	1.483	46.6	0.625
$\rho_0 = 0.79$			

LIQUIDS (cont)

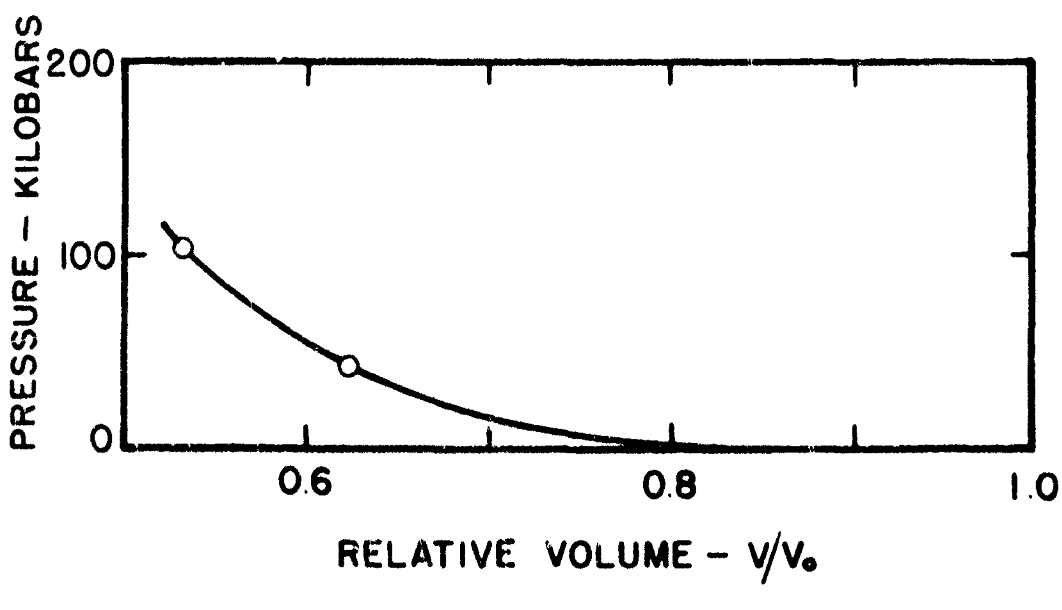
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Mononitrotoluene			
5.64	2.300	151.5	0.592
4.20	1.340	65.8	0.681
$\rho_o = 1.17$			
N-Amyl Alcohol			
5.81	2.465	115.9	0.576
4.26	1.466	50.9	0.656
$\rho_o = 0.81$			
Toluene			
5.73	2.412	121.5	0.579
4.12	1.443	52.1	0.650
$\rho_o = 0.88$			

Water (see separate table)

Source: Walsh and Rice (1957)

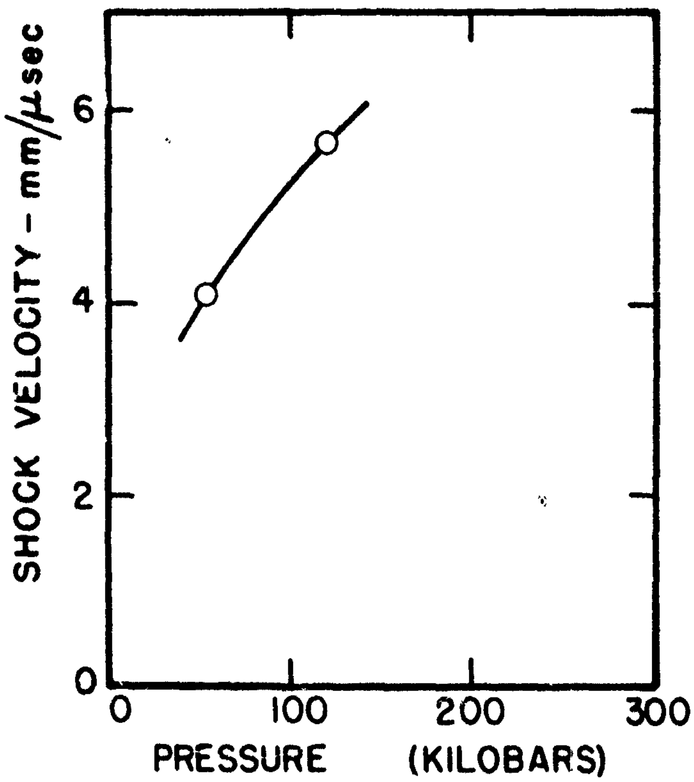


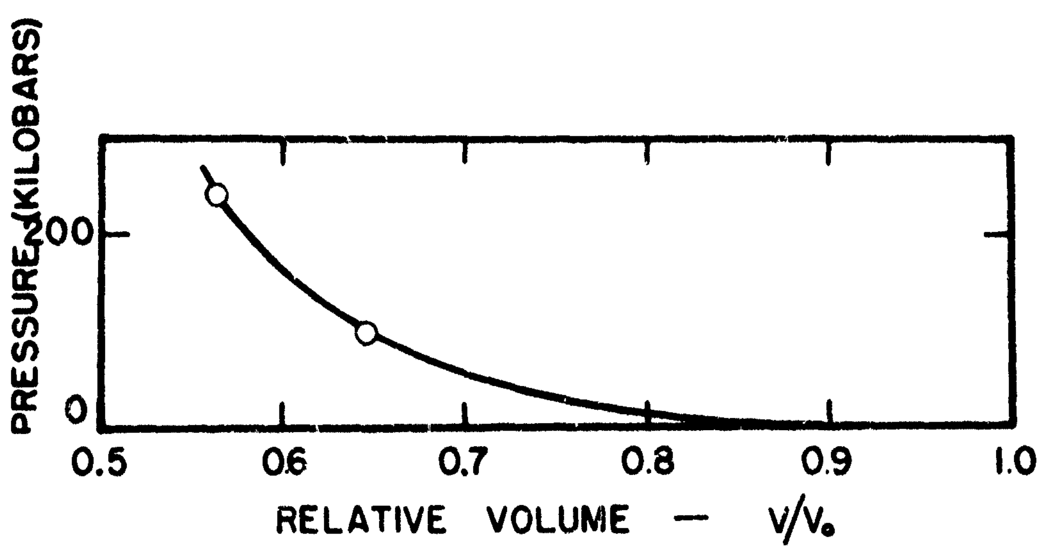
SHOCK VELOCITY – mm/μSEC
0
2
4
6
0
100
200
PRESSURE - KILOBARS



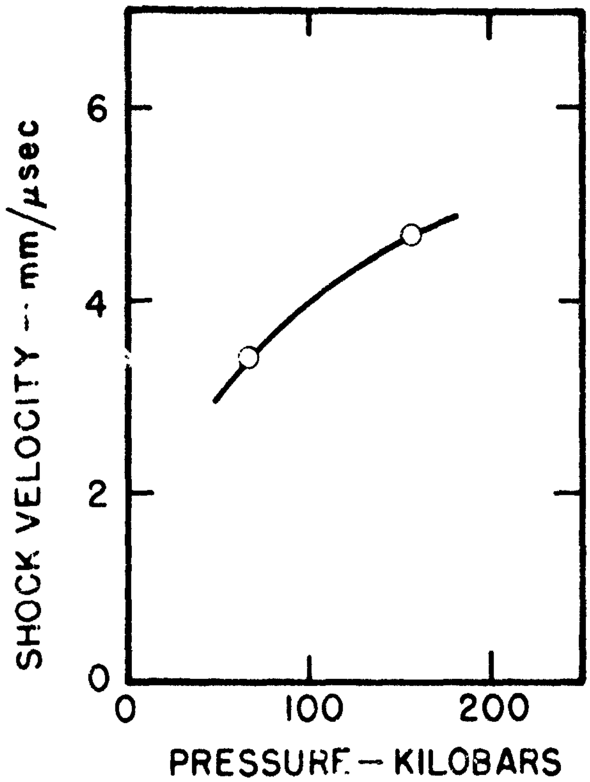
PRESSURE – KILOBARS
0
100
200
0.6
0.8
1.0
RELATIVE VOLUME – V/V₀

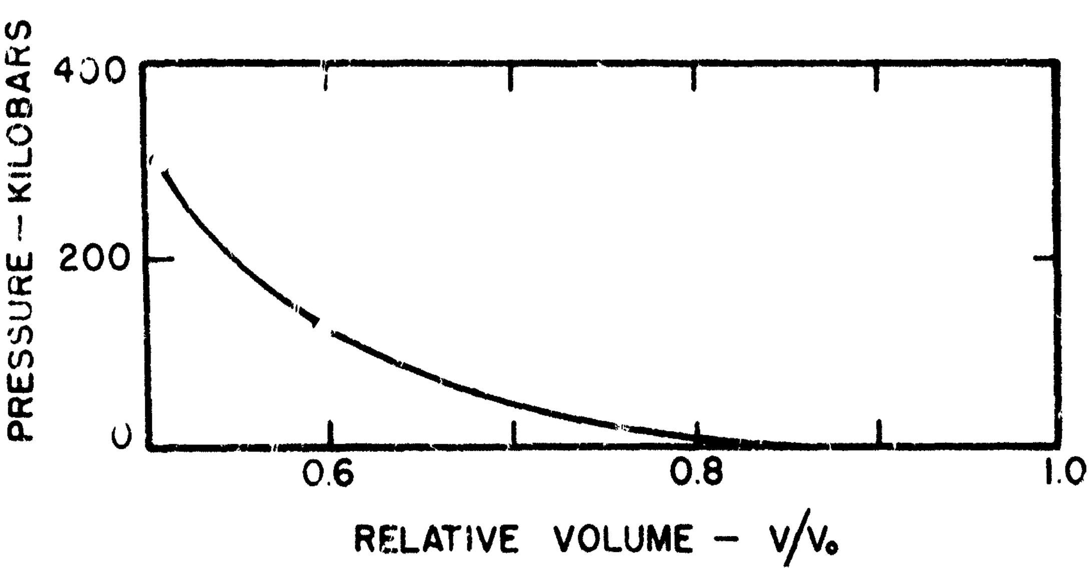
ACETONE


SHOCK VELOCITY - mm/μsec
0
2
4
6
0
100
200
300
PRESSURE (KILOBARS)

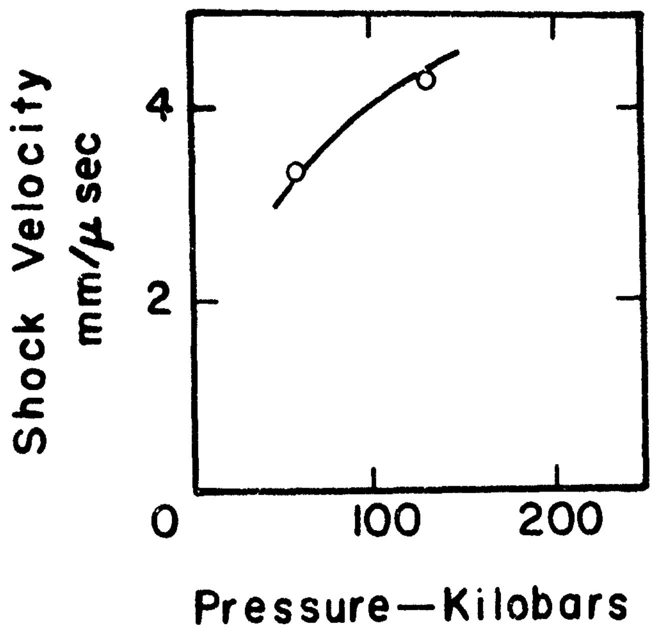

PRESSURE (KILOBARS)
0
200
0.5
0.6
0.7
0.8
0.9
1.0
RELATIVE VOLUME — V/V₀

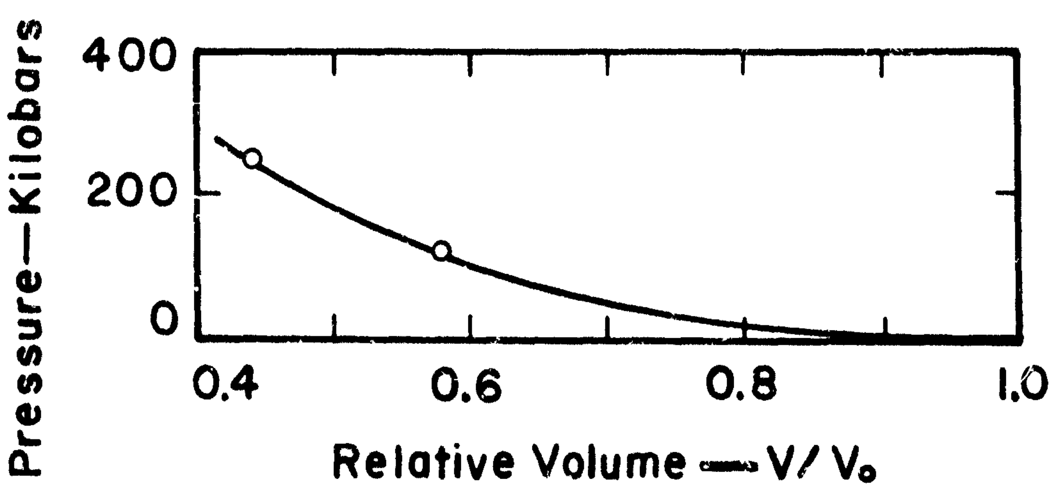
BENZENE



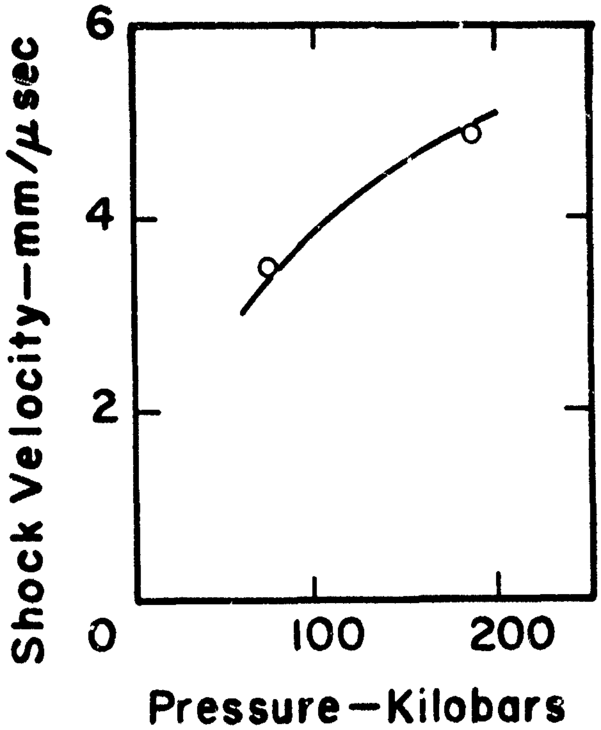


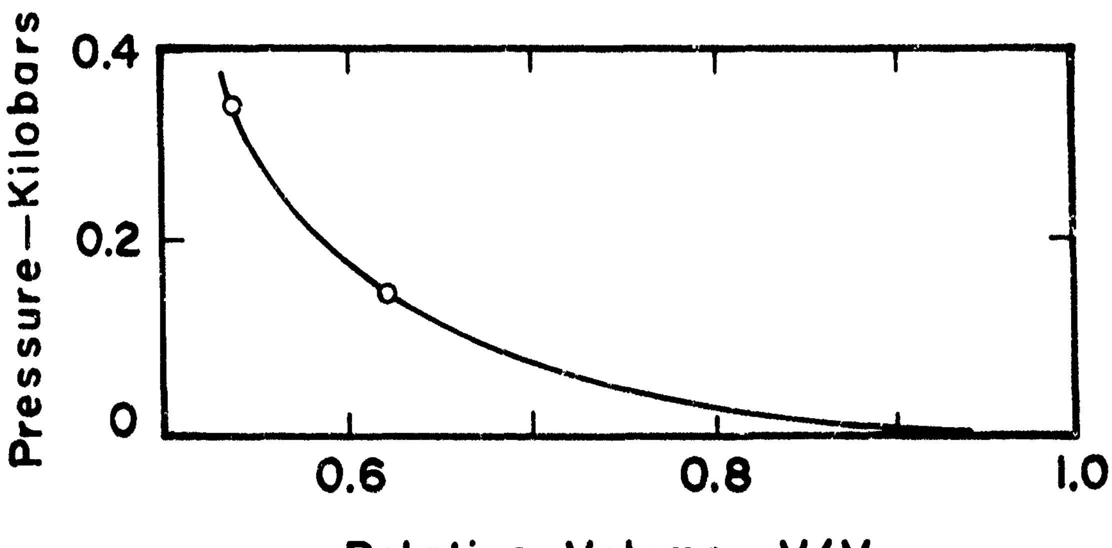
BROMOETHANE



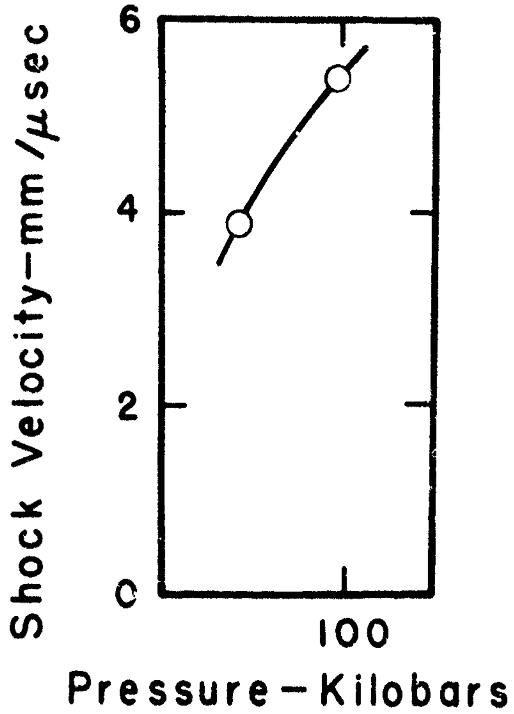


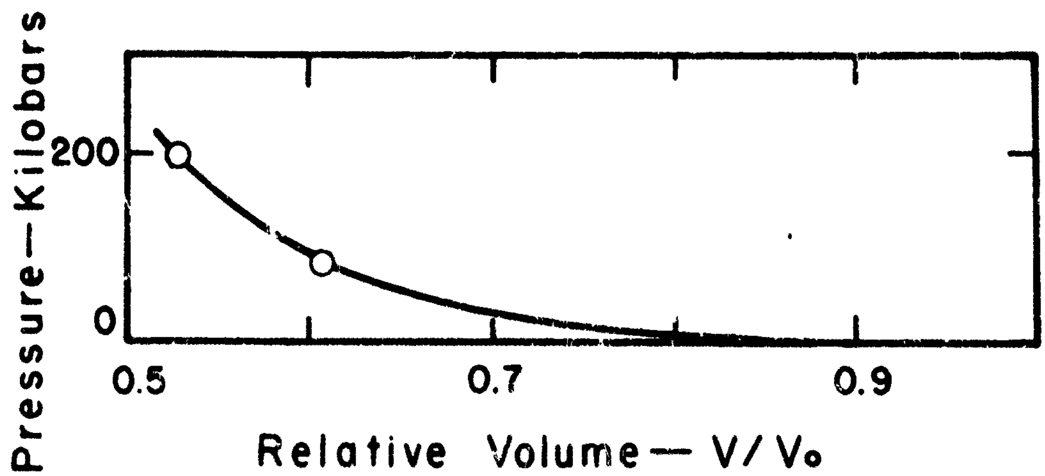
CARBON DISULFIDE



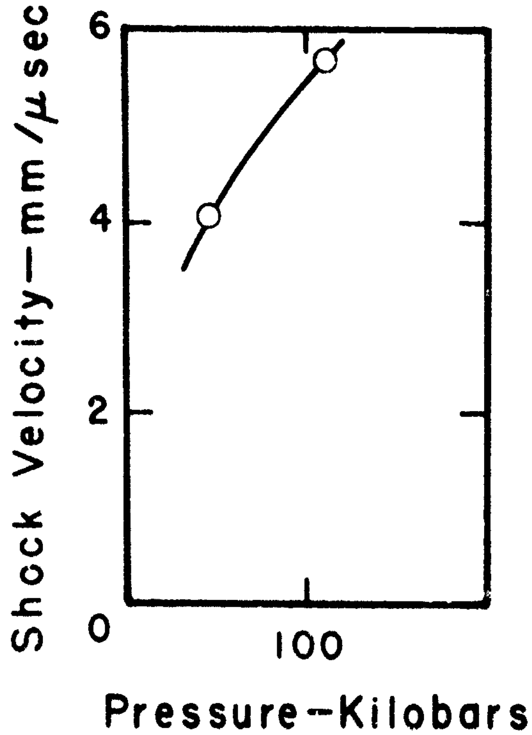


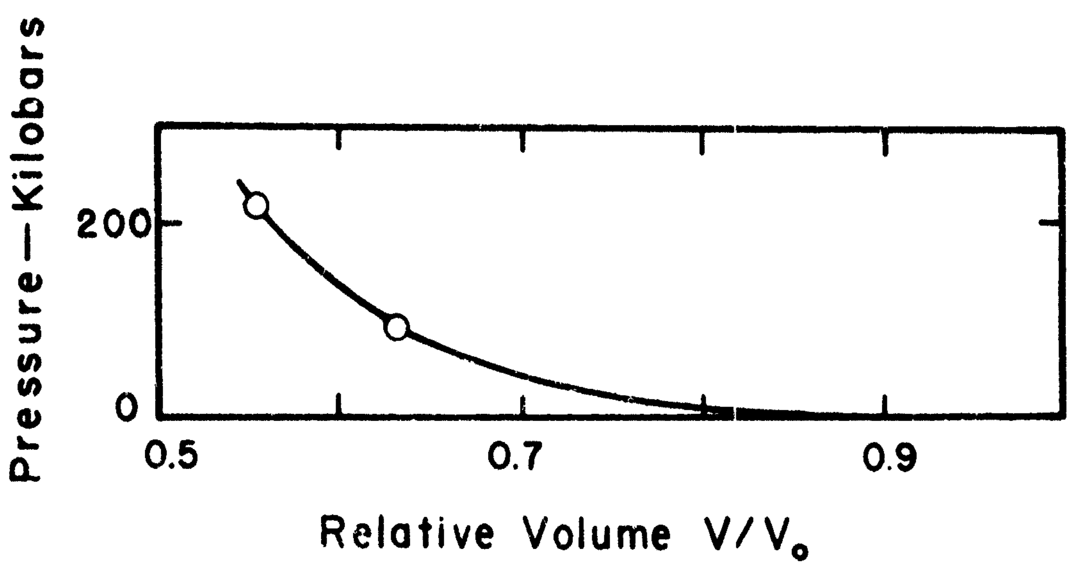
CARBON TETRACHLORIDE


Shock Velocity—mm/μsec
6
4
2
0
100
Pressure—Kilobars

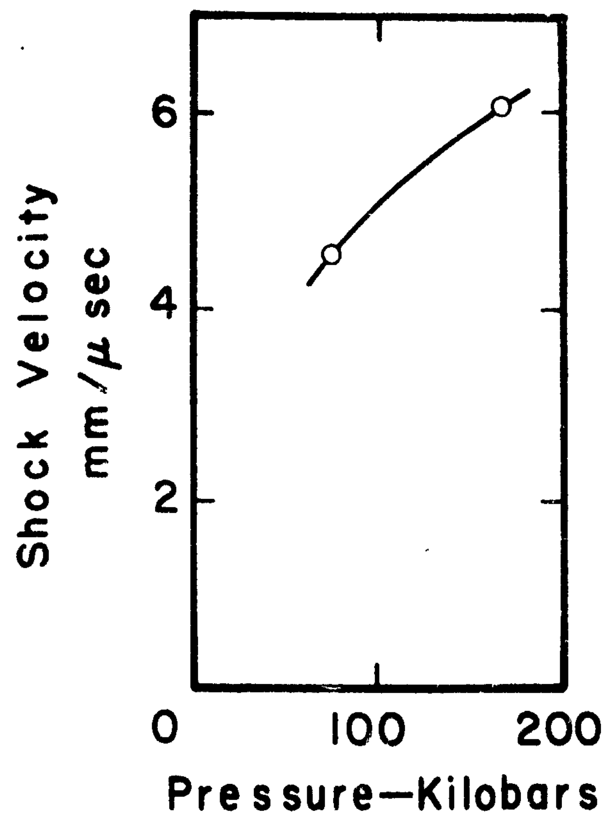

Pressure—Kilobars
200
0
0.5
0.7
0.9
Relative Volume—V/Vo

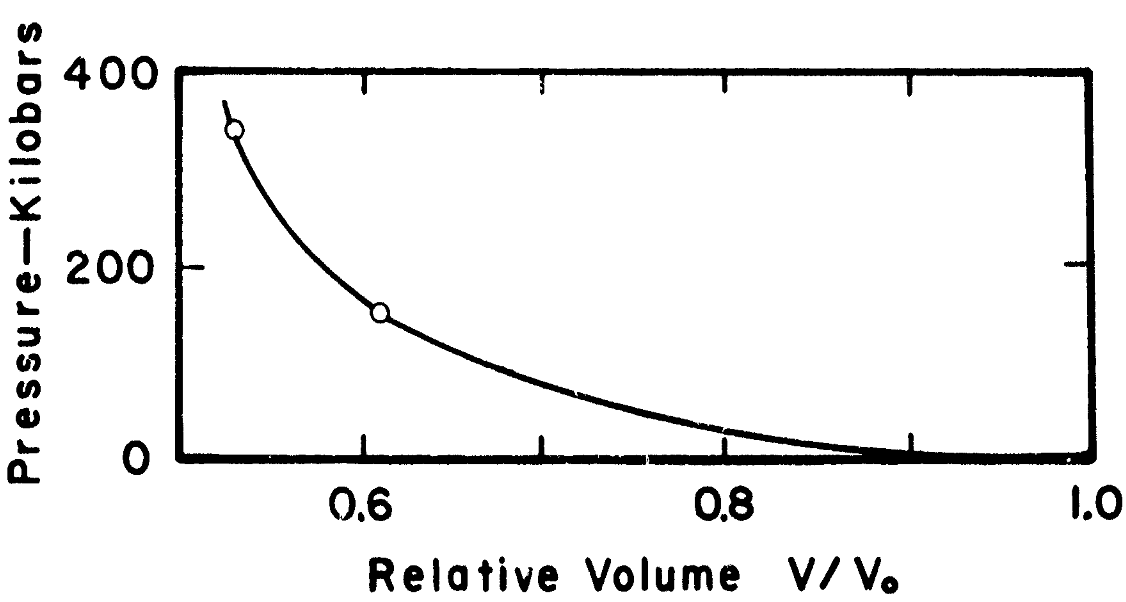
ETHYL ETHER



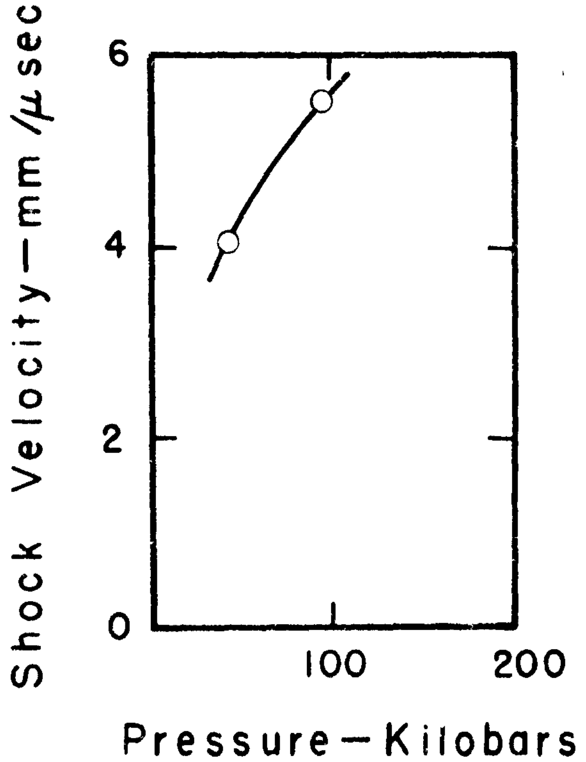


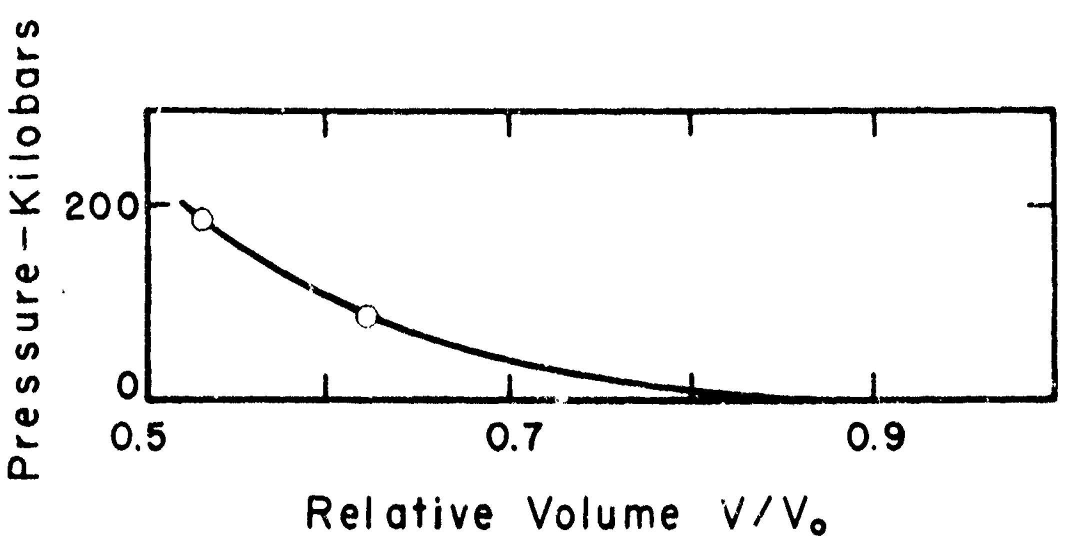
ETHYL ALCOHOL


Shock Velocity
mm/μ sec
6
4
2
0
100
200
Pressure—Kilobars

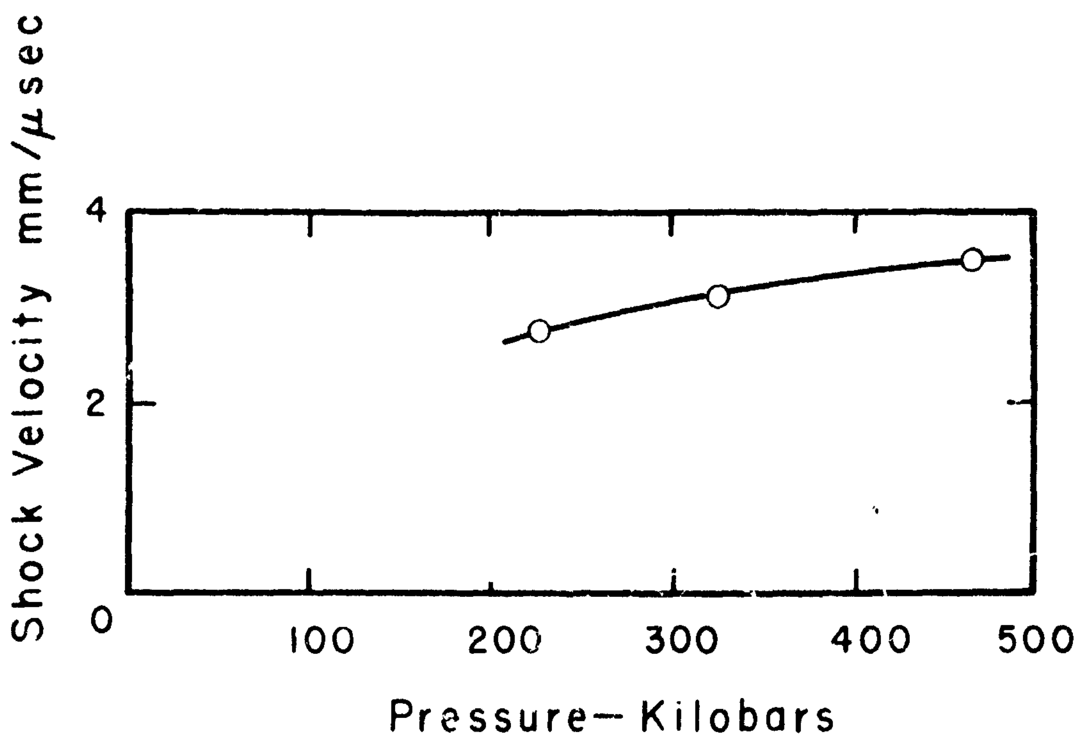

Pressure—Kilobars
400
200
0
0.6
0.8
1.0
Relative Volume V/V₀

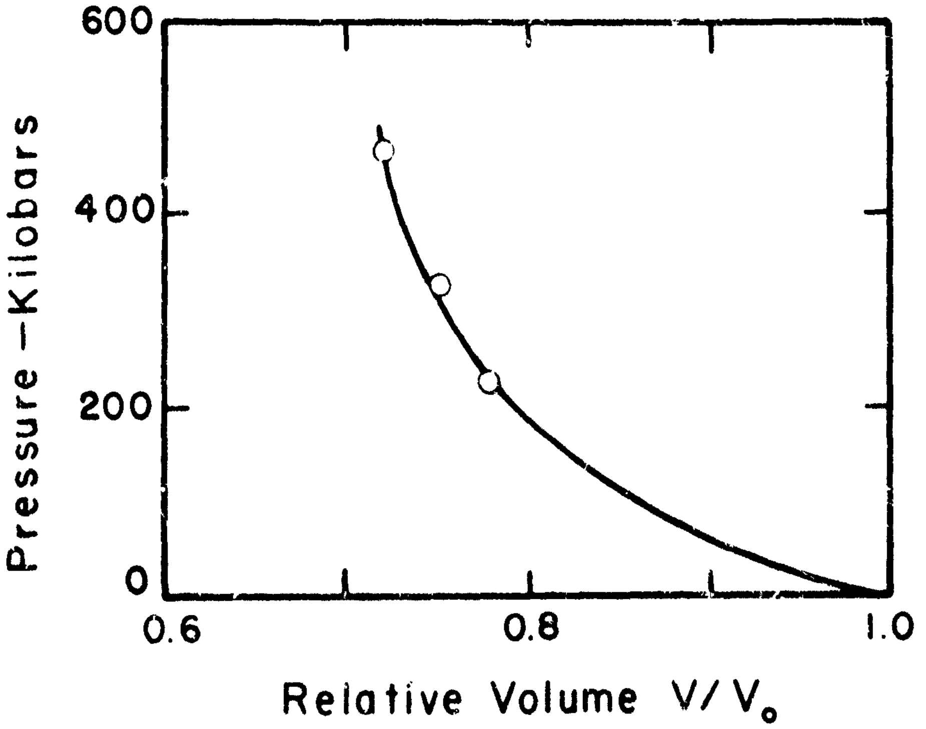
GLYCERINE


Shock Velocity—mm/μsec
6
4
2
0
100
200
Pressure—Kilobars

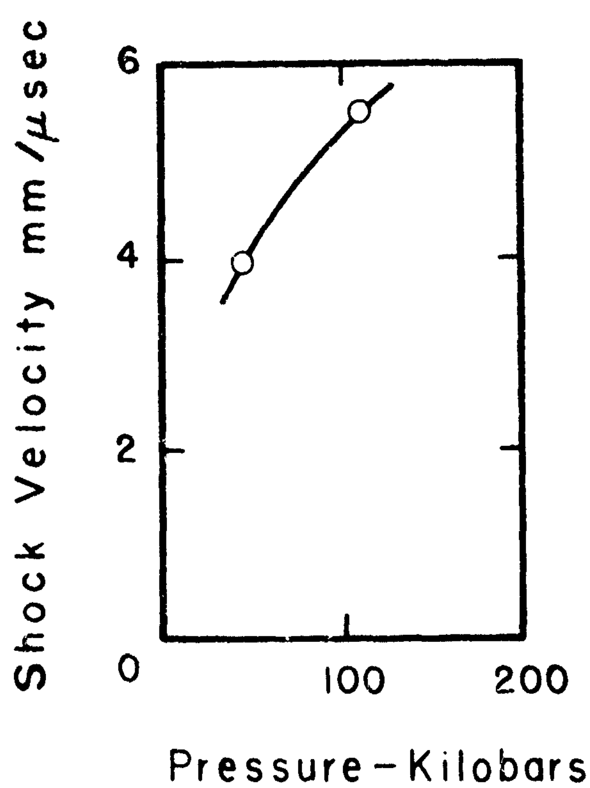

Pressure-Kilobars
200
0
0.5
0.7
0.9
Relative Volume V/V₀

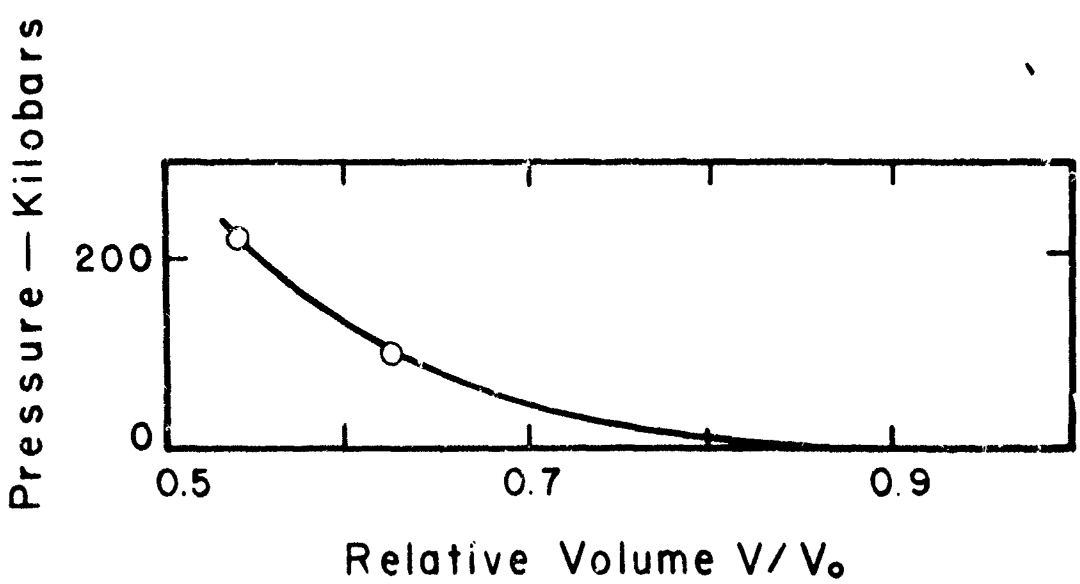
HEXANE


Shock Velocity mm/μsec
4
2
0
100
200
300
400
500
Pressure— Kilobars

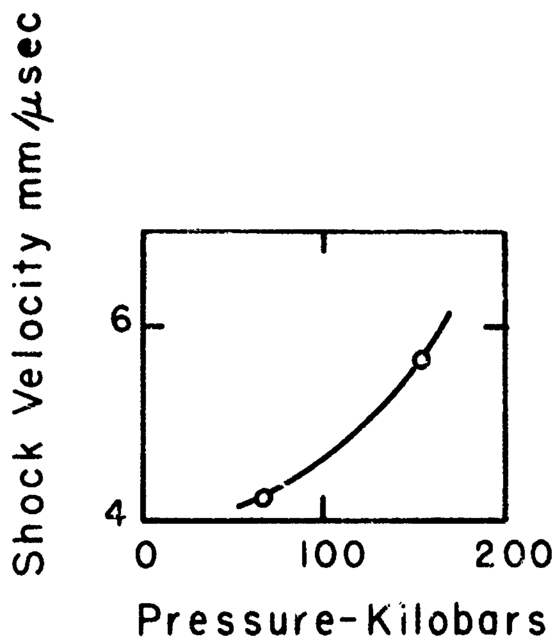

600
400
200
0
Pressure —Kilobars
0.6
0.8
1.0
Relative Volume V/V₀

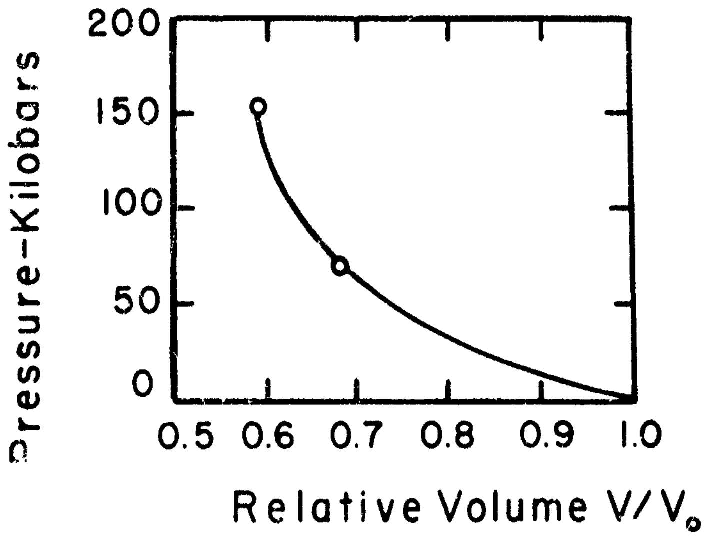
MERCURY


Shock Velocity mm/μsec
6
4
2
0
100
200
Pressure-Kilobars

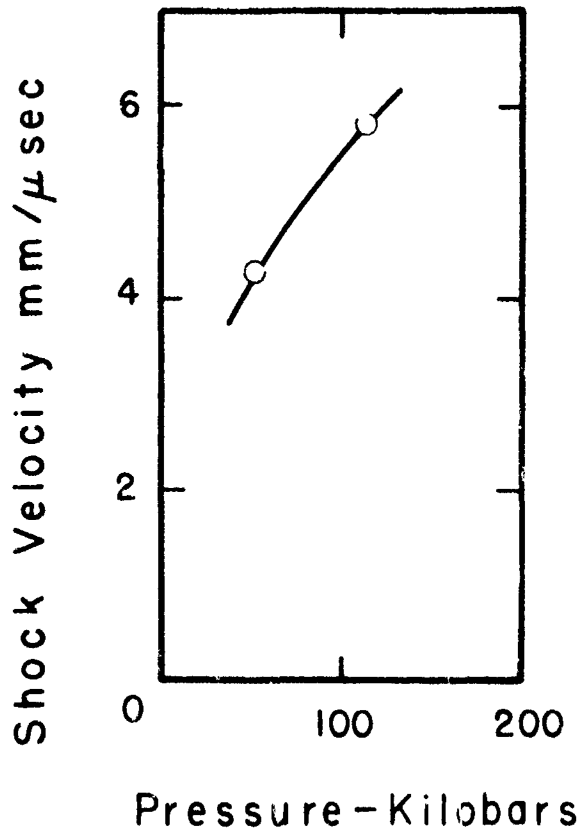

Pressure — Kilobars
200
0
0.5
0.7
0.9
Relative Volume V/V₀

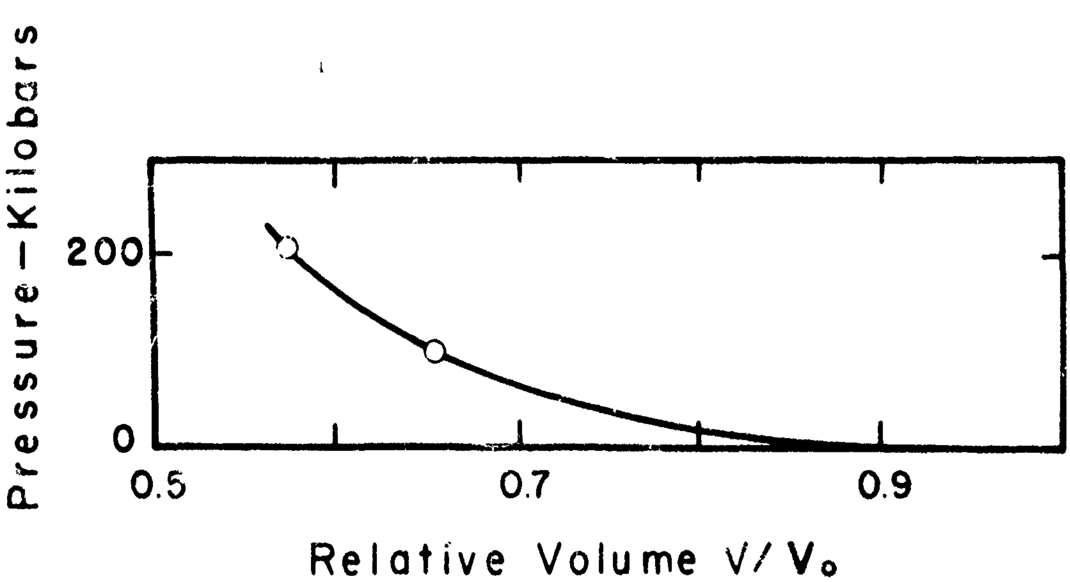
METHANOL



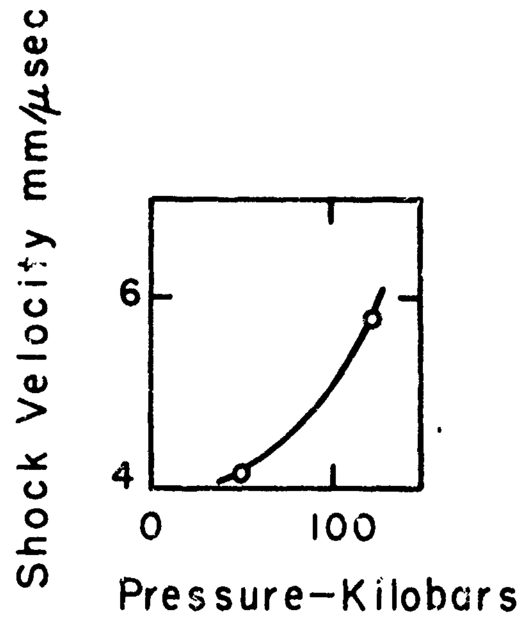


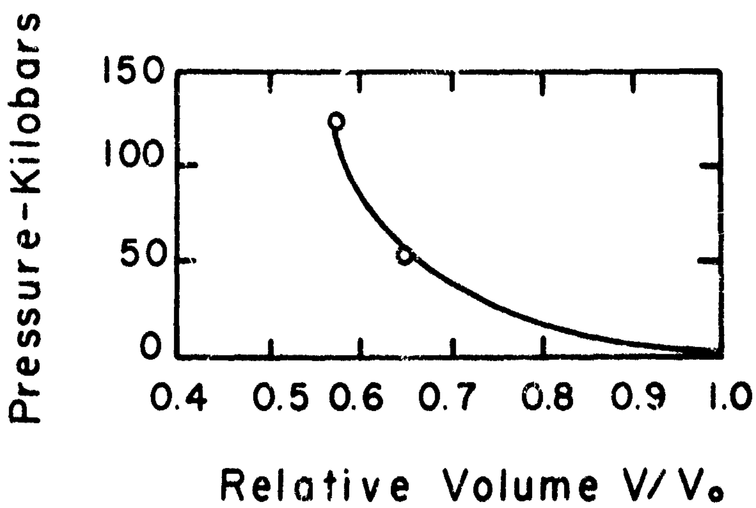
MONONITROTOLUENE





N-AMYL ALCOHOL


Shock Velocity mm/μsec
6
4
0
100
Pressure-Kilobars


Pressure-Kilobars
150
100
50
0
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Relative Volume V/Vo

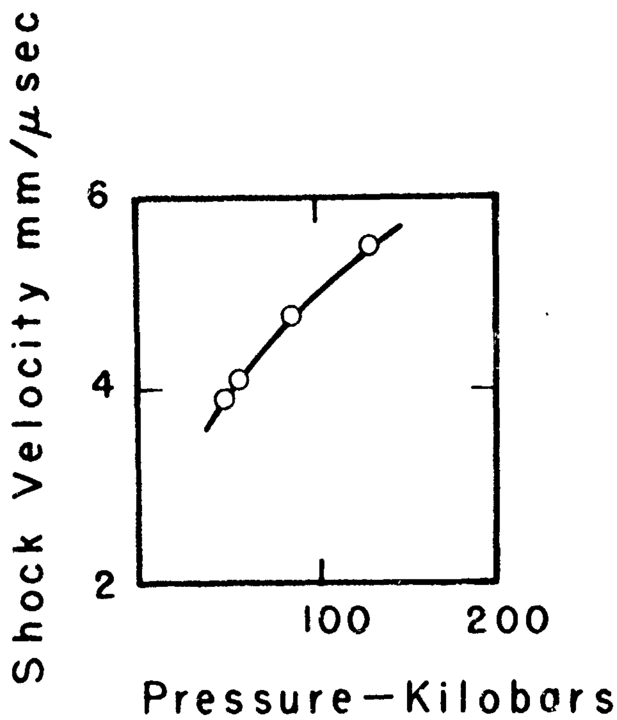
TOLUENE

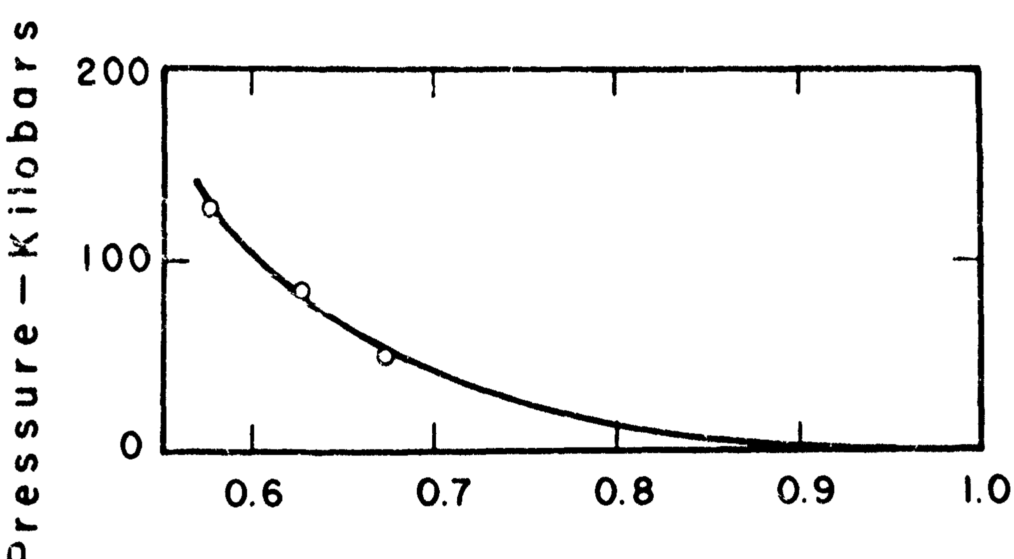
WATER

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.354	0.952	31.8	0.716
4.093	1.392	56.8	0.660
4.126	1.411	58.2	0.658
4.536	1.655	74.9	0.635
4.813	1.829	87.8	0.620
4.777	1.806	86.1	0.622
4.757	1.798	85.4	0.622
5.626	2.385	133.9	0.576
5.604	2.370	132.5	0.577
5.601	2.335	130.5	0.583
8.07	4.13	333.0	0.488
8.07	4.24	342.0	0.475
8.45	4.60	388.0	0.456
8.49	4.72	400.0	0.444
8.59	4.72	405.0	0.450
8.74	4.81	419.0	0.450

$\rho_0 = 1.0$

Source: Walsh and Rice (1957)


Shock Velocity mm/μsec
6
4
2
100
200
Pressure—Kilobars


Pressure — Kilobars
200
100
0
0.6
0.7
0.8
0.9
1.0
Relative Volume V/V₀

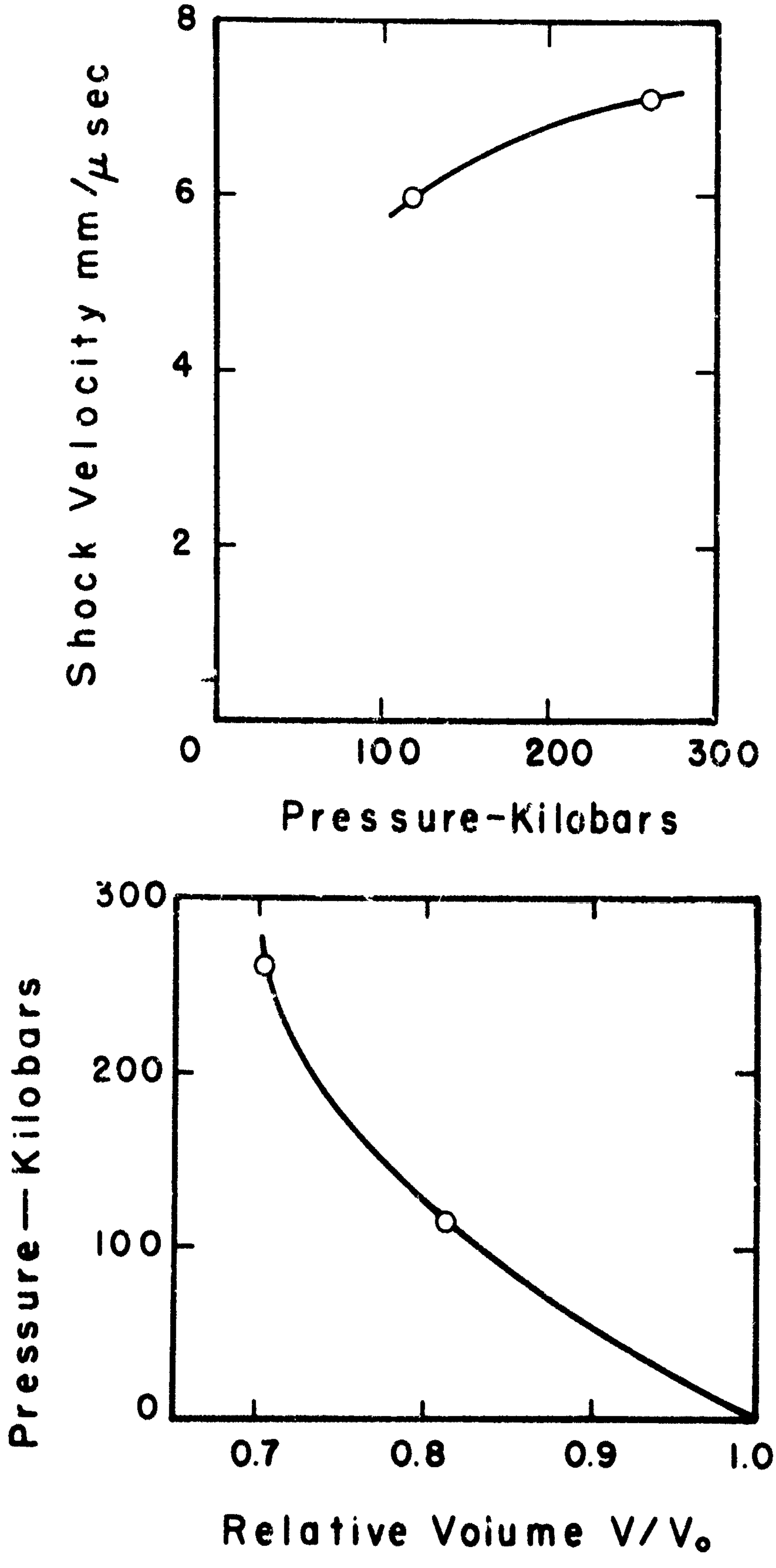
WATER

MAGNESIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.987	1.121	116.4	0.8128
7.082	2.078	260.4	0.7066

ρ_o = 1.735

Source: Walsh, Rice, McQueen and Yarger (1957)


Shock Velocity mm/μ sec
8
6
4
2
0
100
200
300
Pressure-Kilobars
Pressure—Kilobars
300
200
100
0
0.7
0.8
0.9
1.0
Relative Volume V/V₀

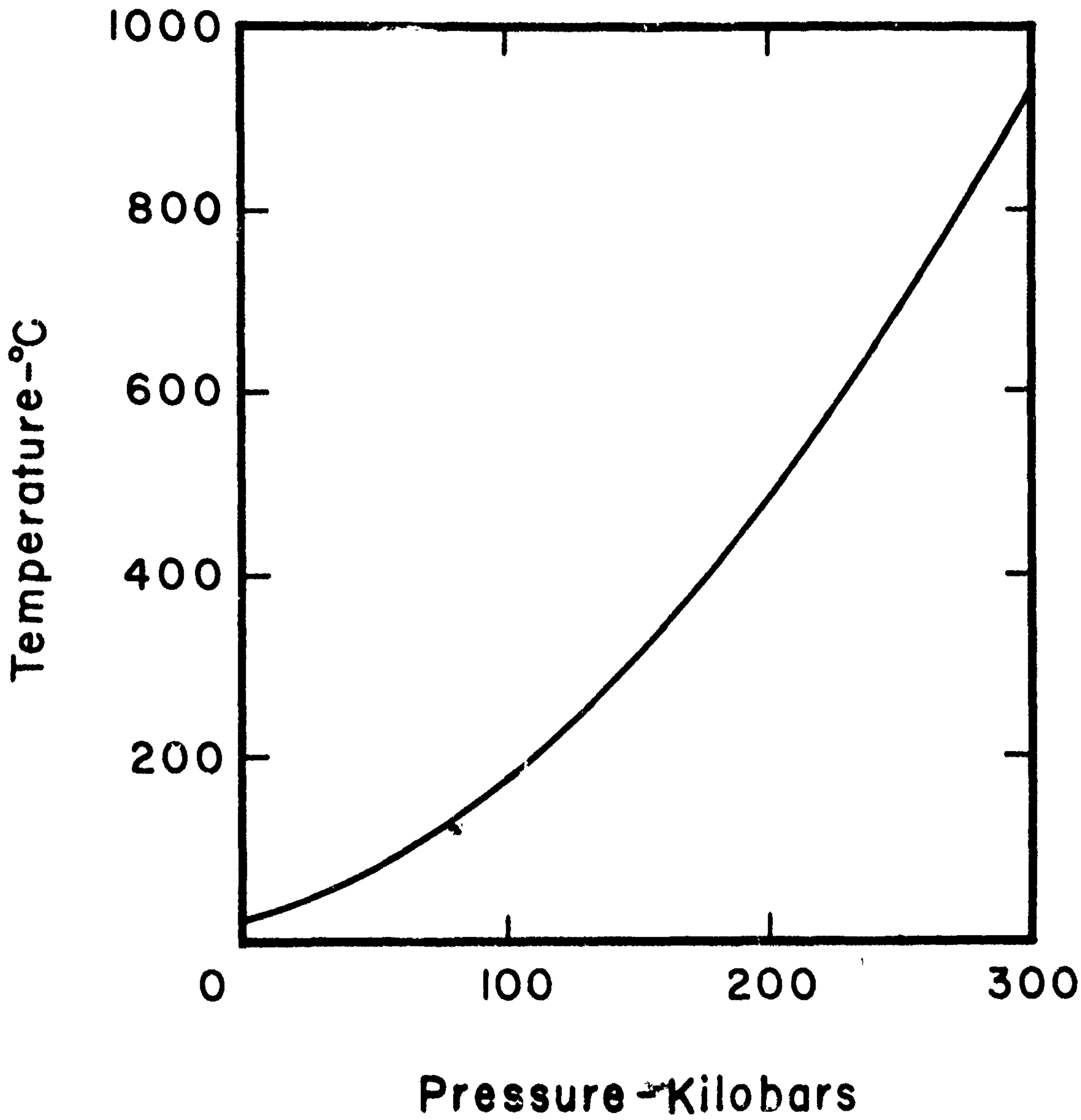
MAGNESIUM

Temperatures associated with shock

Magnesium

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	
100	174	
150	313	
200	487	
250	691	
300	923	

Source: Rice, McQueen and Walsh, 1958


1000
800
600
400
200
0
100
200
300
Temperature-°C
Pressure-Kilobars

MAGNESIUM

MARBLE*

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
	Light Marble		
6.620	0.913	171	0.862
7.347	1.422	297	0.806
7.658	1.93	418	0.748
	Dark Marble		
5.464	0.983	156	0.820
7.304	1.425	296	0.805
7.737	2.13	468	0.725

ρ_0 = 2.84 - 2.90

Source: Lombard (1961)

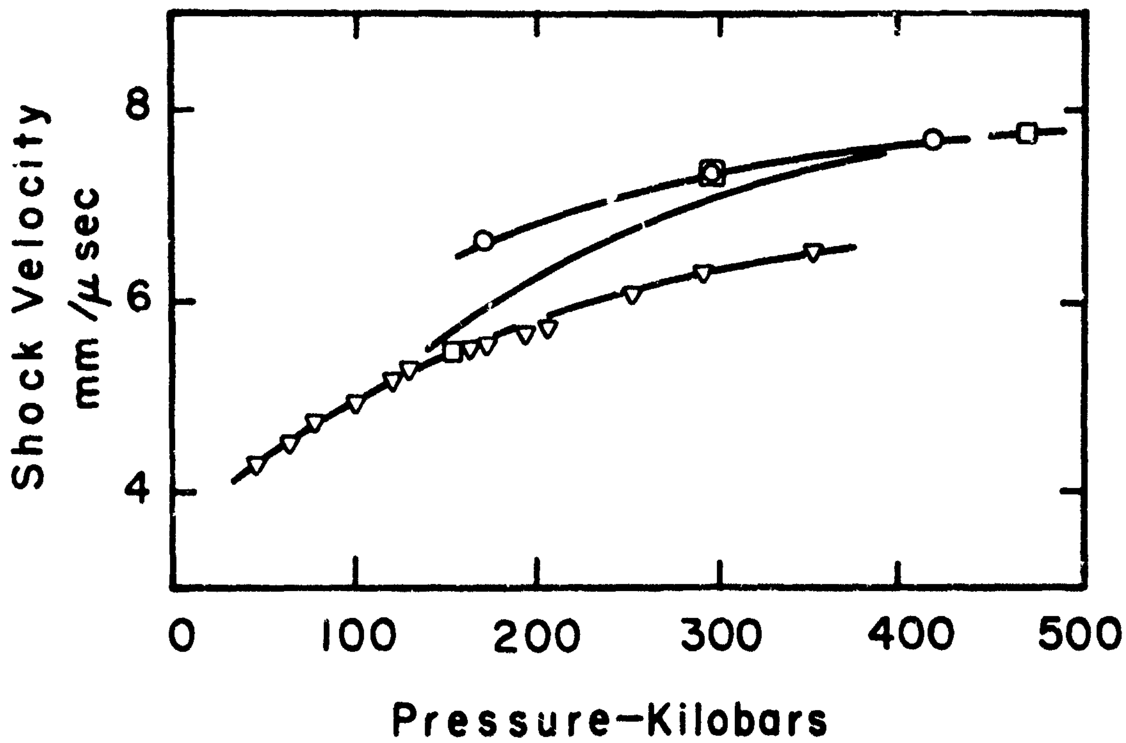
* From surface, Nevada Test Site Area 15

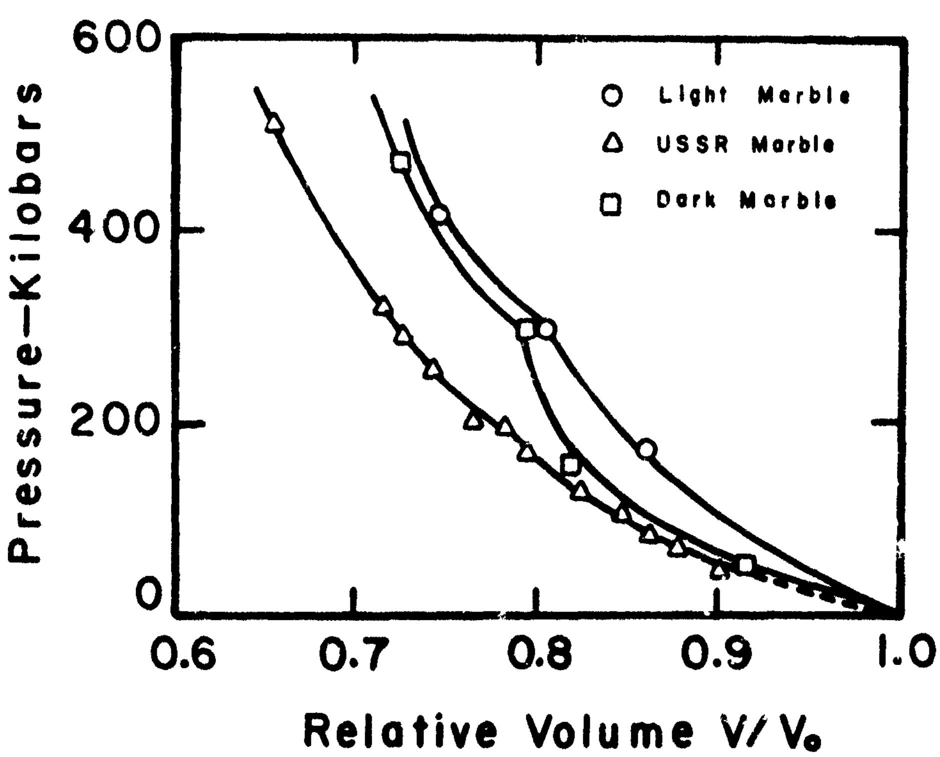
MARBLE

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.26	0.43	50	0.901
4.51	0.56	68	0.877
4.70	0.64	80	0.862
4.92	0.77	102.5	0.846
5.18	0.90	125	0.826
5.26	0.92	131	0.825
5.47	1.125	166	0.794
5.51	1.17	174	0.786
5.66	1.26	193	0.781
5.76	1.33	108	0.763
6.04	1.56	252	0.741
6.27	1.72	291	0.725
6.47	1.85	325	0.715
7.35	2.56	508	0.653

ρ_0 = 2.70

Source: Dremin and Adadurov (1959)


Shock Velocity mm /μ sec
8
6
4
0
100
200
300
400
500
Pressure—Kilobars


600
400
200
0
Pressure—Kilobars
Light Marble
USSR Marble
Dark Marble
0.6
0.7
0.8
0.9
1.0
Relative Volume V/V₀

MARBLE

MOLYBDENUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.699	0.437	254.0	0.9233
5.647	0.444	255.2	0.9214
5.955	0.591	359.0	0.9008
5.861	0.606	362.3	0.8966
6.210	0.850	538.4	0.8631
6.124	0.792	494.7	0.8707

$\rho_0 = 10.20$

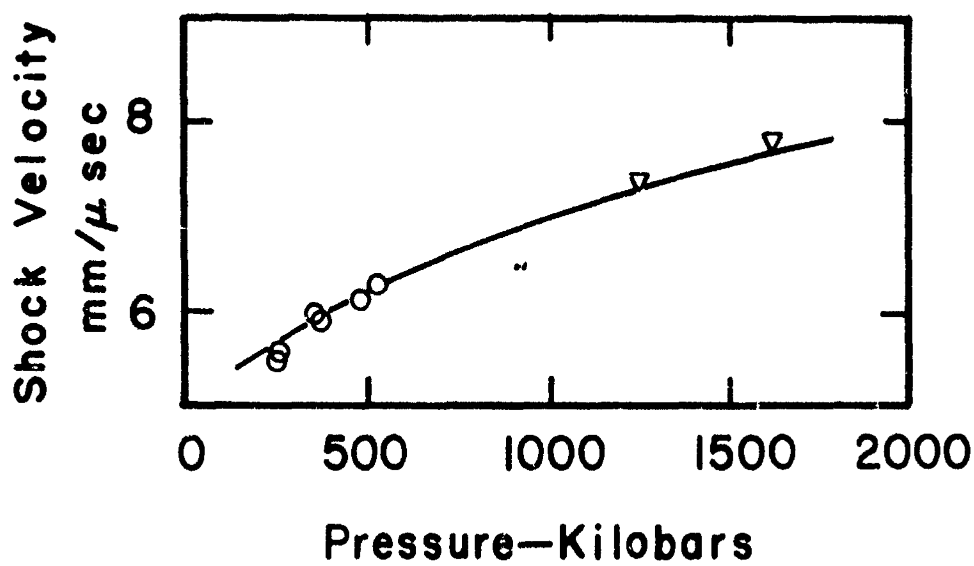
Source: Walsh, Rice, McQueen and Yarger (1957)

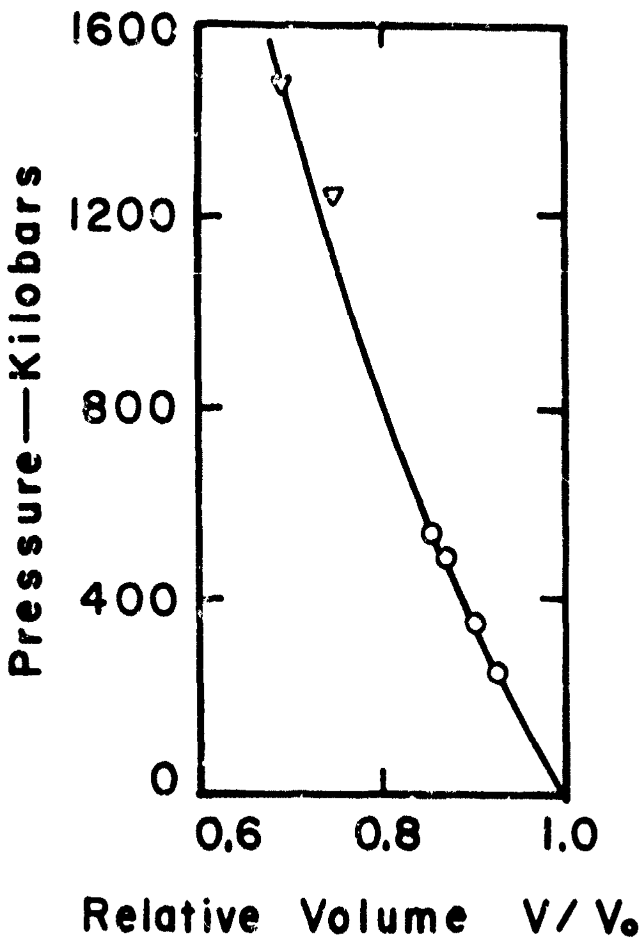
MOLYBDENUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
7.29	1.69	1256	0.769
7.20	1.70	1245	0.764
7.29	1.68	1250	0.770
7.65	2.06	1604	0.731
7.71	2.06	1618	0.733
7.75	2.07	1633	0.733

$\rho_0 = 10.20$

Source: McQueen and Marsh (1960)


Shock Velocity mm/μ sec
8
6
0
500
1000
1500
2000
Pressure—Kilobars


1600
1200
800
400
0
Pressure—Kilobars
0.6
0.8
1.0
Relative Volume V/ V₀

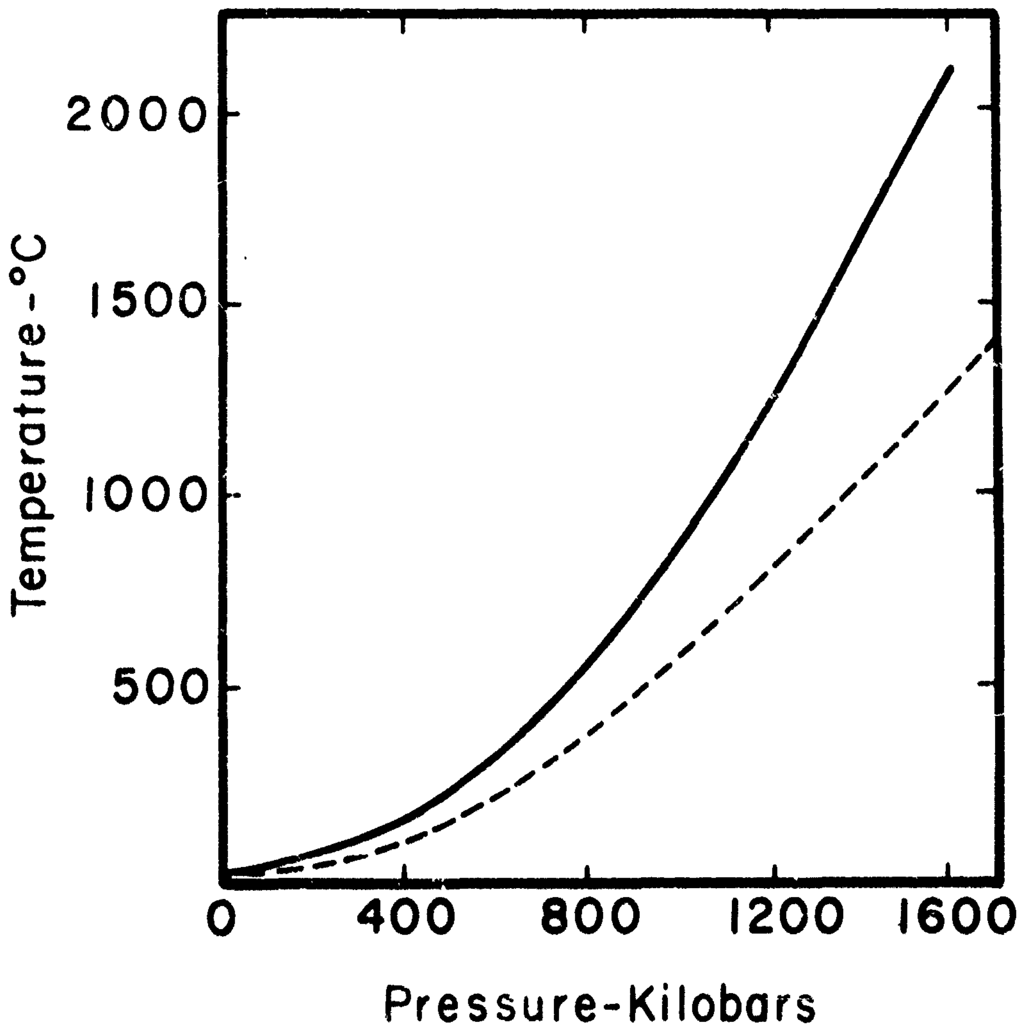
MOLYBDENUM

Temperatures associated with shock

Molybdenum

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	37	22
200	62	32
300	99	54
400	153	90
500	226	139
600	313	202
700	429	276
800	559	362
900	707	457
1000	871	560
1100	1051	670
1200	1244	786
1300	1449	905
1400	1665	1027
1500	1888	1149
1600	2116	1270
1700	2347	1387

Source: McQueen and Marsh, 1960


2000
1500
1000
500
Temperature - °C
0
400
800
1200
1600
Pressure-Kilobars

MOLYBDENUM

NICKEL

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.417	0.490	235.0	0.9095
5.653	0.678	339.4	0.8801
5.620	0.687	341.8	0.8778
6.031	0.957	511.0	0.8413
5.969	0.982	519.0	0.8355
5.952	0.887	467.4	0.8510

$\rho_0 = 8.86$

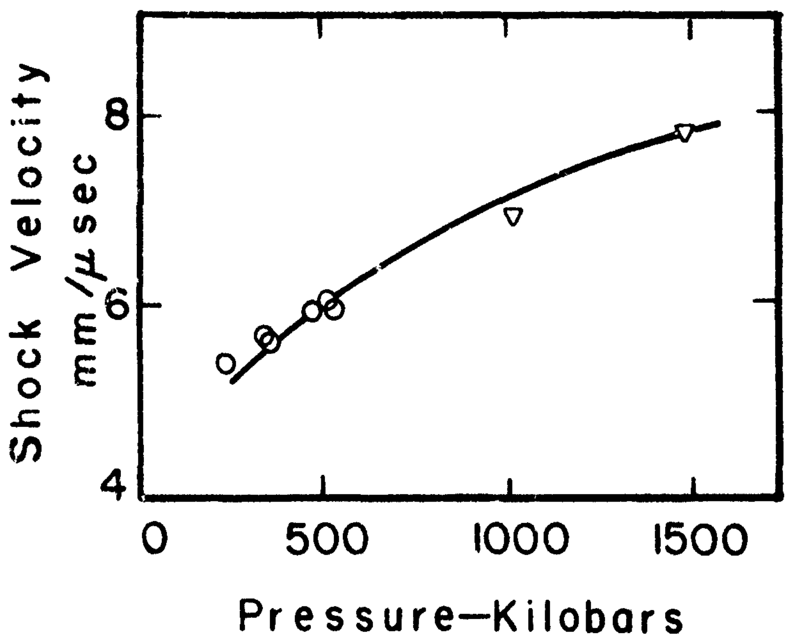
Source: Walsh, Rice, McQueen and Yarger (1957)

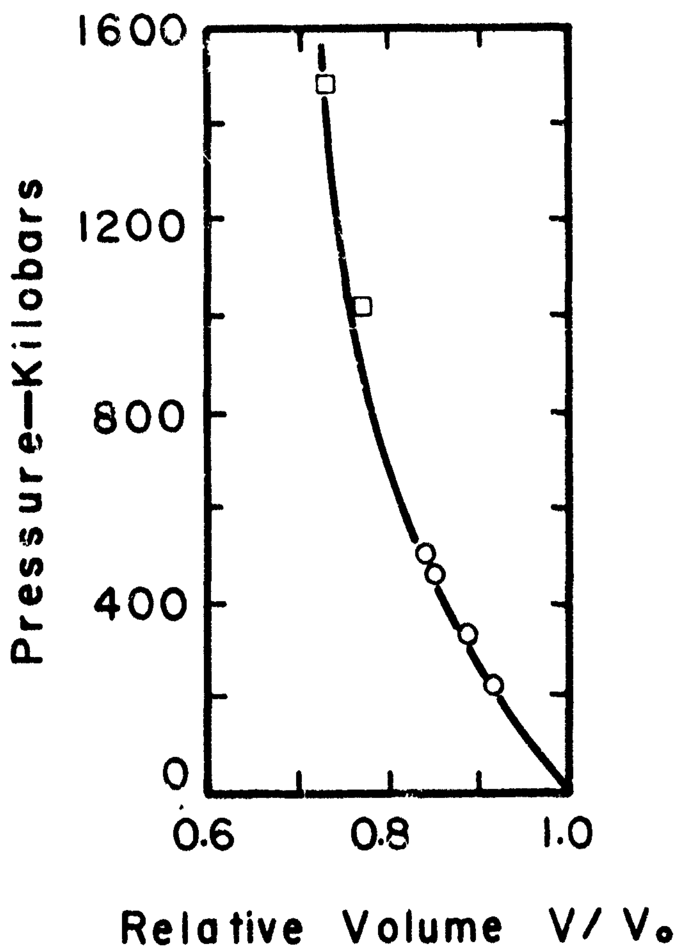
NICKEL

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
6.95	1.64	1009	0.764
6.99	1.64	1014	0.766
7.11	1.62	1022	0.772
7.78	2.15	1478	0.724
7.76	2.17	1491	0.721
7.80	2.16	1490	0.723

$\rho_0 = 8.86$

Source: McQueen and Marsh (1960)


Shock Velocity mm/μsec
8
6
4
0
500
1000
1500
Pressure—Kilobars


1600
1200
800
400
0
Pressure—Kilobars
0.6
0.8
1.0
Relative Volume V/V₀

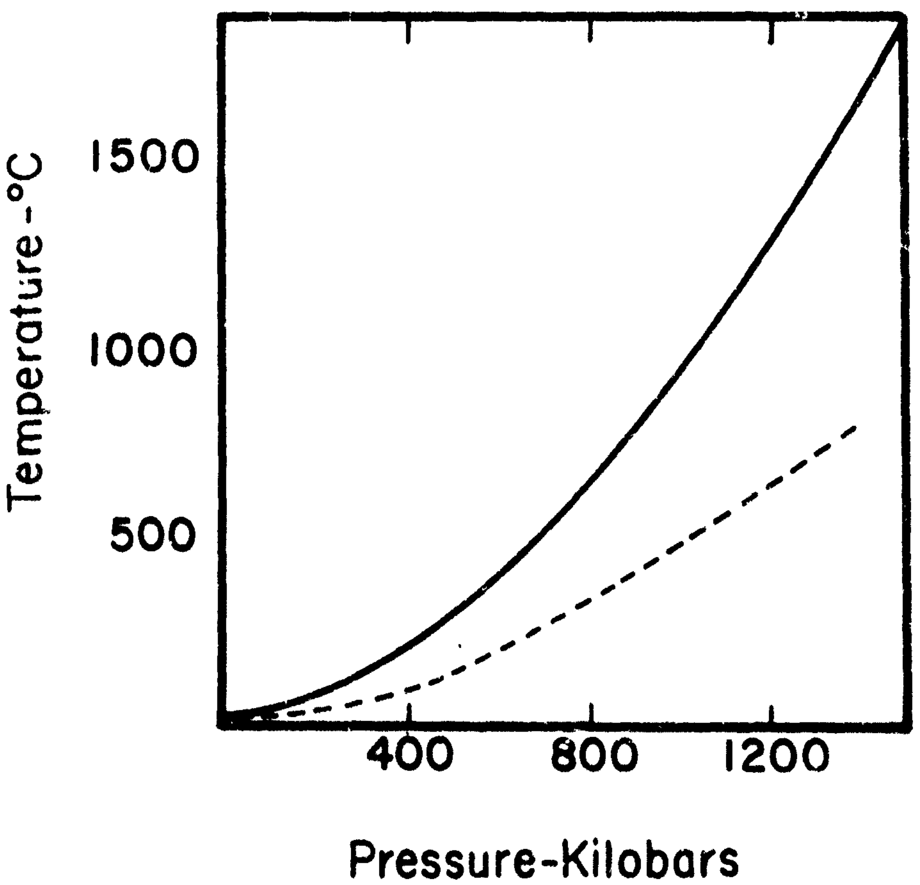
NICKEL

Temperatures associated with shock

Nickel

Pressure (kilobars)	Temperature behind shock (C^o)	Residual temperature (C^o)
0	20	20
100	48	22
200	83	34
300	132	57
400	198	92
500	281	137
600	381	191
700	495	252
800	624	319
900	767	391
1000	922	466
1100	1087	544
1200	1263	623
1300	1447	703
1400	1640	784
1500	1837	864

Source: McQueen and Marsh, 1960



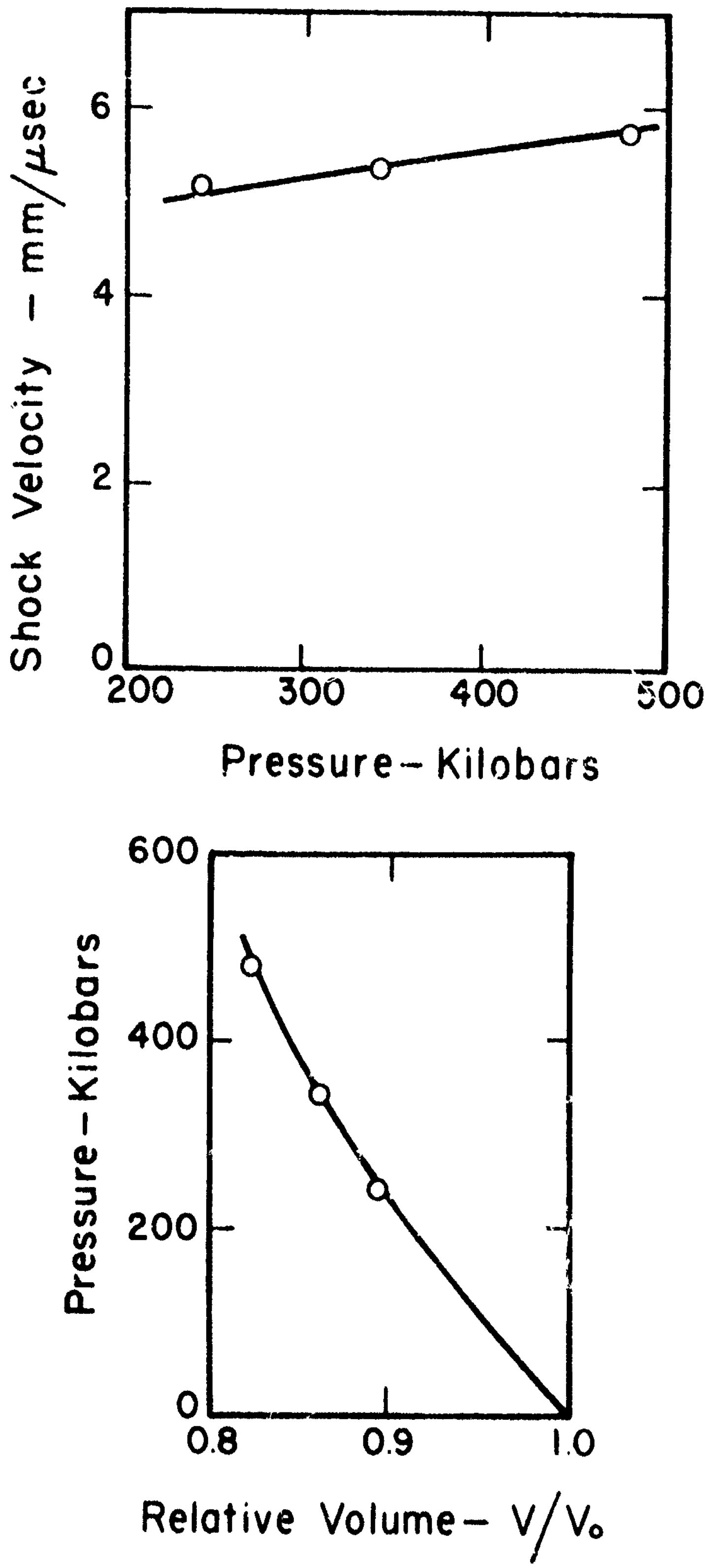
NICKEL

NIOBIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.177	0.5489	244.5	0.9040
5.311	0.7434	341	0.8606
5.642	0.9929	482	0.8240

$\rho_o = 8.604$

Source: Walsh, Rice, McQueen and Yarger (1957)


Shock Velocity - mm/μsec
0
2
4
6
200
300
400
500
Pressure - Kilobars
Pressure - Kilobars
0
200
400
600
0.8
0.9
1.0
Relative Volume - V/V₀

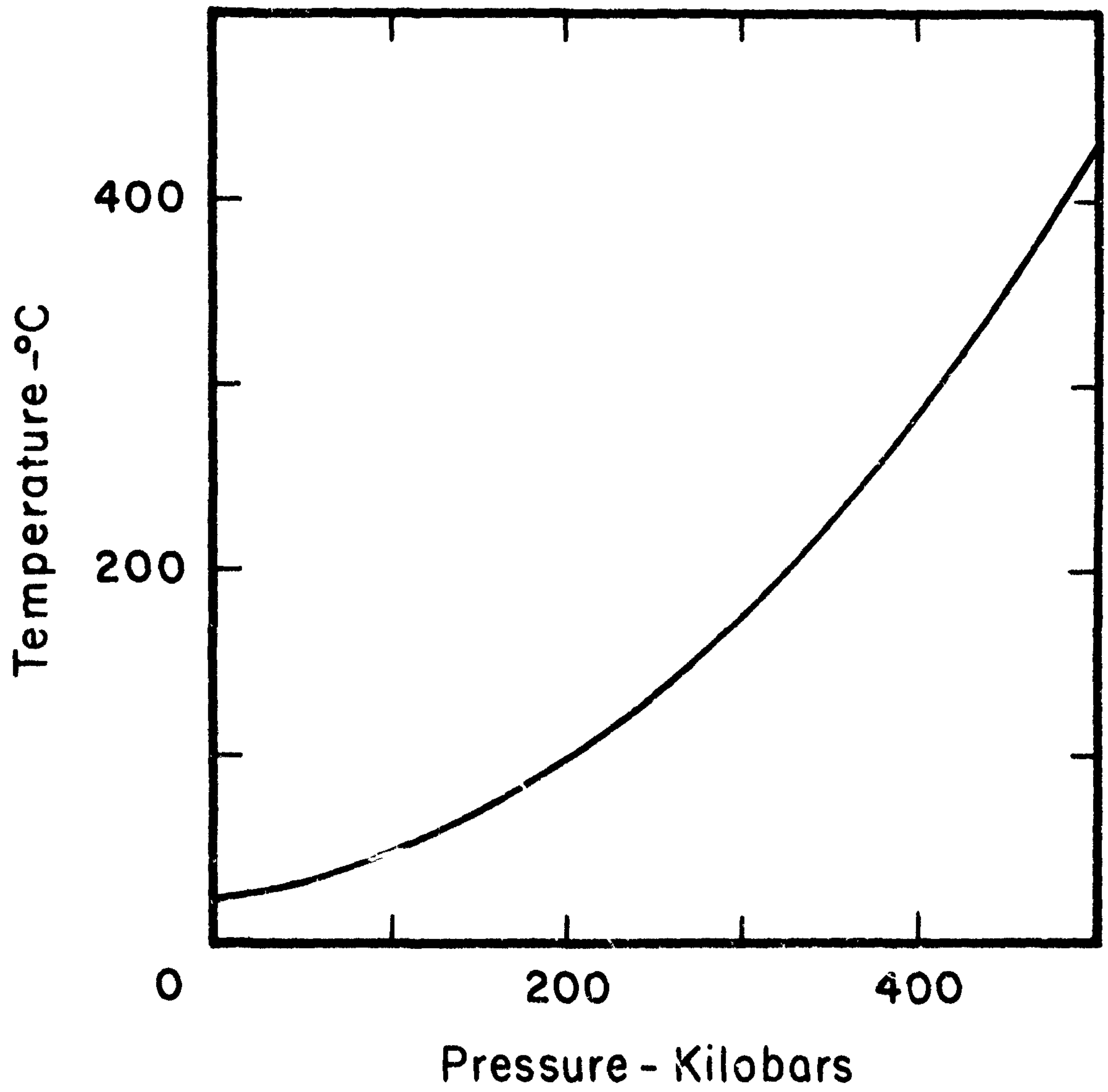
NIOBIUM

Temperatures associated with shock

Niobium

Pressure (kilobars)	Temperature behind shock (C^o)	Residual temperature (C^o)
0	20	
100	49	
150	73	
200	97	
250	133	
300	177	
350	227	
400	284	
450	351	
500	427	

Source: Rice, McQueen and Walsh, 1958



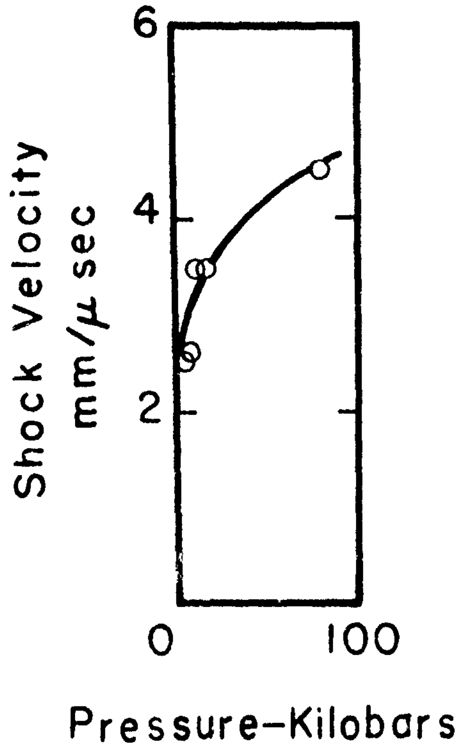
NIOBIUM

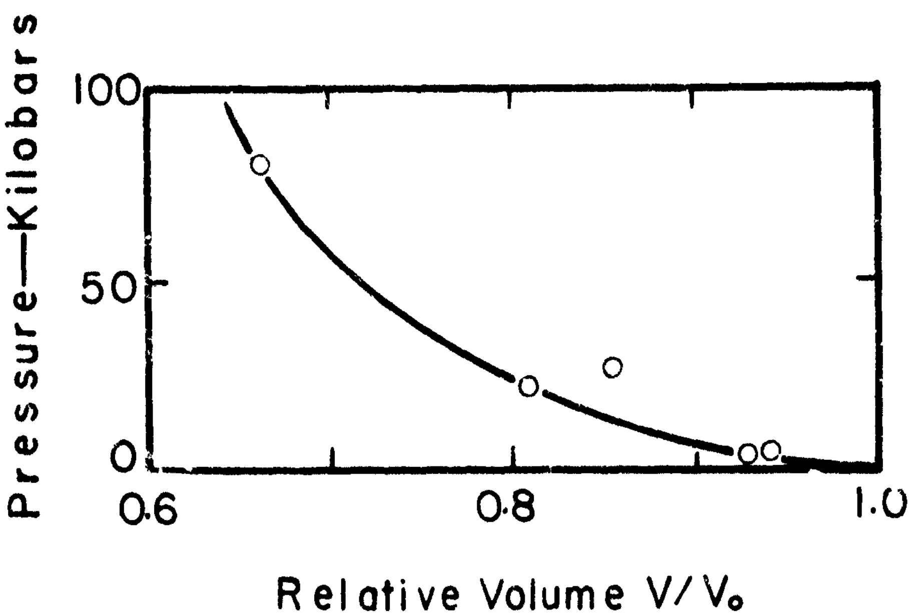
NYLON

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
2.38	0.135	4.50	0.945
2.40	0.165	3.64	0.930
3.51	0.505	26.6	0.856
3.52	0.665	20.2	0.810
4.56	1.55	80.2	0.661

$\rho_0 = 1.14$

Source: Wagner, Waldorf and Louie (1962)


Shock Velocity mm/μ sec
6
4
2
0
100
Pressure–Kilobars


Pressure—Kilobars
100
50
0
0.6
0.8
1.0
Relative Volume V/V₀

NYLON

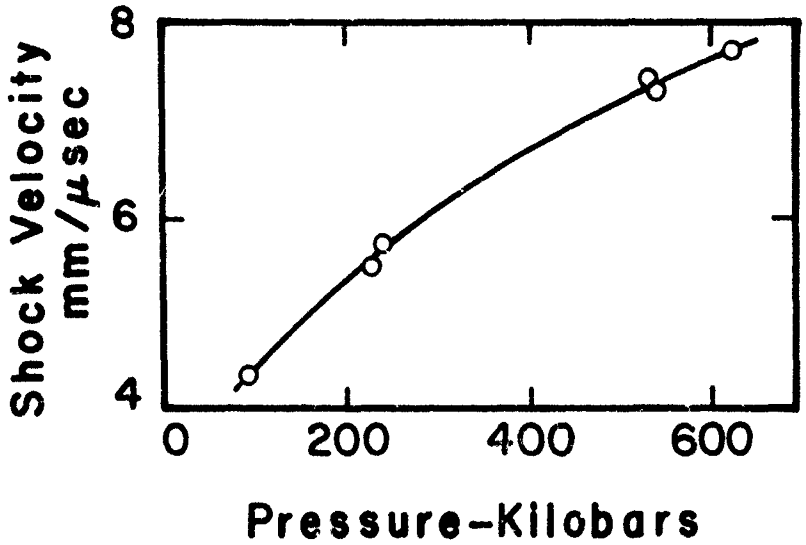
OIL SAND*

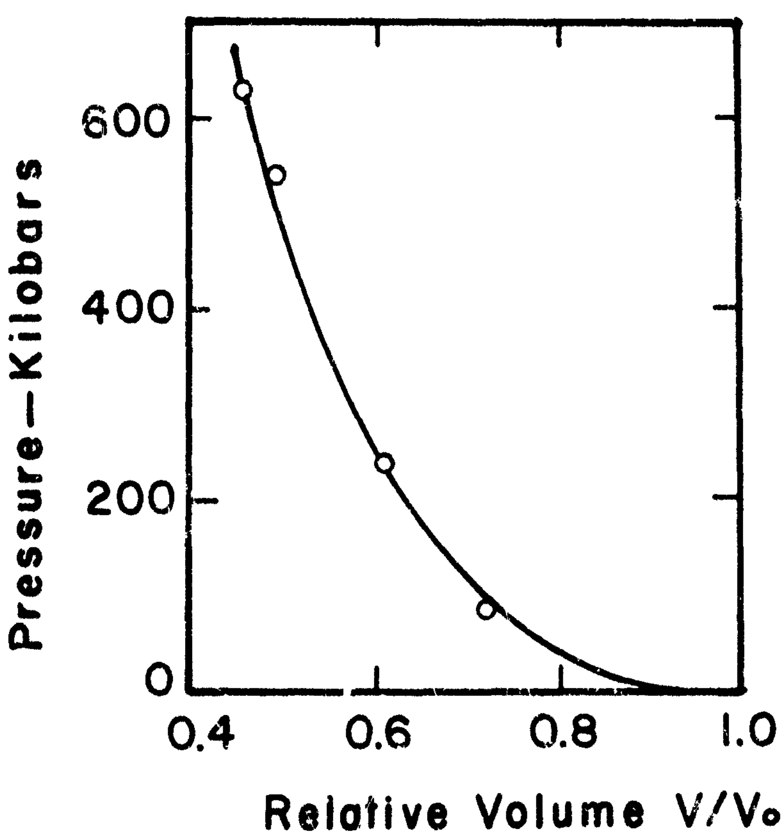
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.372	1.215	98	0.722
5.69	2.21	242	0.612
5.48	2.26	231	0.588
7.45	3.80	540	0.490
7.31	3.78	546	0.483
7.79	4.25	634	0.455

ρ_o = 1.84 - 1.98

Source: Lombard (1961)

* McMurray formation, Pony Creek No. 2 core, Richfield Oil Co., Alberta, Canada


Shock Velocity mm/μsec
8
6
4
0
200
400
600
Pressure–Kilobars


Pressure—Kilobars
600
400
200
0
0.4
0.6
0.8
1.0
Relative Volume V/Vo

OIL SAND

OIL SHALE*

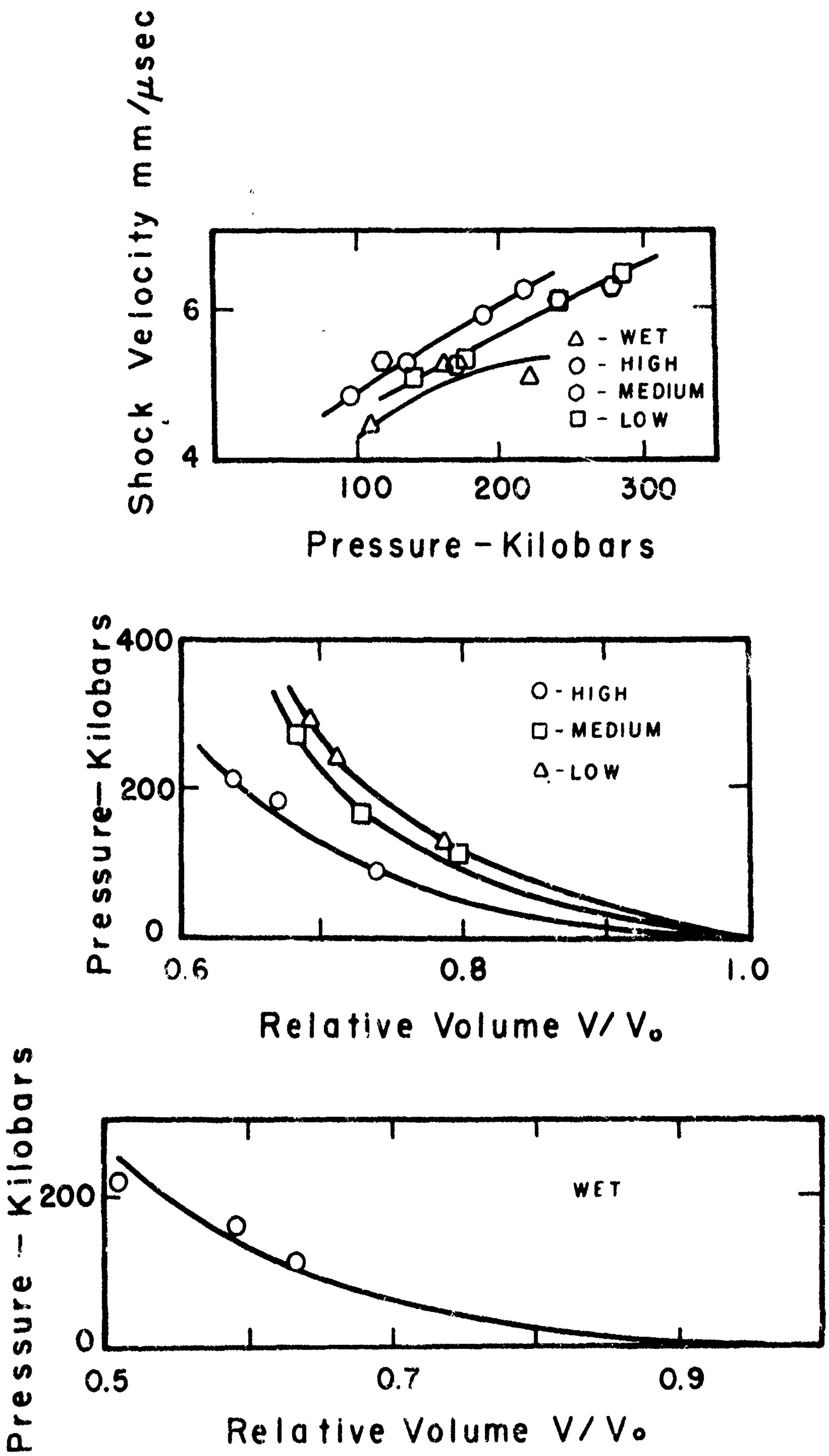
Shock Velocity (mm/µsec)	Particle Velocity (mm/µsec)	Pressure (kilobars)	Relative Volume
	Ore Grade# - High		
4.86	1.27	96	0.739
5.33	1.59	135	0.701
5.96	1.97	189	0.669
6.23	2.26	219	0.637
	Ore Grade - Medium		
5.30	1.09	119	0.794
6.27	1.43	170	0.729
6.09	1.75	242	0.713
6.29	2.00	279	0.682
	Ore Grade - Low		
5.08	1.09	130	0.765
5.36	1.40	175	0.738
6.04	1.75	241	0.710
6.41	1.98	286	0.691
	Oil Shale - Wet		
4.43	1.64	110	0.630
5.16	2.68	222	0.507
5.25	2.11	164	0.590

ρ_o = High - 1.6; Medium - 2.2 - 2.3; Low - 2.3; Wet - 1.51

Source: Lombard (1961)

* Pony Creek No. 2 core, Richfield Oil Co., Alberta, Canada

\# Ore grade - a qualitative term denoting the relative oil yield per unit volume of rock


Shock Velocity mm/μsec
6
4
100
200
300
Pressure - Kilobars
Δ - WET
O - HIGH
O - MEDIUM
□ - LOW
Pressure— Kilobars
400
200
0
0.6
0.8
1.0
Relative Volume V/ Vo
O - HIGH
□ - MEDIUM
Δ - LOW
Pressure - Kilobars
200
0
0.5
0.7
0.9
Relative Volume V/ Vo
WET

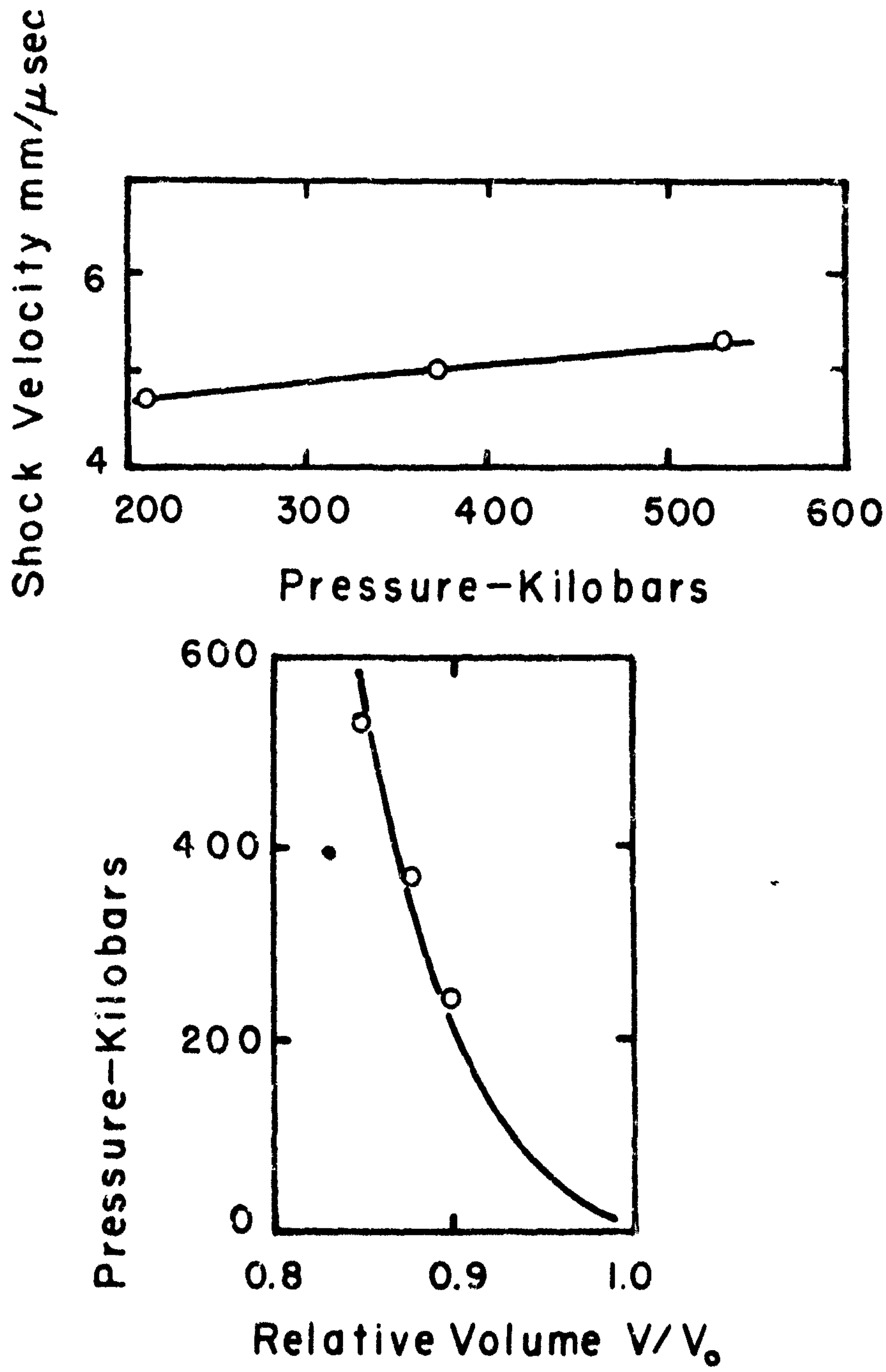
OIL SHALE

PALLADIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.673	0.4728	262.5	0.8988
5.004	0.6200	372	0.8761
5.374	0.8219	531	0.8471

$\rho_0 = 11.95$

Source: Walsh, Rice, McQueen and Yarger (1957)



Shock Velocity mm/μsec
6
4
200
300
400
500
600
Pressure-Kilobars
600
400
200
0
Pressure-Kilobars
0.8
0.9
1.0
Relative Volume V/V₀

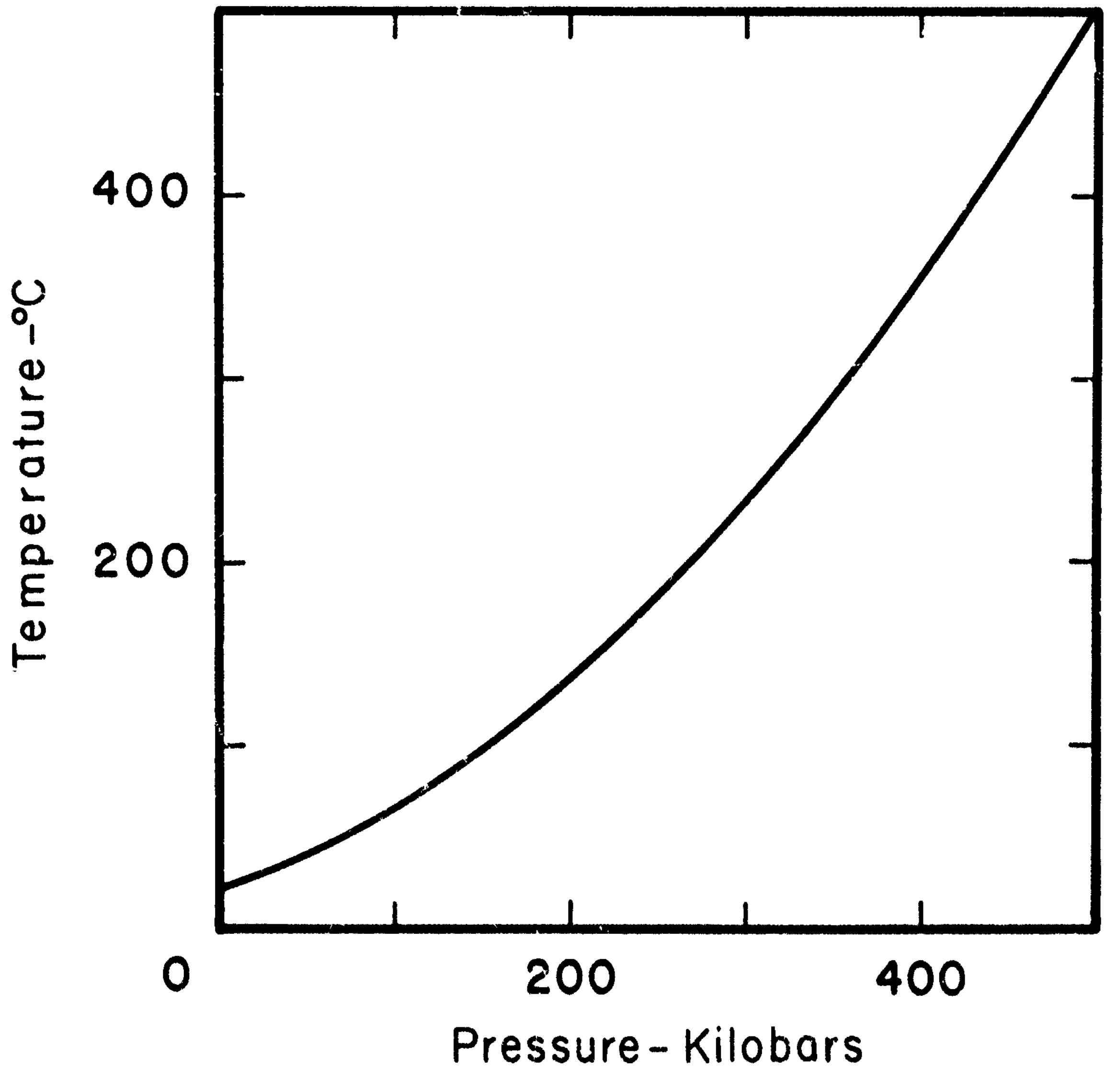
PALLADIUM

Temperatures associated with shock

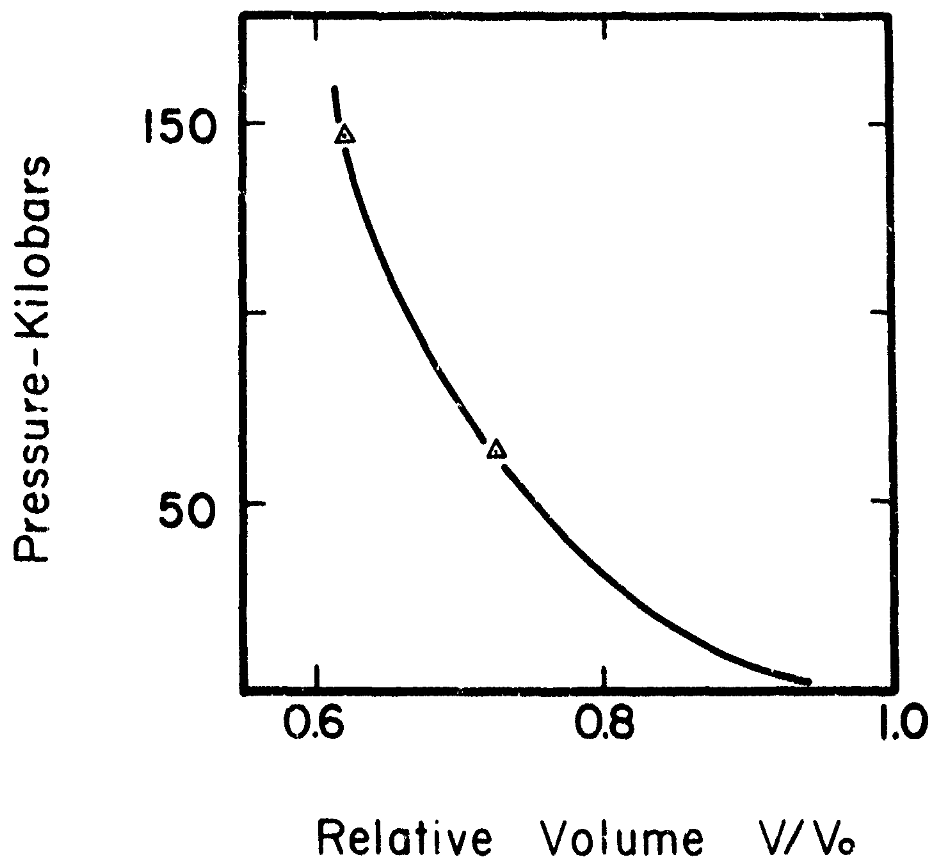
Palladium

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	
100	65	
150	97	
200	135	
250	180	
300	231	
350	289	
400	353	
450	423	
500	497	

Source: Rice, McQueen and Marsh, 1958



PALLADIUM



PARAFFIN

Source: Los Alamos (private communication)

AVCO PHENOLIC FIBERGLASS

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
2.19	0.444	18.5	0.797
2.43	0.568	26.2	0.766
3.03	0.866	49.9	0.716
3.32	1.38	86.8	0.586
4.28	2.19	178.0	0.488

$\rho_0 = 1.90$

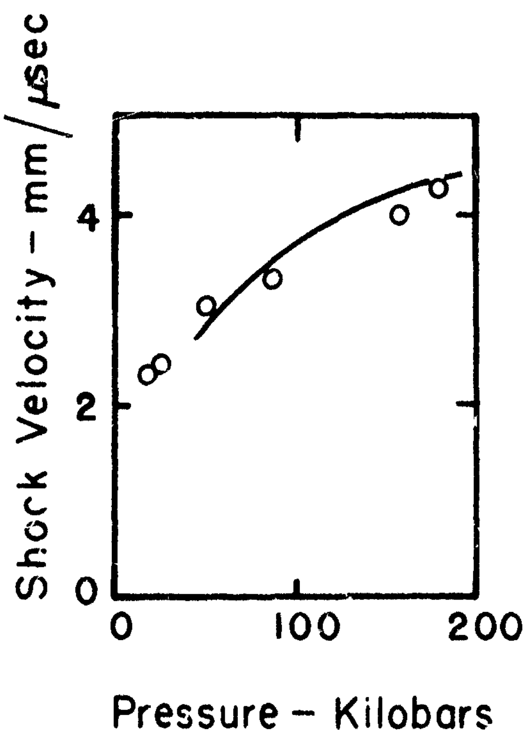
Source: Wagner, Waldorf and Louie (1962)

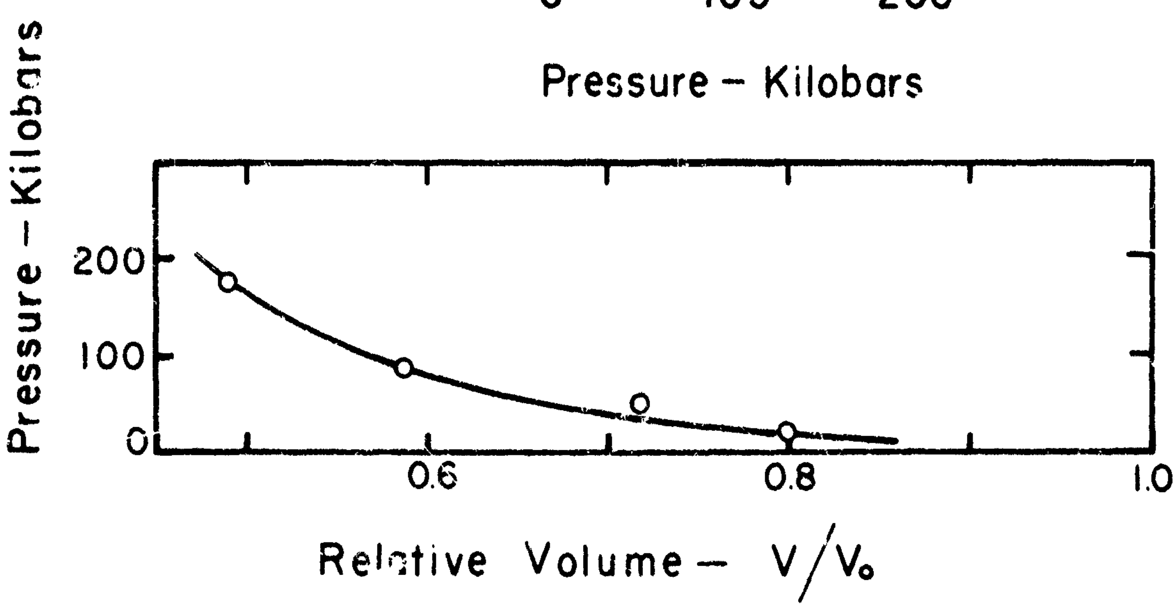
G E PHENOLIC FIBERGLASS

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.69	0.385	27.5	0.896
3.80	0.500	36.9	0.868
4.09	0.791	62.7	0.306
4.36	1.01	85.7	0.768
4.59	1.25	111.0	0.728

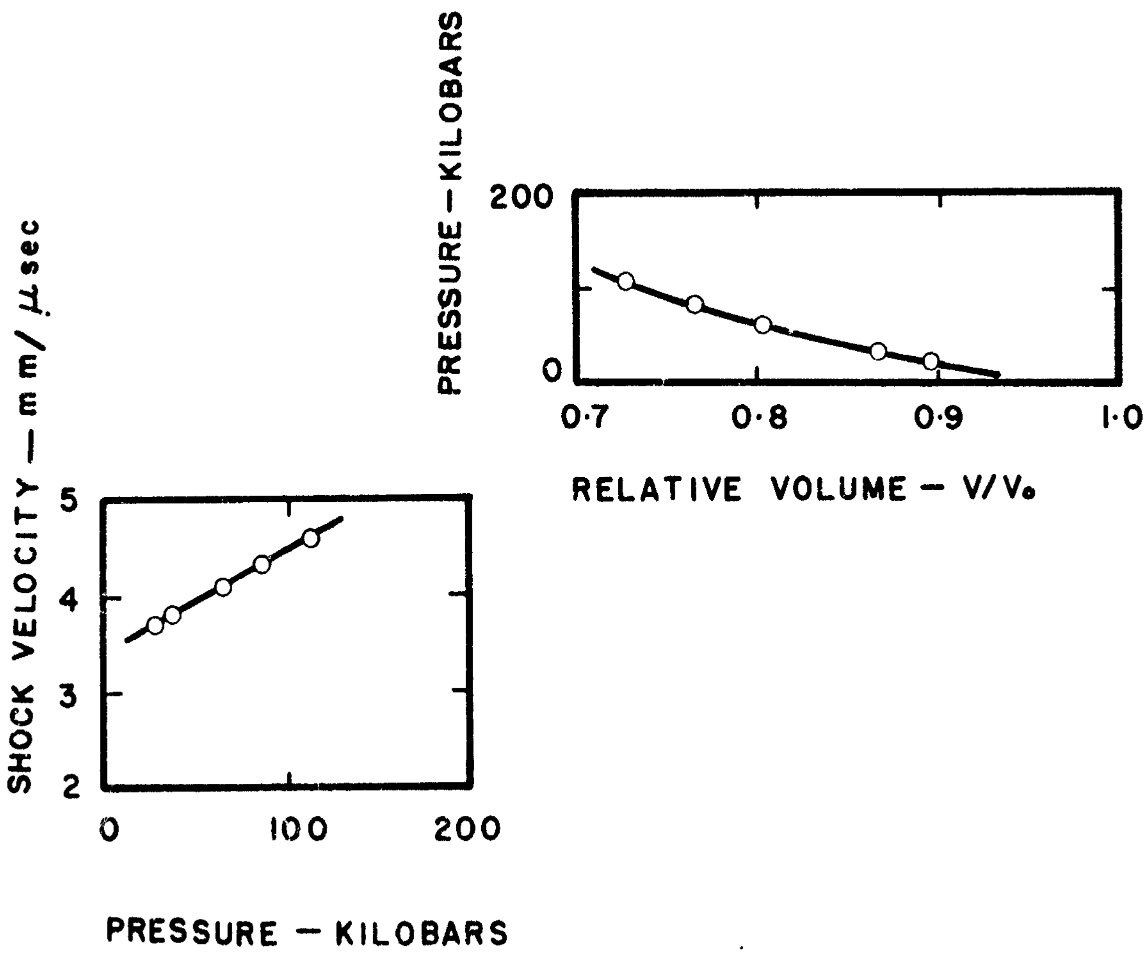
$\rho_0 = 1.94$

Source: Wagner, Waldorf and Louie (1962)





AVCO PHENOLIC FIBERGLASS



G.E. PHENOLIC FIBERGLASS

CHOPPED NYLON PHENOLIC

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.47	0.928	38.6	0.732
6.03	2.33	169	0.614
7.38	3.09	274	0.581

$\rho_o = 1.20$

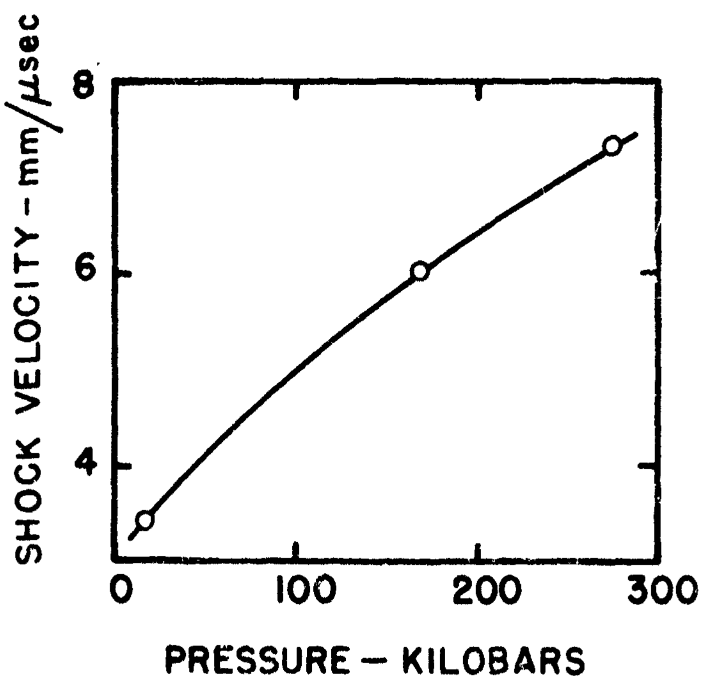
Source: Wagner, Waldorf and Louie (1962)

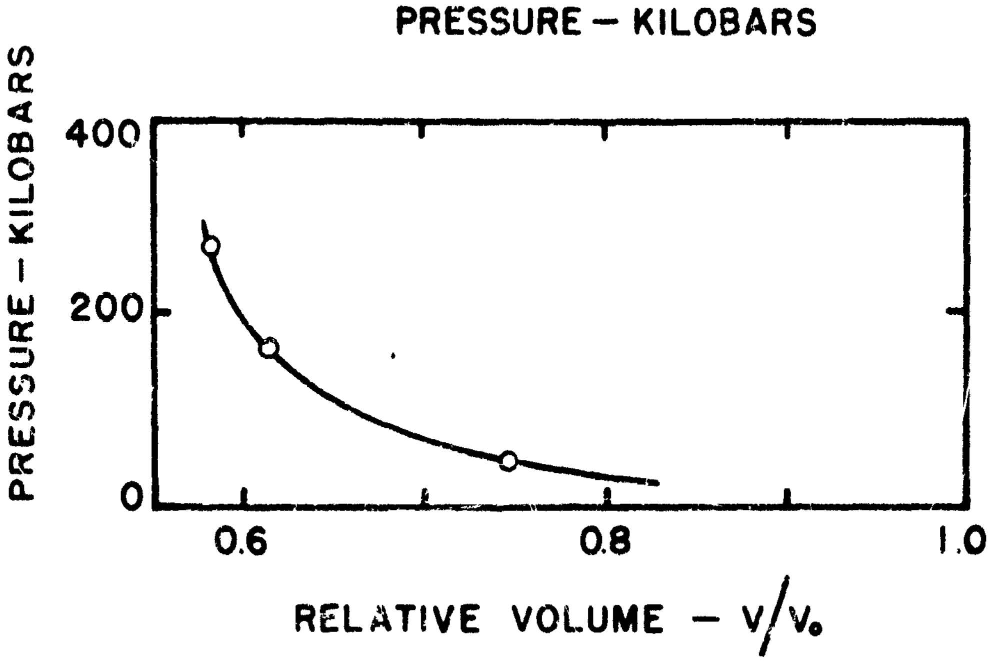
TAPE WOUND NYLON PHENOLIC

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.83	0.433	20.2	0.889
3.97	0.562	27.2	0.859
4.22	0.891	45.8	0.790
4.64	1.13	64.0	0.755
5.12	1.38	86.1	0.731

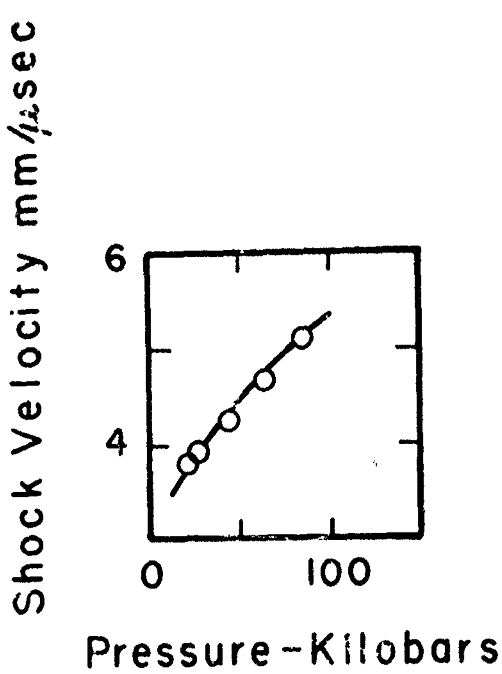
$\rho_o = 1.22$

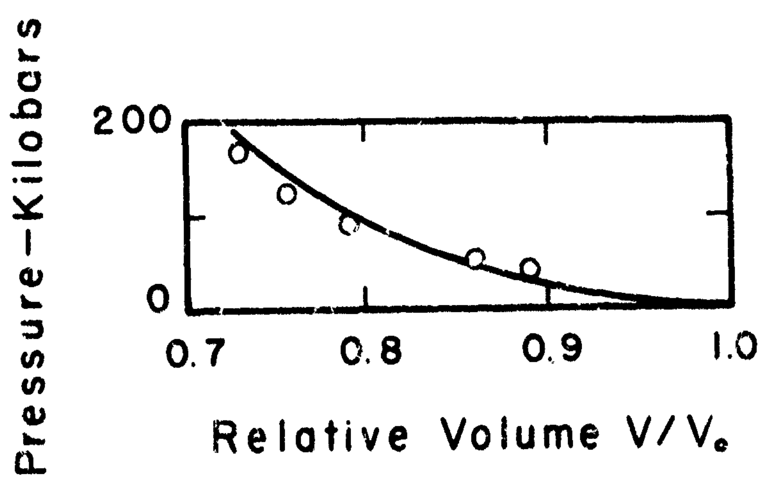
Source: Wagner, Waldorf and Louie (1962)





CHOPPED NYLON PHENOLIC





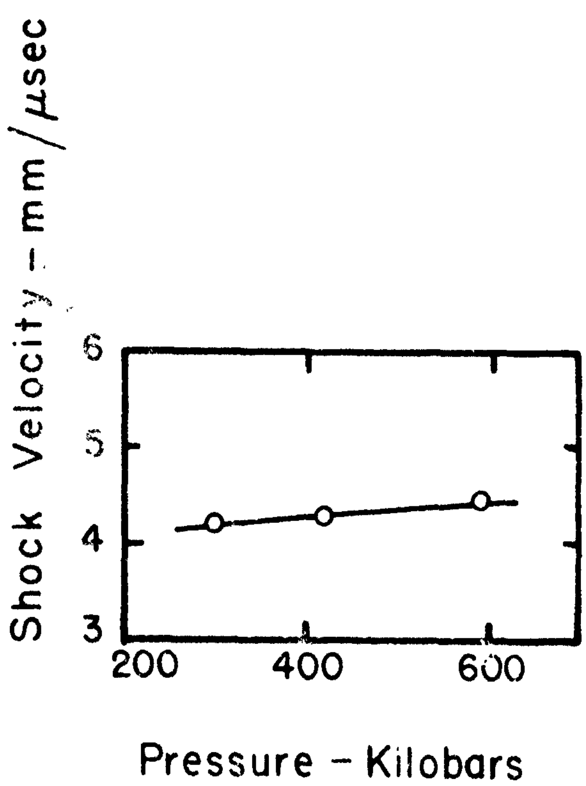
TAPE WOUND NYLON PHENOLIC

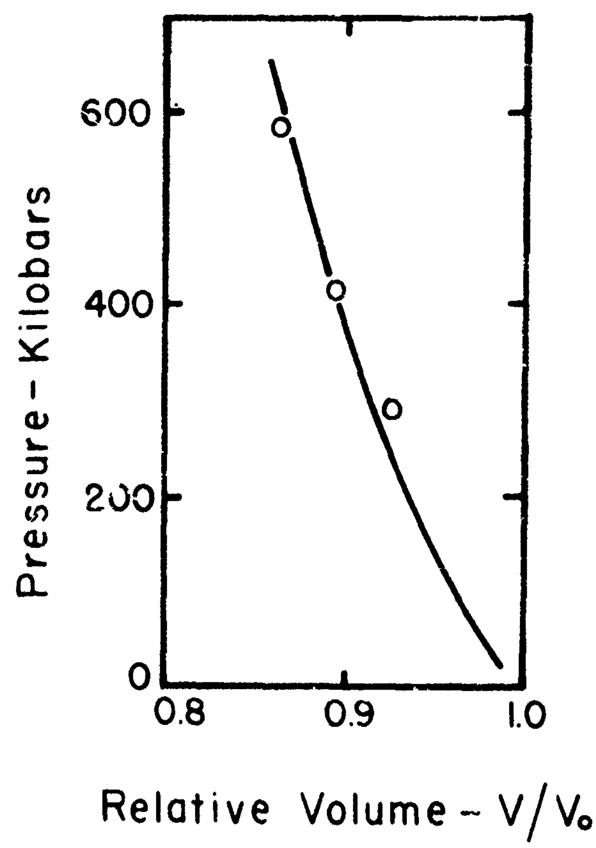
PLATINUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.199	0.329	295	0.9238
4.306	0.4550	416.5	0.8943
4.495	0.6102	586	0.8642

$\rho_0 = 21.37$

Source: Walsh, Rice, McQueen and Yarger (1957)


Shock Velocity - mm/μsec
6
5
4
3
200
400
600
Pressure - Kilobars


Pressure - Kilobars
600
400
200
0
0.8
0.9
1.0
Relative Volume - V/V₀

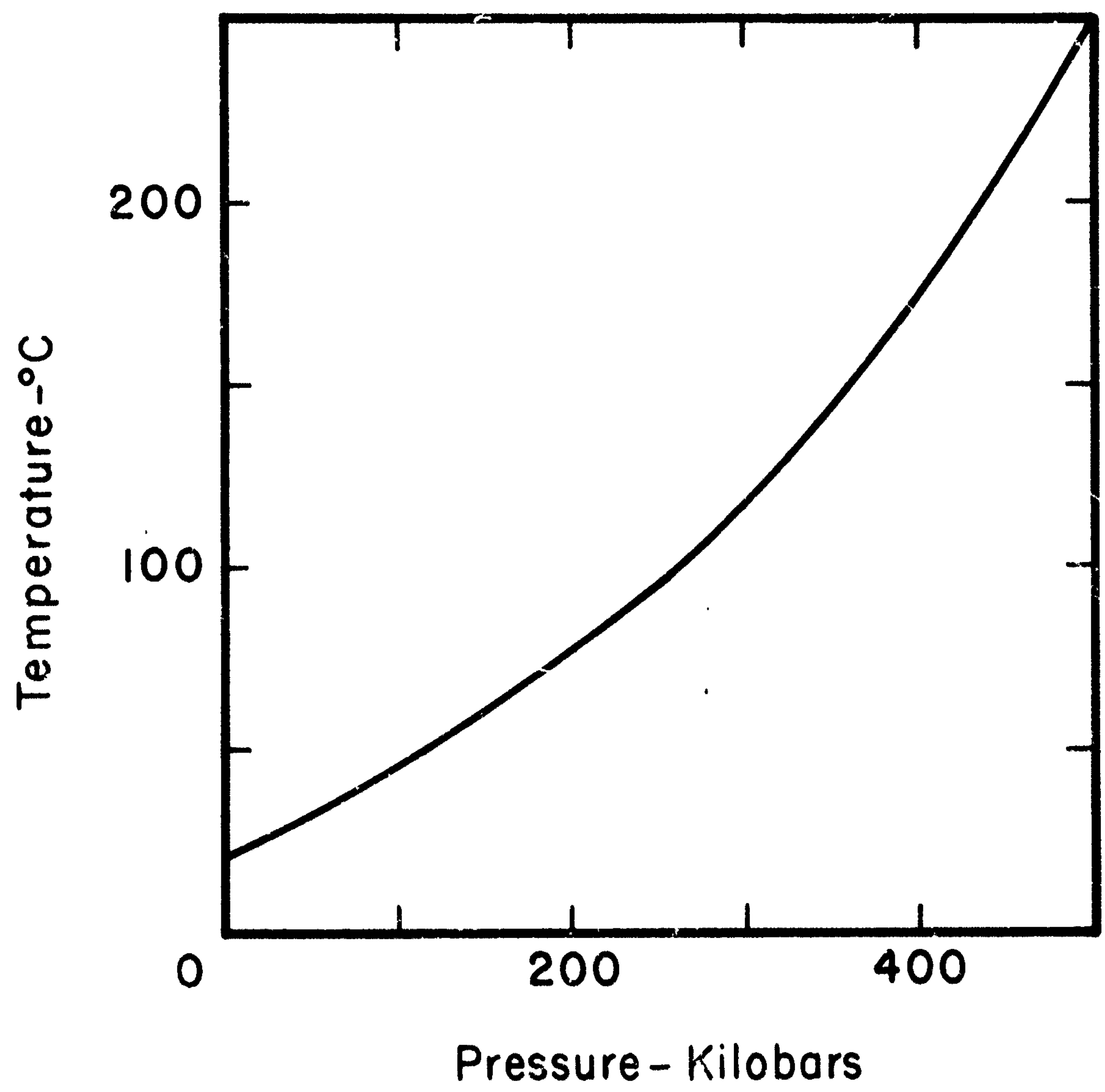
PLATINUM

Temperatures associated with shock

Platinum

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	
100	46	
150	60	
200	77	
250	95	
300	117	
350	144	
400	174	
450	207	
500	244	

Source: Rice, McQueen and Walsh, 1958



PLATINUM

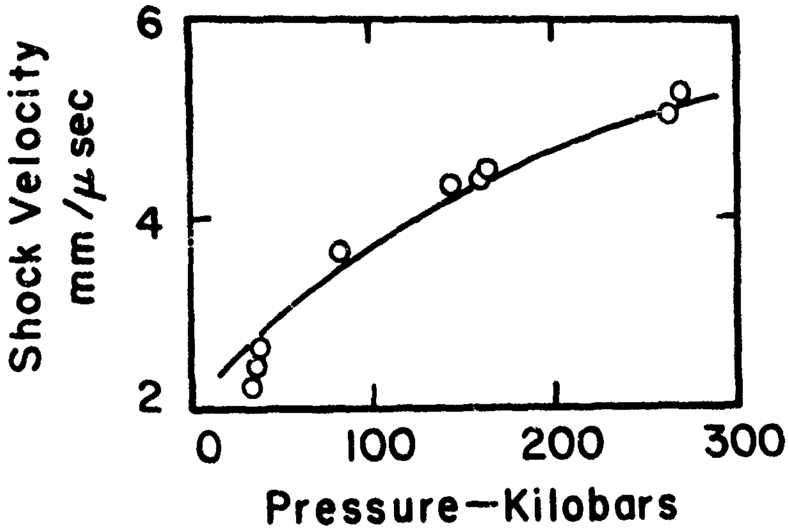
PLAYA*

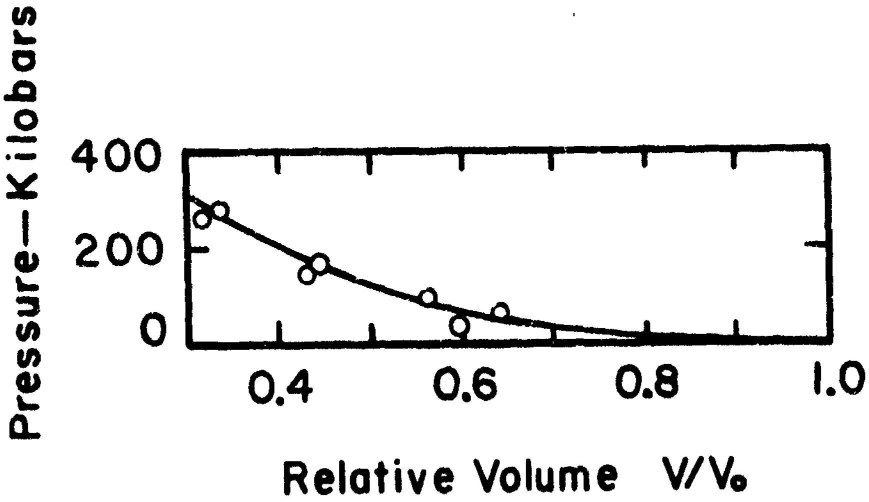
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
2.70	1.04	40	0.615
4.40	2.48	148	0.436
3.00	1.08	48	0.640
2.58	1.04	39	0.597
3.69	1.60	87	0.566
4.47	2.52	166	0.436
4.36	2.50	160	0.427
5.07	3.54	264	0.302
5.24	3.52	271	0.328

ρ_0 = 1.41 - 1.47

Source: Bass, Hawk and Chabai (1963)

* Samples from 100 ft depth, Nevada Test Site Area 5


Shock Velocity
mm/μ sec
6
4
2
0
100
200
300
Pressure—Kilobars


Pressure—Kilobars
400
200
0
0.4
0.6
0.8
1.0
Relative Volume V/V₀

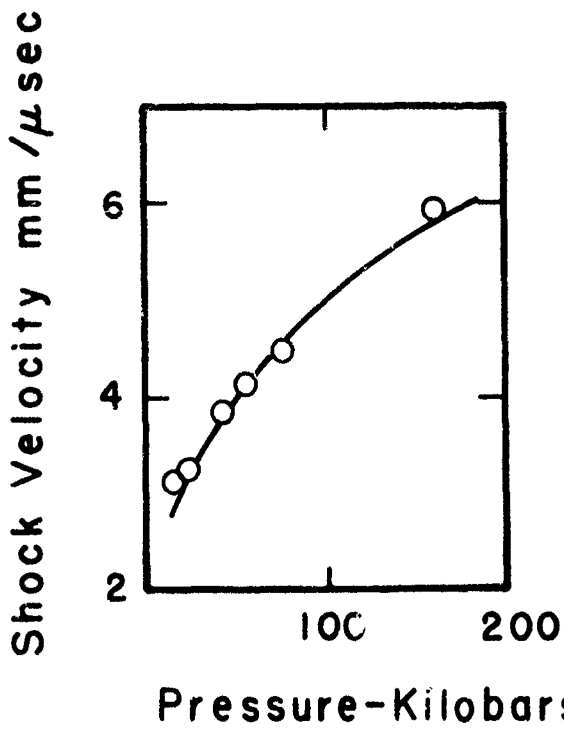
PLAYA

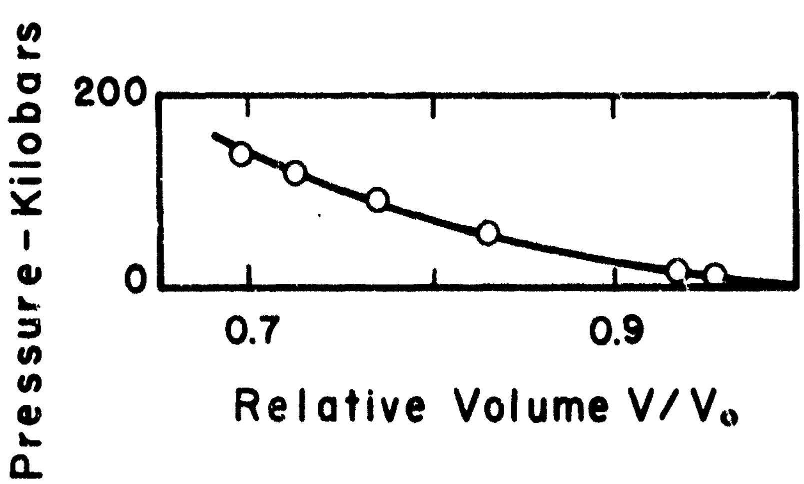
PLEXIGLAS

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.16	0.454	16.9	
3.26	0.590	22.7	
3.85	0.916	41.6	
4.17	1.17	57.6	
4.52	1.43	76.5	
5.97	2.28	160	

$\rho_0 = 1.18$

Source: Wagner, Waldorf and Louie (1962)


Shock Velocity mm/μsec
6
4
2
100
200
Pressure-Kilobars


Pressure-Kilobars
200
0
0.7
0.9
Relative Volume V/V₀

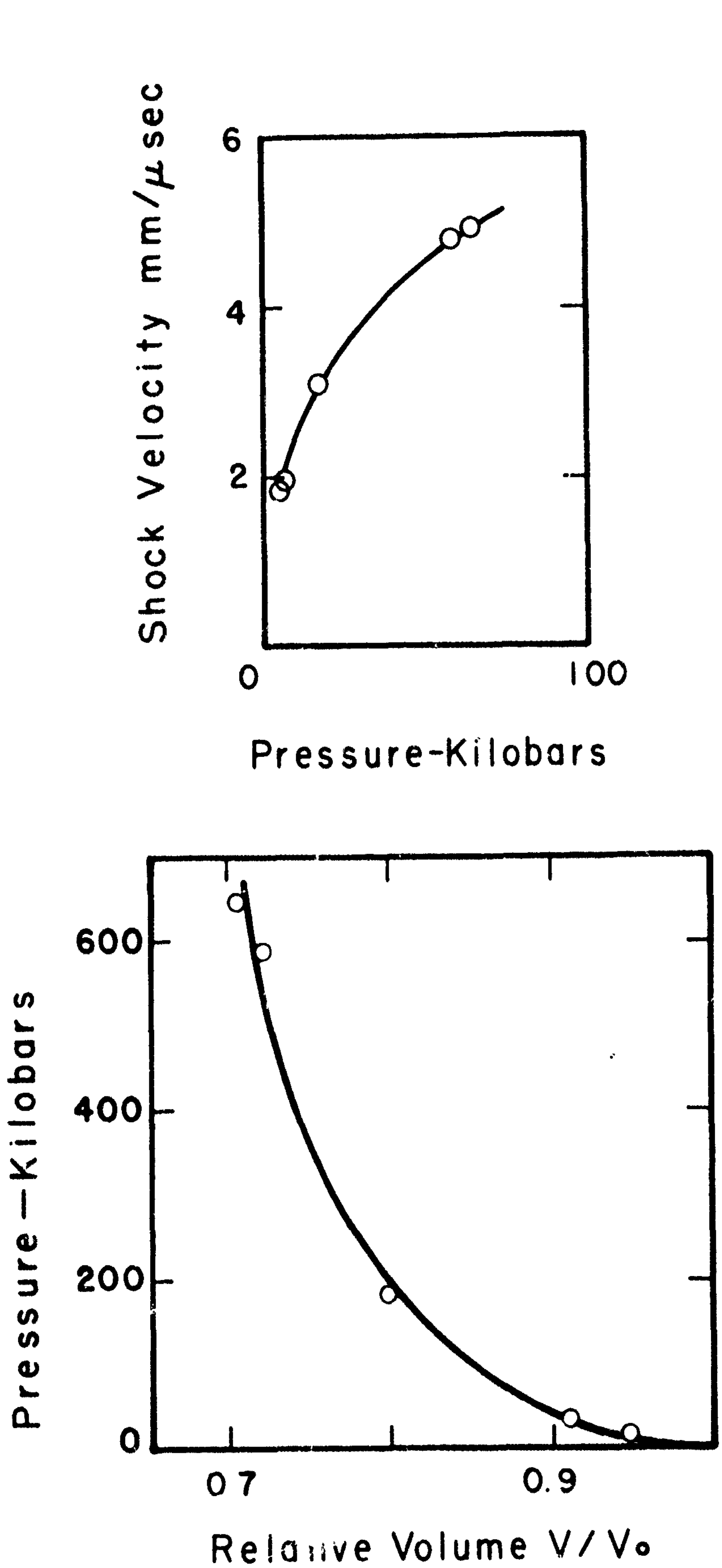
PLEXIGLAS

POLYETHYLENE

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
1.86	0.115	1.96	0.938
1.90	0.170	2.95	0.910
3.14	0.625	18.1	0.800
4.30	1.33	58.8	0.723
4.88	1.44	64.5	0.706

$\rho_0 = 0.92$

Source: Wagner, Waldorf and Louie (1962)



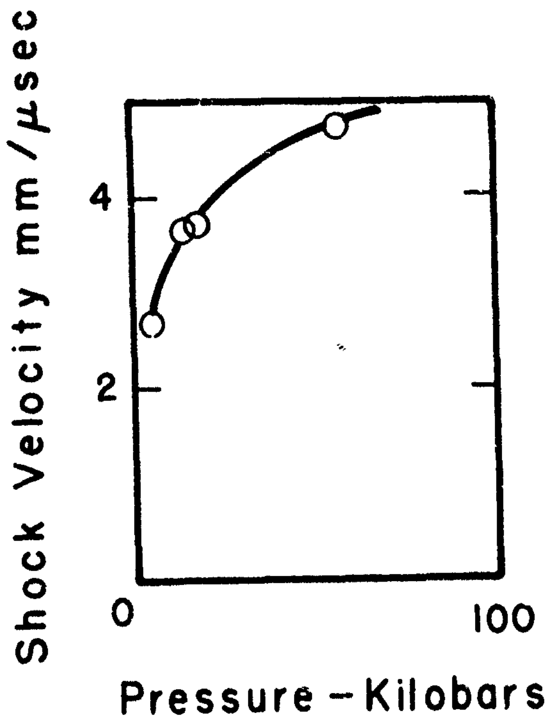
POLYETHYLENE

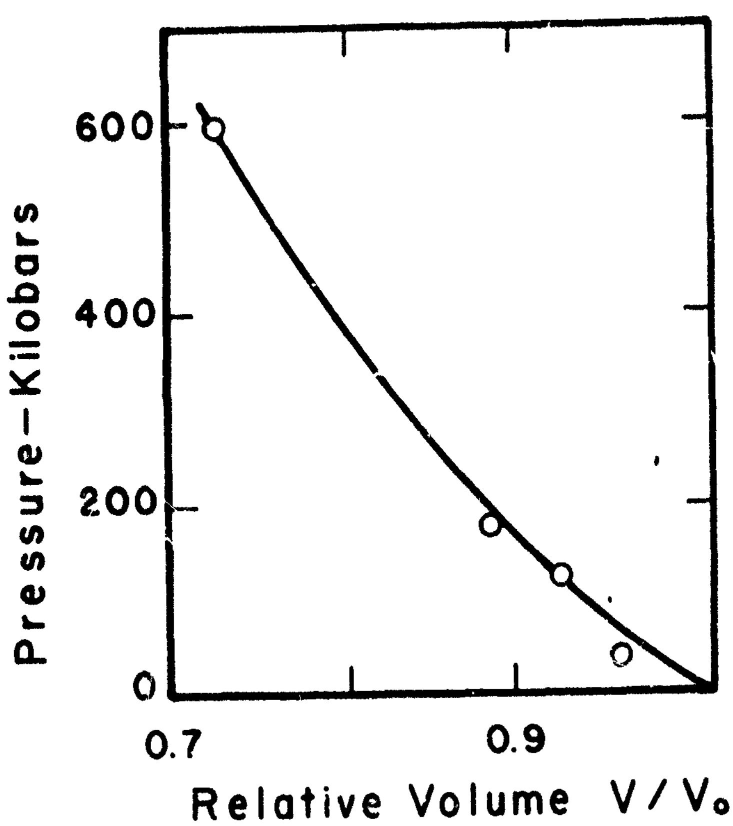
POLYSTYRENE

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
2.74	0.140	4.07	0.948
3.72	0.320	12.5	0.914
3.73	0.460	17.9	0.877
4.56	1.24	59.3	0.729

$\rho_0 = 1.05$

Source: Wagner, Waldorf and Louie (1962)





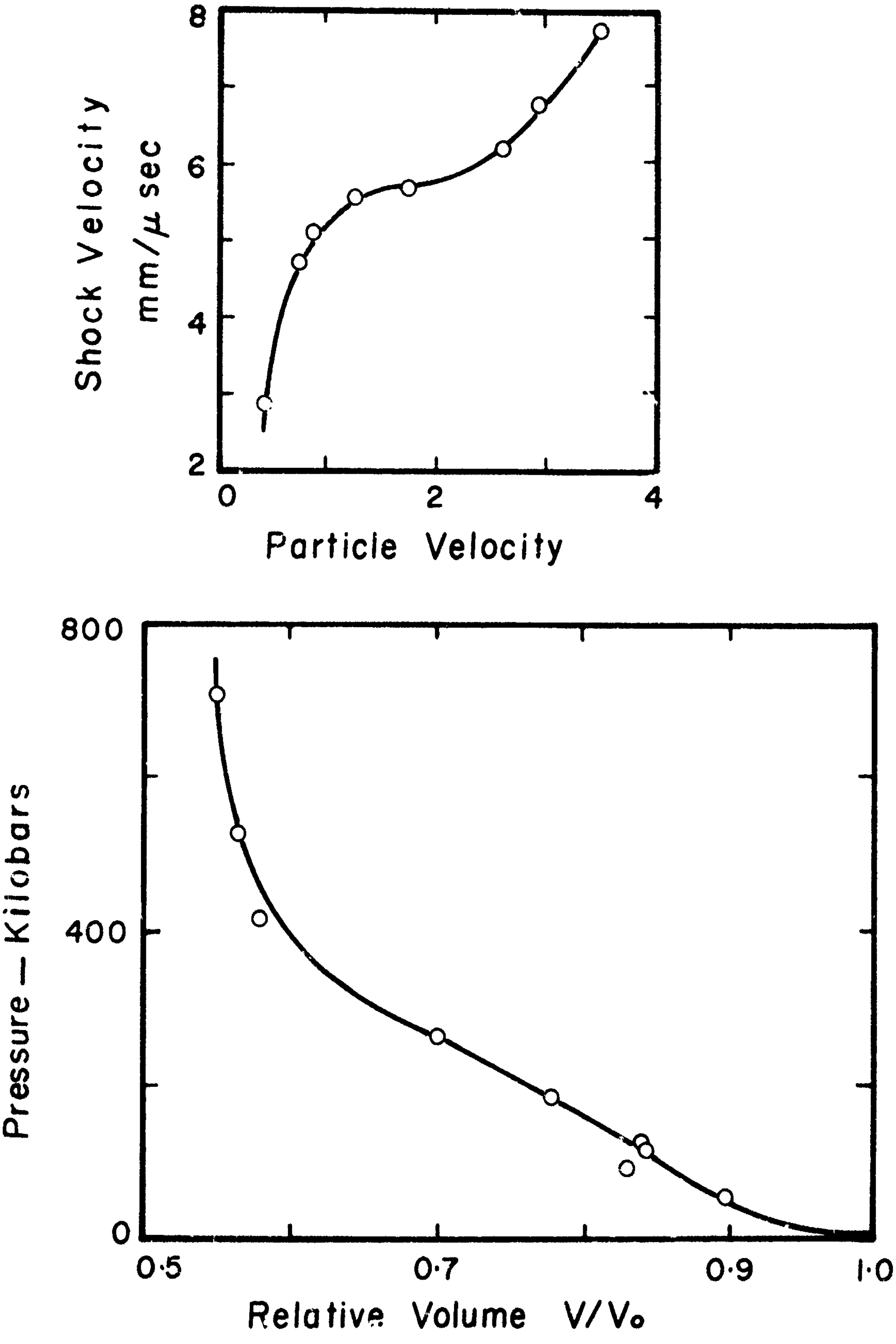
POLYSTYRENE

CRYSTALLINE QUARTZ

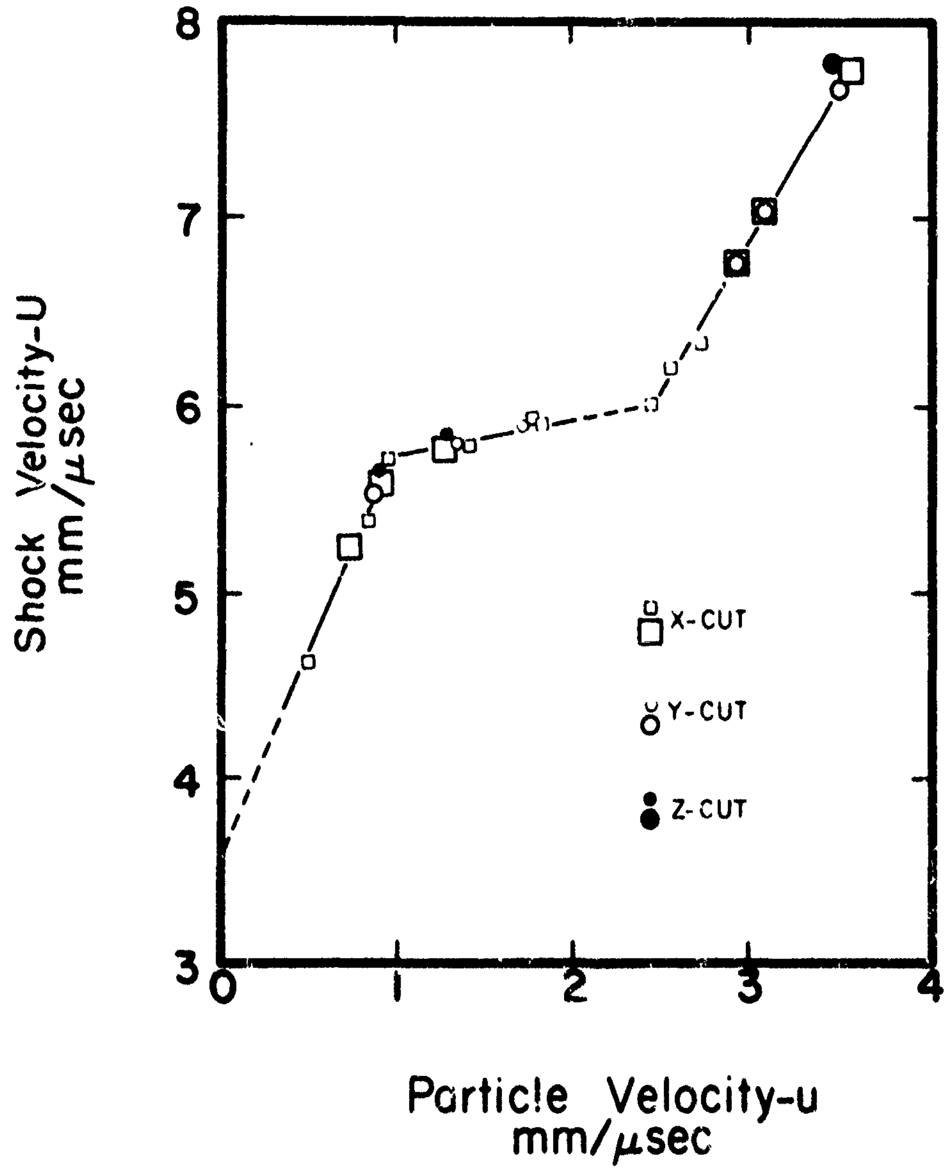
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
2.88	0.43	56	0.900
4.74	0.67	94	0.809
4.74	0.71	99	0.863
5.14	0.82	116	0.847
4.85	0.86	126	0.841
4.88	0.86	126	0.843
5.11	0.83	126	0.842
5.18	0.87	132	0.837
5.24	0.92	135	0.829
5.64	1.24	189	0.785
5.61	1.21	184	0.788
5.47	1.25	190	0.783
4.71	1.23	196	0.783
5.68	1.30	198	0.773
5.61	1.26	200	0.770
5.61	1.71	263	0.705
5.69	1.69	269	0.707
5.76	1.82	277	0.690
6.12	2.55	414	0.585
6.29	2.70	430	0.571
6.66	2.70	511	0.566
6.95	3.03	558	0.564
7.76	3.42	703	0.589
7.70	3.52	708	0.539
7.75	3.52	714	0.548
7.76	3.49	718	0.550
7.75	3.52	723	0.548

$\rho_o = 2.6$

Source: Wackerle (1962)



CRYSTALLINE QUARTZ



CRYSTAL QUARTZ

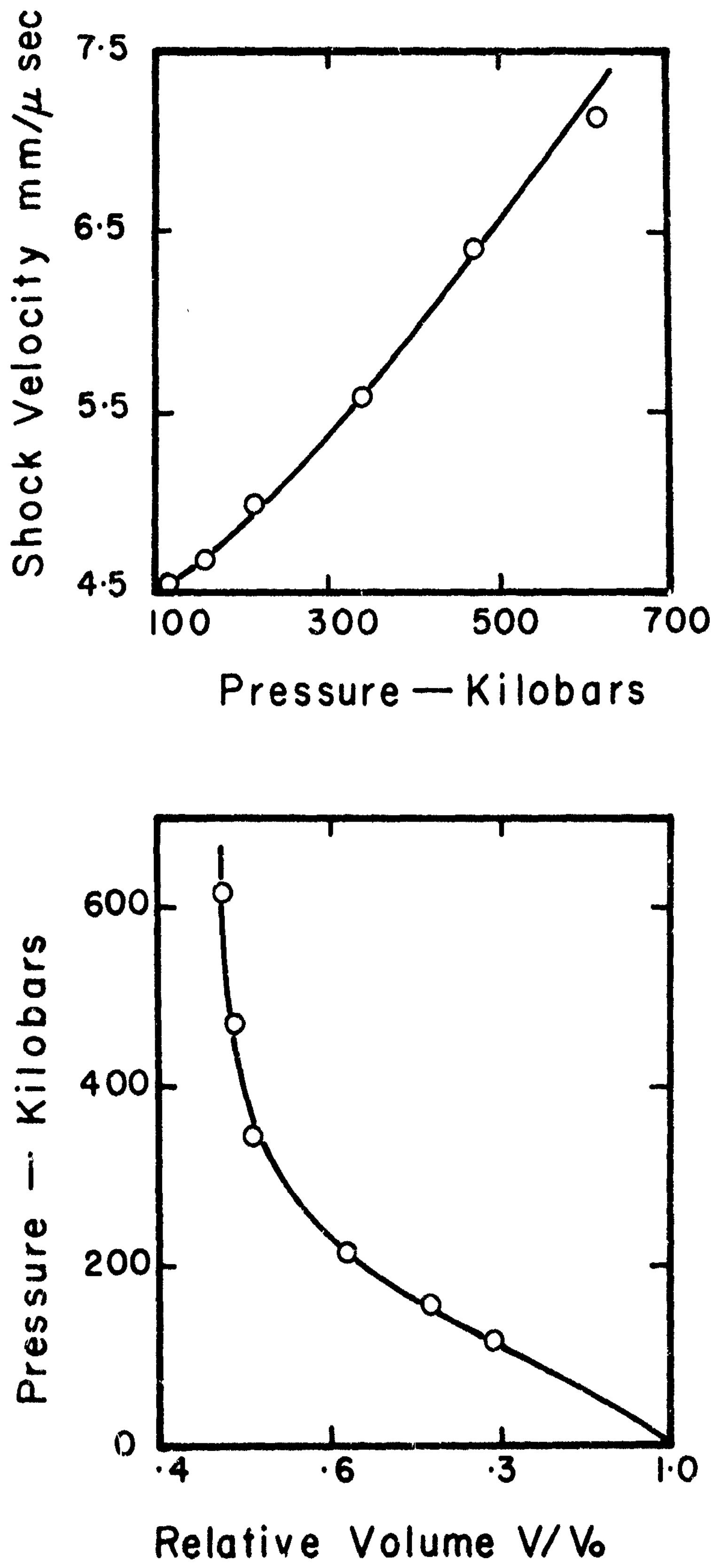
Source: Wackerle (1962)

FUSED QUARTZ

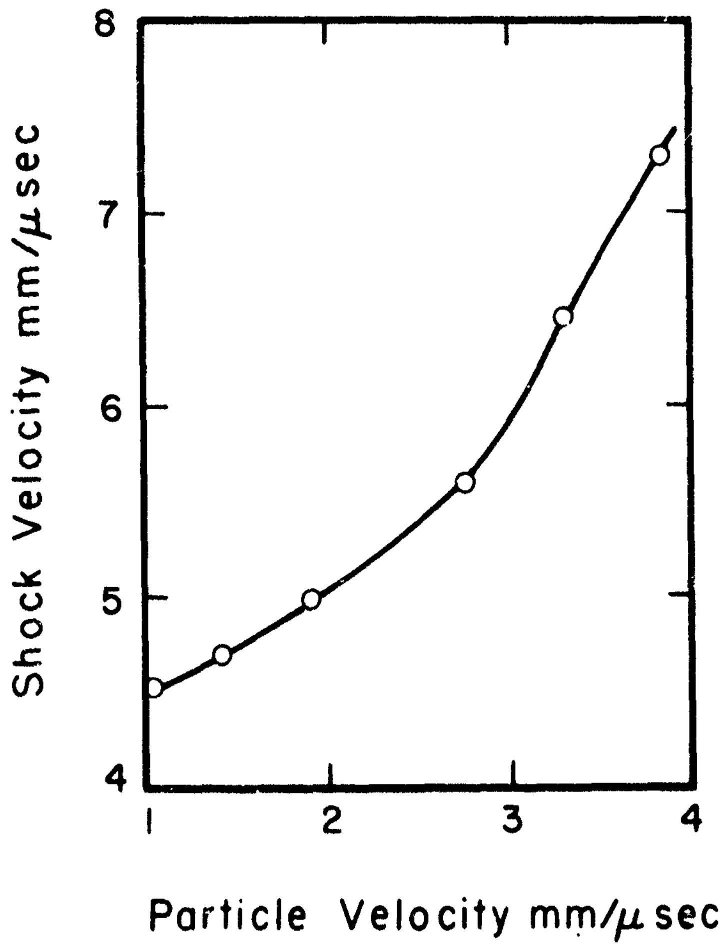
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.52	1.04	117	0.791
4.67	1.40	153	0.717
4.70	1.41	157	0.716
4.97	1.90	211	0.624
4.96	1.95	217	0.614
5.53	2.76	337	0.501
5.62	2.76	342	0.509
5.62	2.78	346	0.512
6.43	3.25	460	0.495
6.44	3.33	482	0.484
7.28	3.81	611	0.477
7.30	3.87	623	0.470

$\rho_o = 2.204$

Source: Wackerle (1962)



FUSED QUARTZ



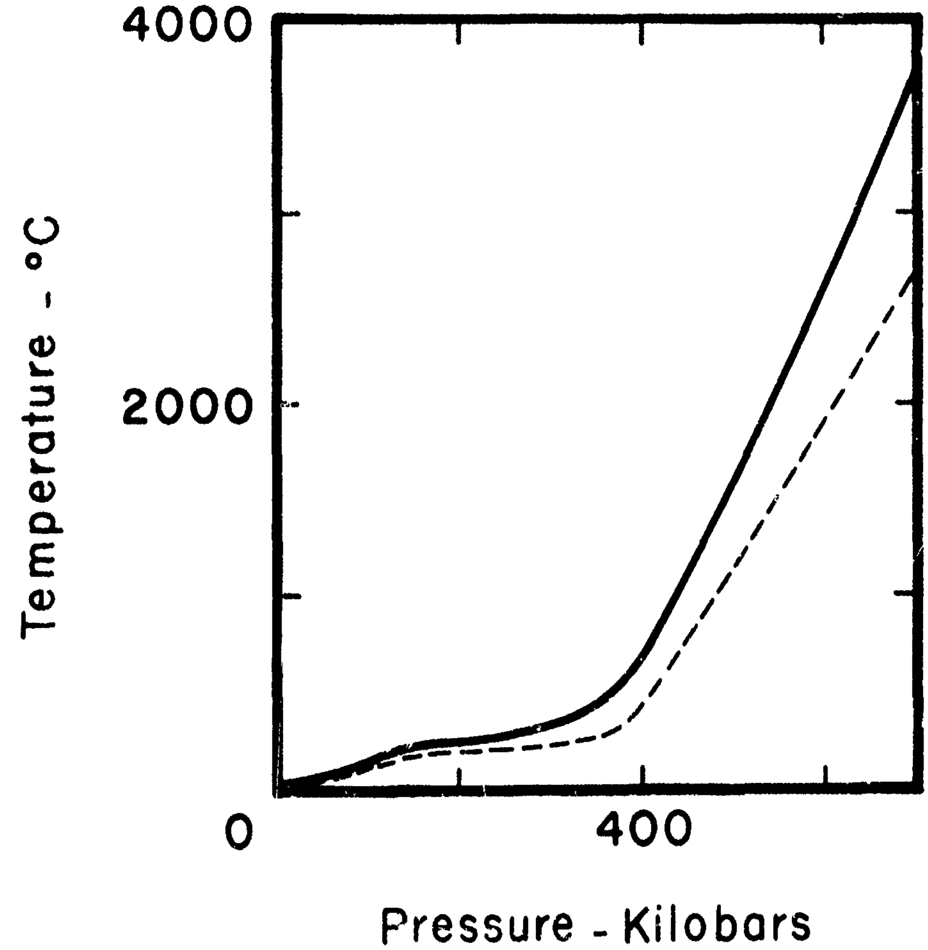
FUSED QUARTZ

Temperatures associated with shock

Crystalline quartz

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
50	36	20
100	117	81
144	203	151
150	206	156
200	238	168
250	282	190
262	-	-
300	336	214
350	398	248
383	454	282
400	640	465
450	1125	780
500	1630	1160
600	2650	1920
700	3665	2670

Source: Wackerle, 1962



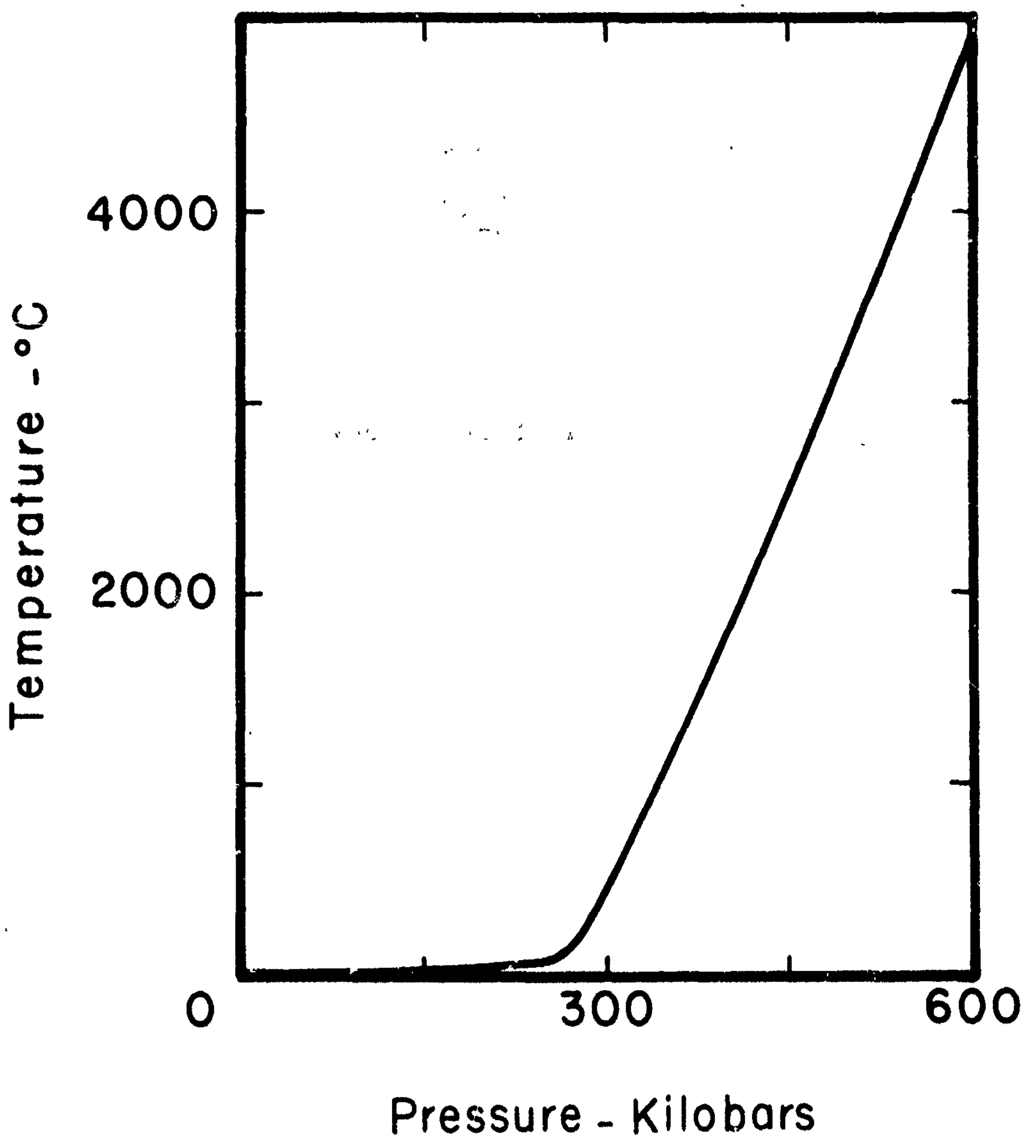
CRYSTALLINE QUARTZ

Temperatures associated with shock

Fused quartz

Pressure (kilobars)	Temperature behind shock (C^o)	Residual temperature (C^o)
50	1	0
100	2	0
144	-	-
150	3	0
200	4	0
250	5	0
262	5	0
300	495	470
350	1185	1155
383	-	-
400	1895	1860
450	2560	2610
500	3390	3310
600	4890	4790
700	-	-

Source: Wackerle, 1962



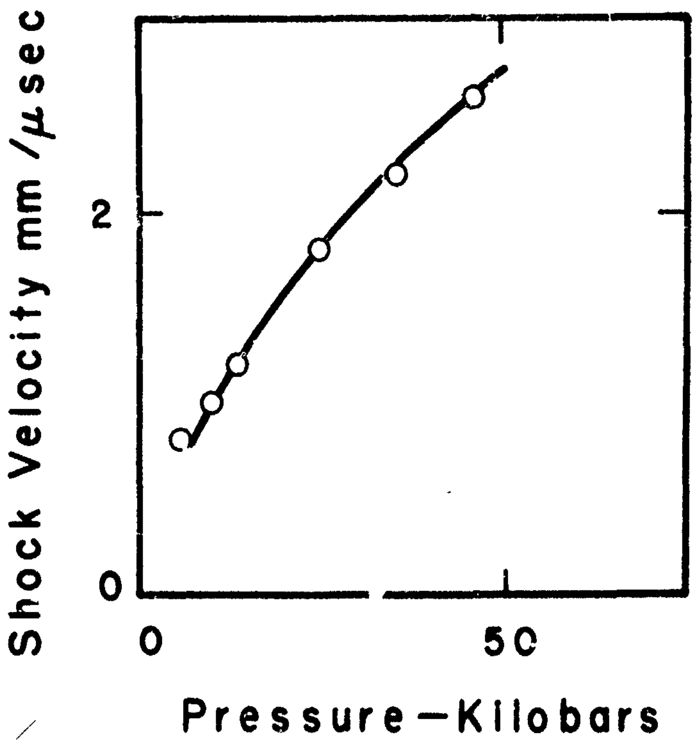
FUSED QUARTZ

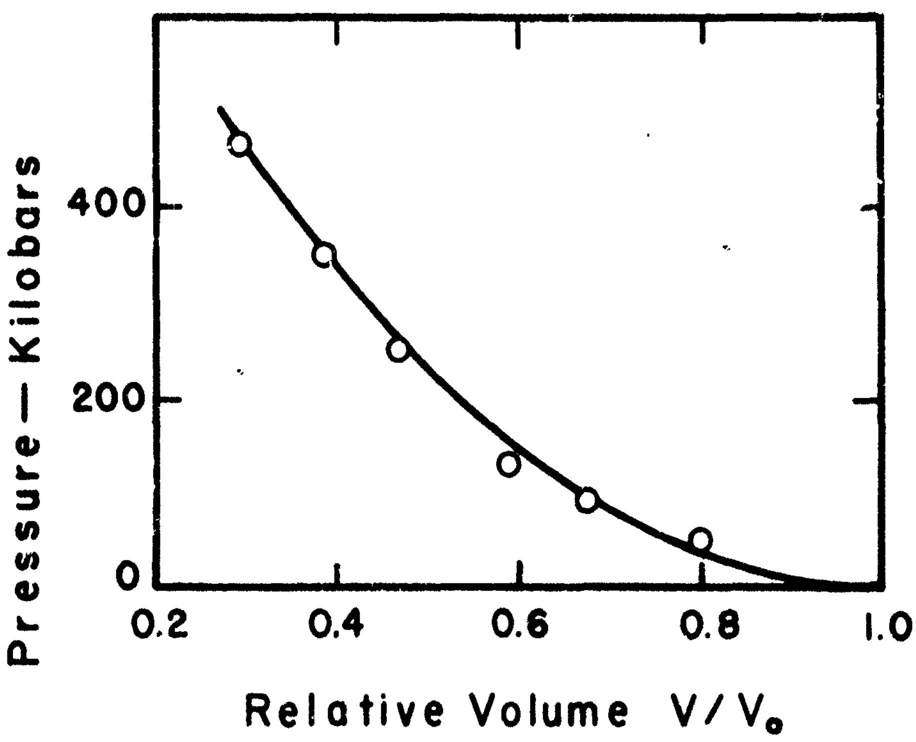
RAD 58B

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
1.43	0.298	5.39	0.794
1.54	0.503	9.77	0.674
1.60	0.654	13.2	0.591
1.92	1.02	24.7	0.467
2.13	1.31	35.1	0.388
2.28	1.61	46.3	0.296

$\rho_o = 1.26$

Source: Wagner, Waldorf and Louie (1962)


Shock Velocity mm /μsec
2
0
0
50
Pressure—Kilobars


Pressure— Kilobars
400
200
0
0.2
0.4
0.6
0.8
1.0
Relative Volume V/V₀

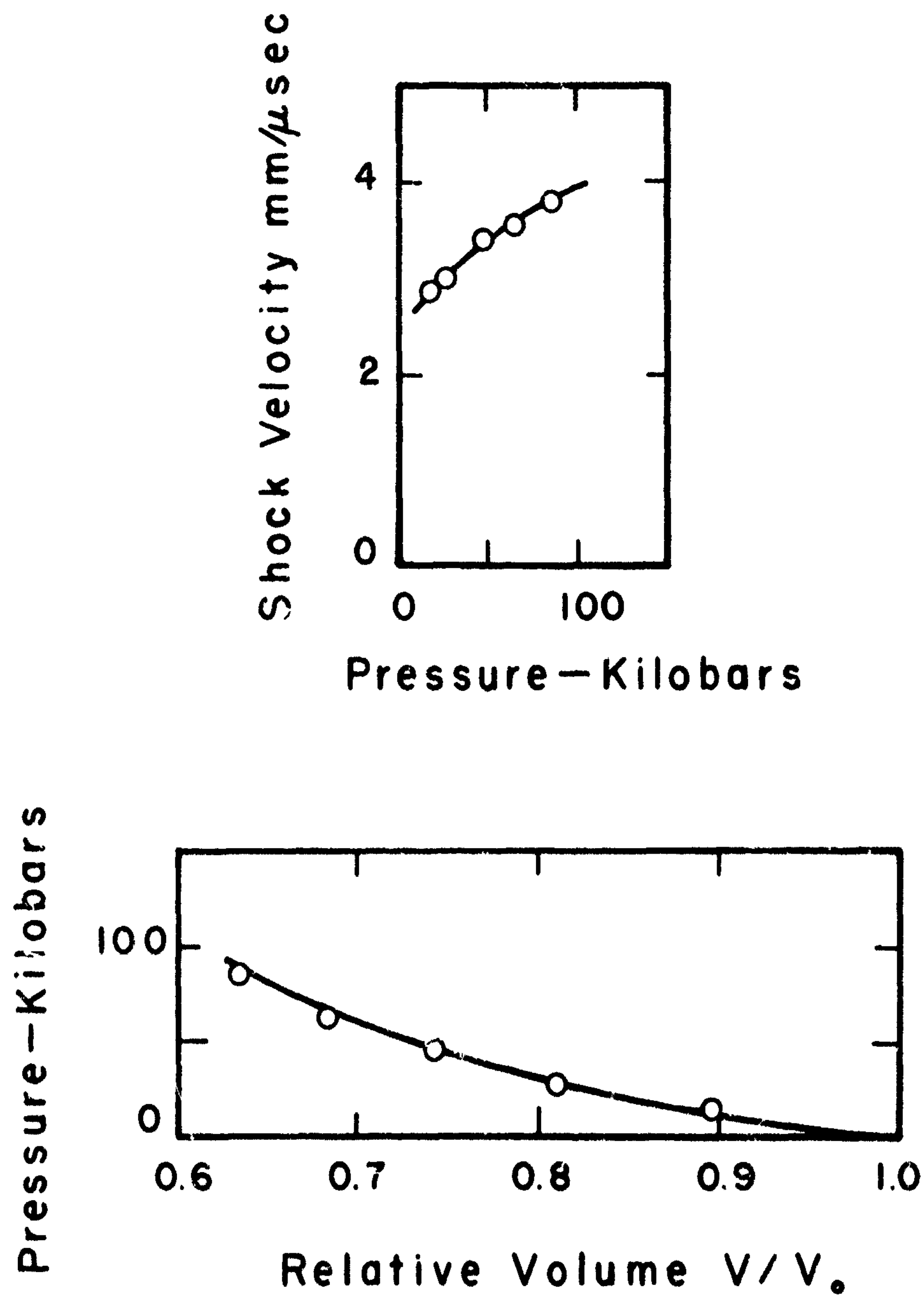
RAD 58B

OBLIQUE TAPE WOUND REFRASIL

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
2.87	0.436	19.6	0.849
3.00	0.565	26.6	0.811
3.41	0.882	47.2	0.742
3.59	1.13	63.9	0.684
3.82	1.39	83.6	0.635

$\rho_0 = 1.57$

Source: Wagner, Waldorf and Louie (1962)



OBLIQUE TAPE WO D REFRASIL

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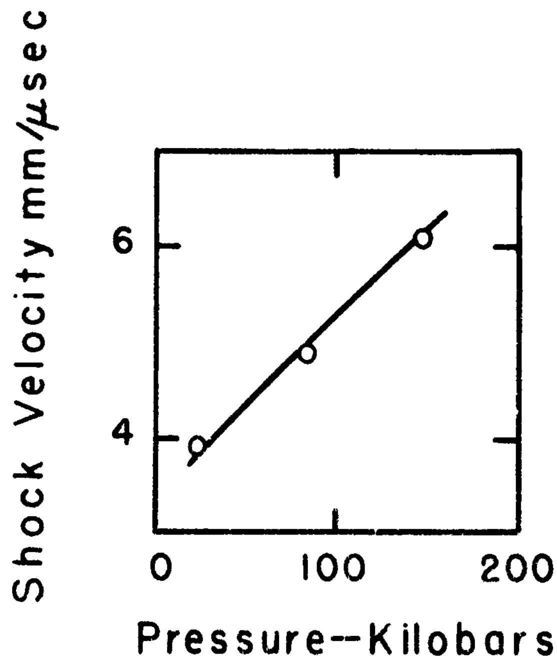
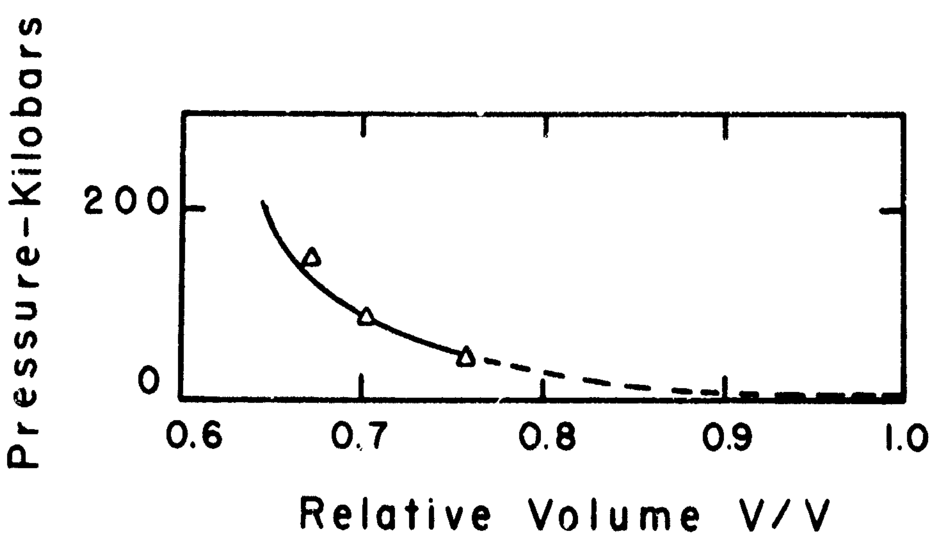
PAGE
IS
MISSING
IN
ORIGINAL
DOCUMENT


Shock Velocity mm/μsec
6
4
0
100
200
Pressure--Kilobars


Pressure-Kilobars
200
0
0.6
0.7
0.8
0.9
1.0
Relative Volume V/V

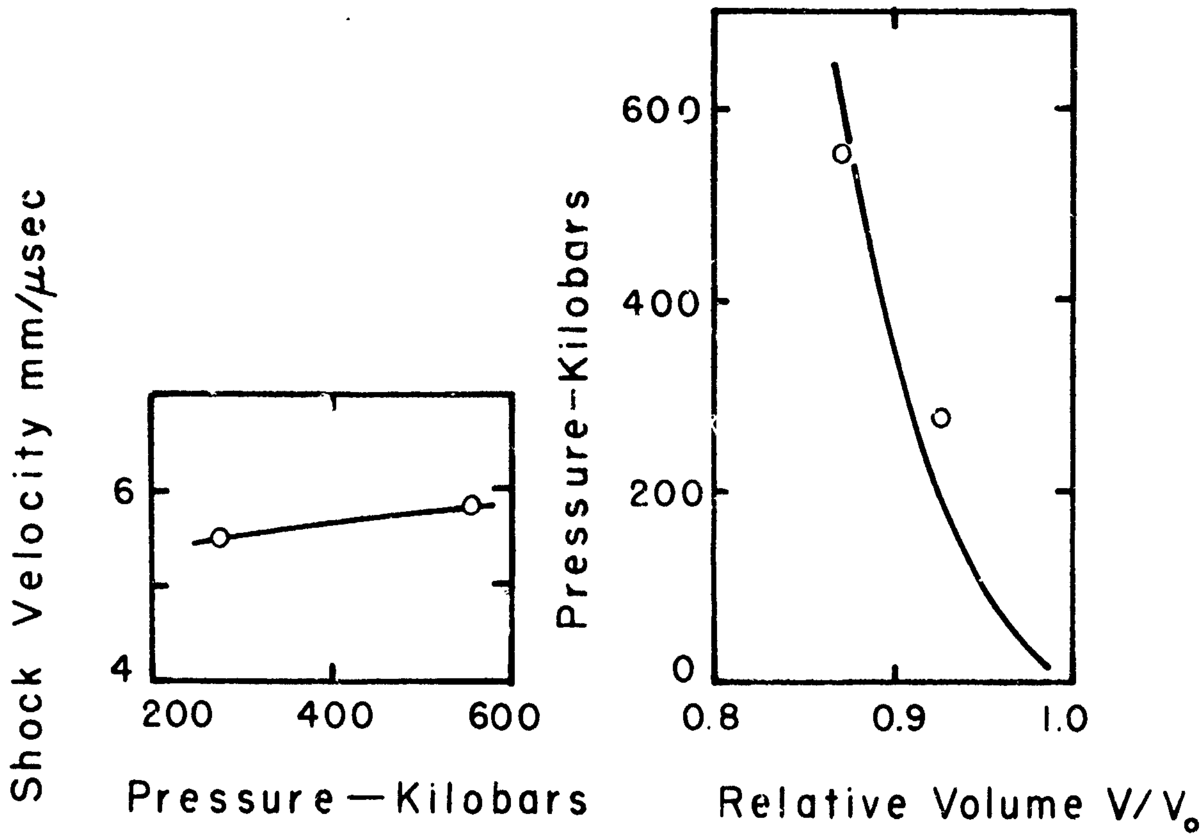
124 RESINS

RHODIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.476	0.4100	278.5	0.9250
5.865	0.7566	551	0.8710

$\rho_0 = 12.42$

Source: Walsh, Rice, McQueen and Yarger (1957)


Shock Velocity mm/μsec
6
4
200
400
600
Pressure—Kilobars
Pressure—Kilobars
600
400
200
0
0.8
0.9
1.0
Relative Volume V/V₀

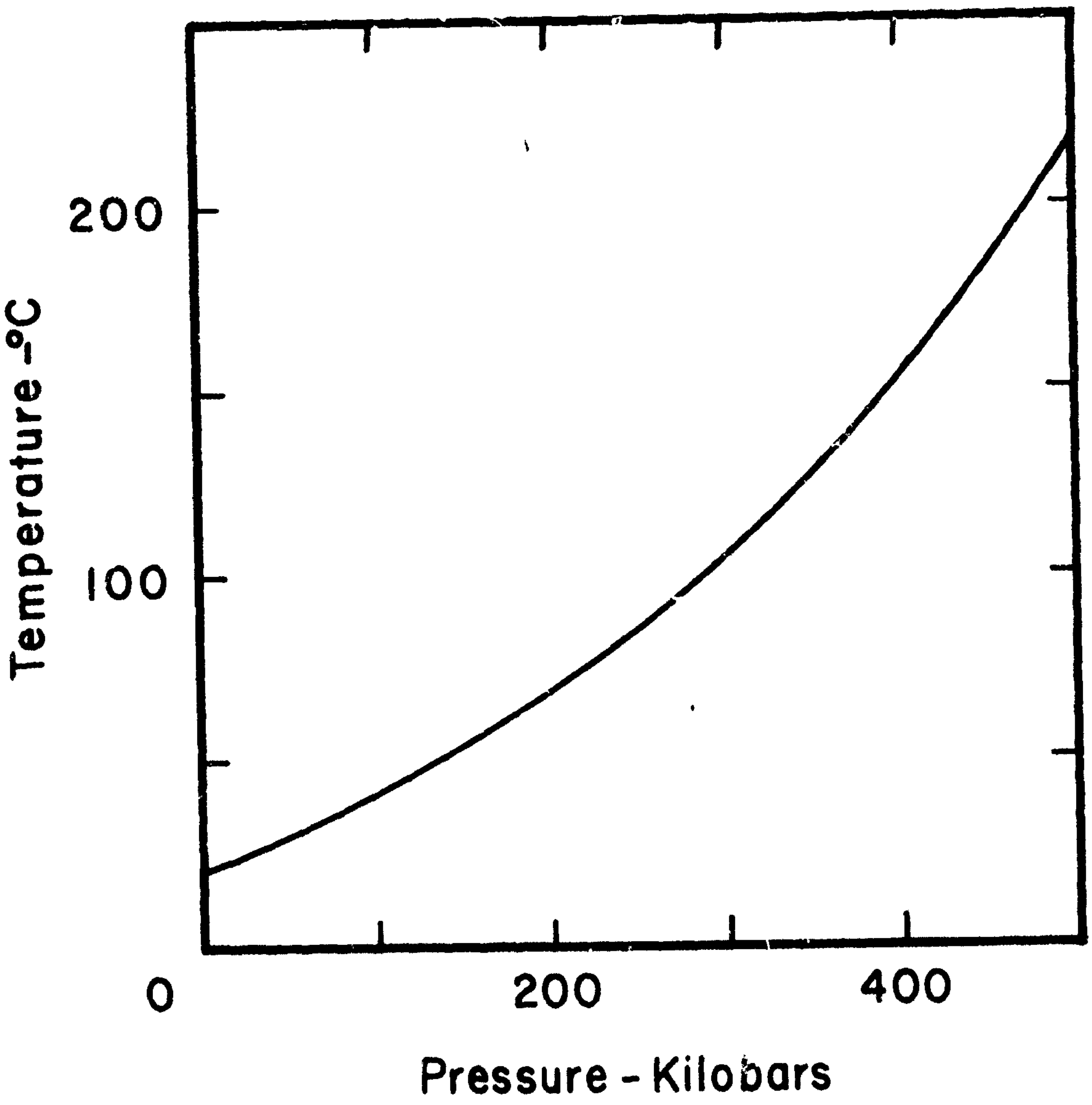
RHODIUM

Temperatures associated with shock

Rhodium

Pressure (kilobars)	Temperature behind shock (C^o)	Residual temperature (C^o)
0	20	
100	42	
150	54	
200	69	
250	85	
300	104	
350	127	
400	153	
450	181	
500	218	

Source: Rice, McQueen and Walsh, 1958



RHODIUM

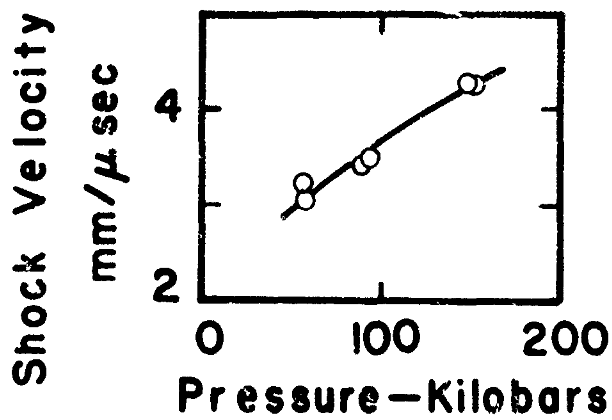
SILICA SAND*

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Dry Silica Sand - Porosity 41%			
3.13	1.17	58	0.626
3.23	1.16	59	0.641
3.42	1.61	88	0.529
3.47	1.70	93	0.510
4.26	2.25	150	0.472
4.24	2.23	153	0.474
Dry Silica Sand - Porosity 22%			
3.45	1.07	75	0.690
3.70	1.46	116	0.605
4.78	2.03	197	0.575
Water-Saturated Silica Sand - Porosity 41%			
4.53	0.98	90	0.784
5.00	1.45	143	0.710
5.63	1.94	213	0.655
5.59	1.93	216	0.655

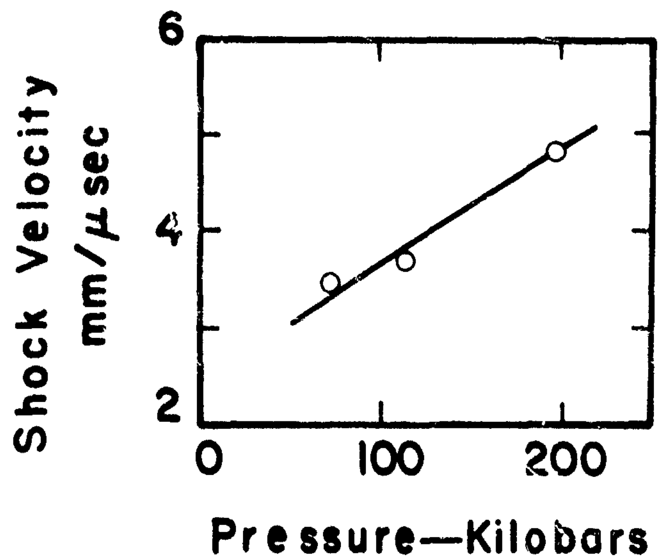
ρ_o = Dry (porosity 41%) - 1.6; Dry (porosity 22%) - 2.0; Wet - 2.0

Source: Bass, Hawk and Chabai (1963)

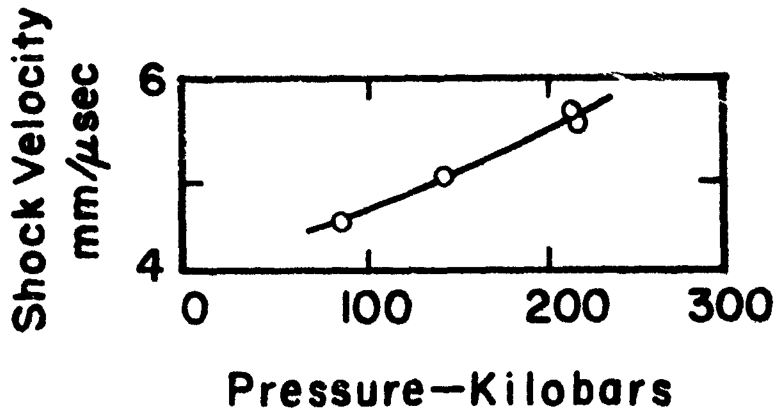
* Fine, pure silica sand, called oven furnace sand, composed of particles 80% of which have diameters less than 75 microns. Maximum particle size 150 microns. Grain density 2.65 gm/cm^3, the same as that of crystalline quartz.

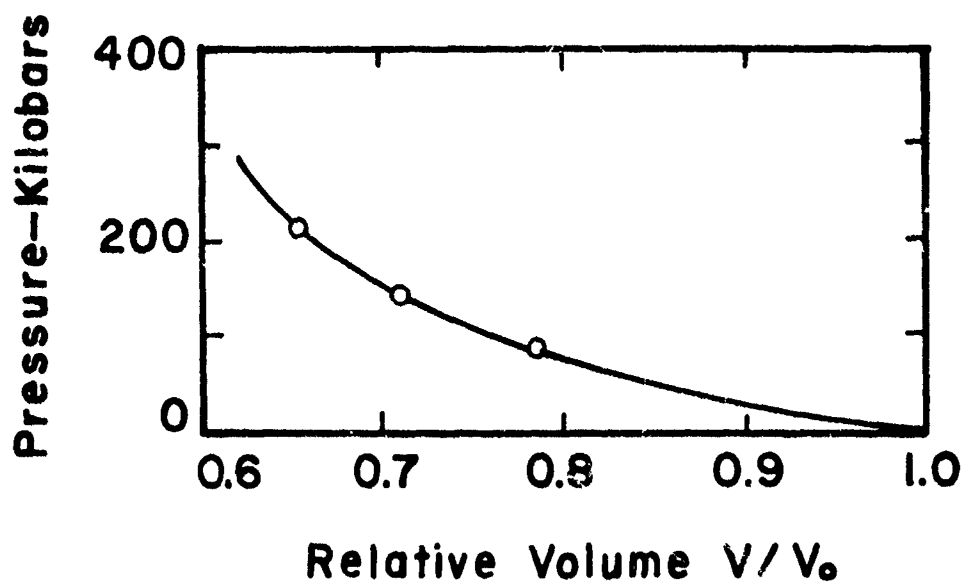


Dry Silica Sand—Porosity = 41 %

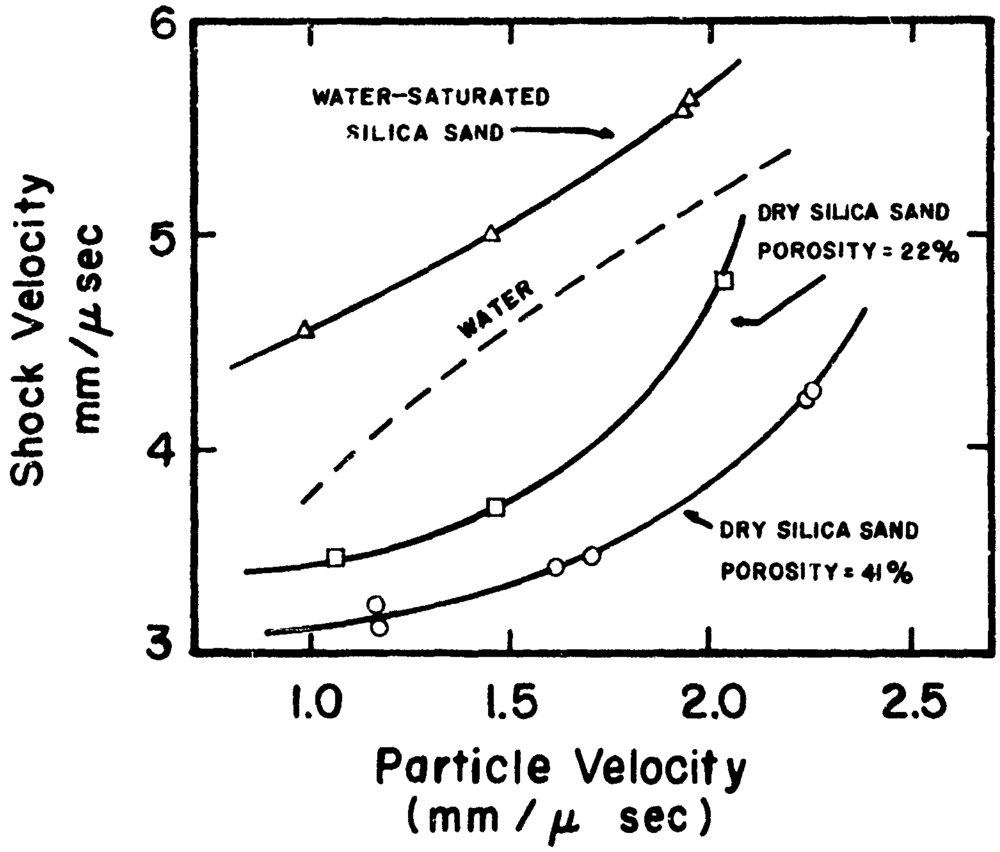


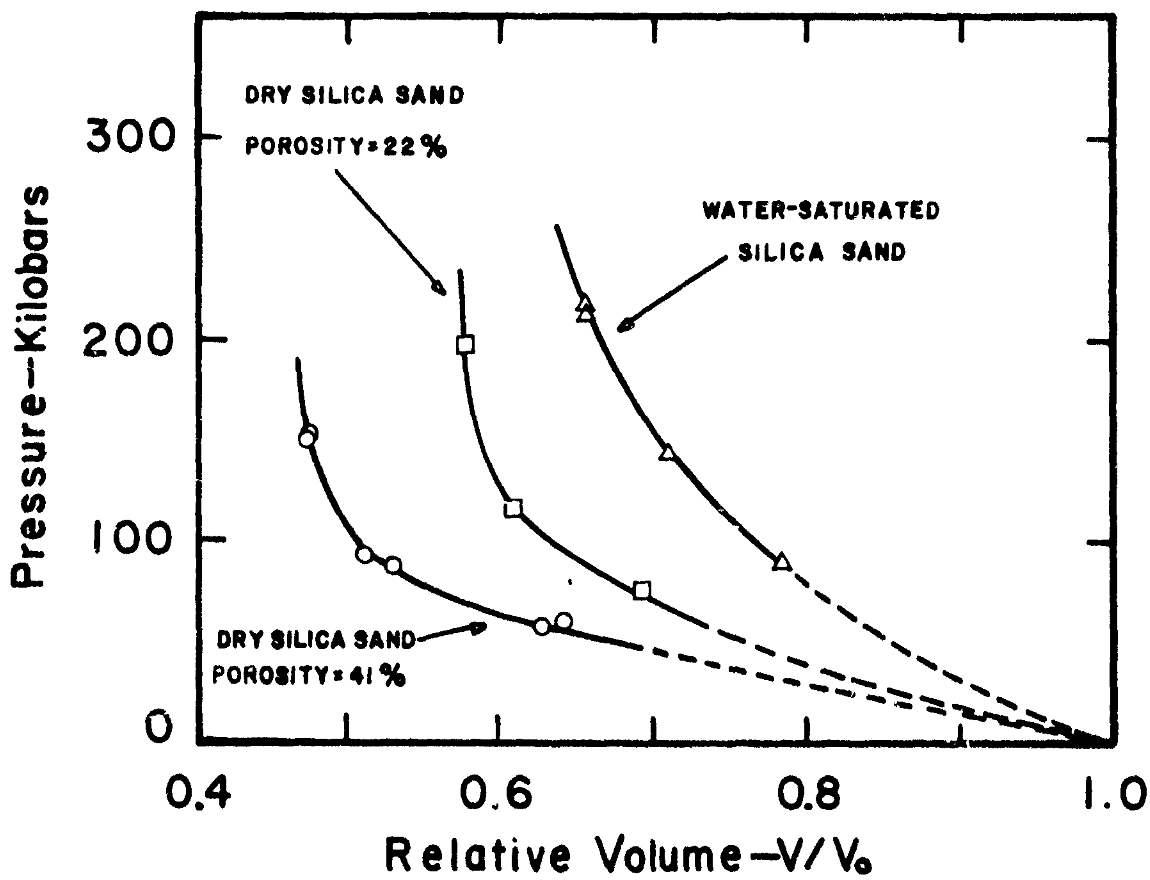
Dry Silica Sand—Porosity = 22 %





WATER SATURATED SILICA SAND


6
5
4
3
Shock Velocity mm/μ sec
WATER-SATURATED
SILICA SAND
WATER
DRY SILICA SAND
POROSITY = 22%
DRY SILICA SAND
POROSITY = 41%
1.0
1.5
2.0
2.5
Particle Velocity
(mm / μ sec)


300
200
100
0
Pressure–Kilobars
DRY SILICA SAND
POROSITY = 22%
WATER-SATURATED
SILICA SAND
DRY SILICA SAND
POROSITY = 41%
0.4
0.6
0.8
1.0
Relative Volume–V/Vo

SILICA SAND

SILVER

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.065	0.504	214.9	0.8760
4.113	0.527	227.4	0.8719
4.378	0.717	329.3	0.8362
4.846	0.985	500.7	0.7967
4.848	1.010	513.6	0.7917

$\rho_o = 10.94$

Source: Walsh, Rice, McQueen and Yarger (1957)

SILVER

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.69	0.93	460	0.800
6.76	2.19	1550	0.675
9.45	4.05	4010	0.572

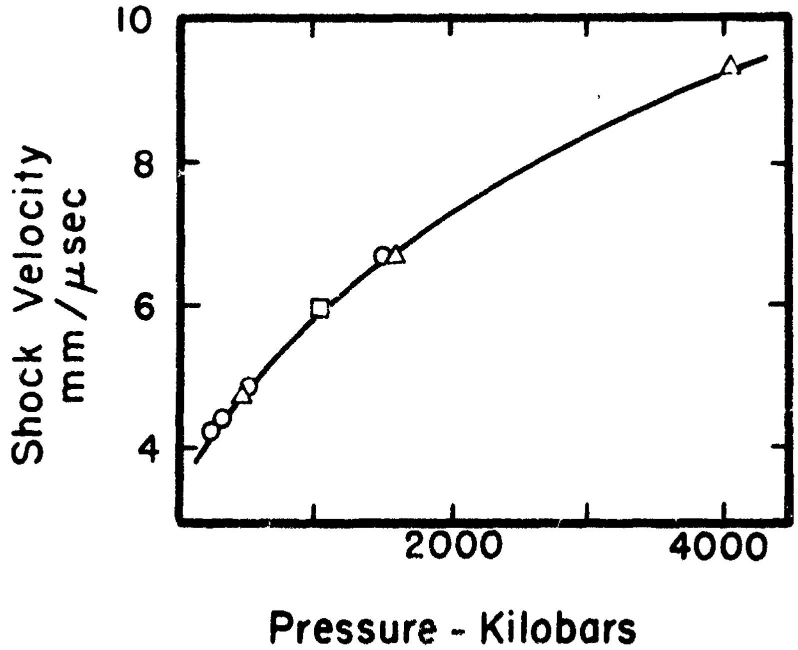
$\rho_o = 10.94$

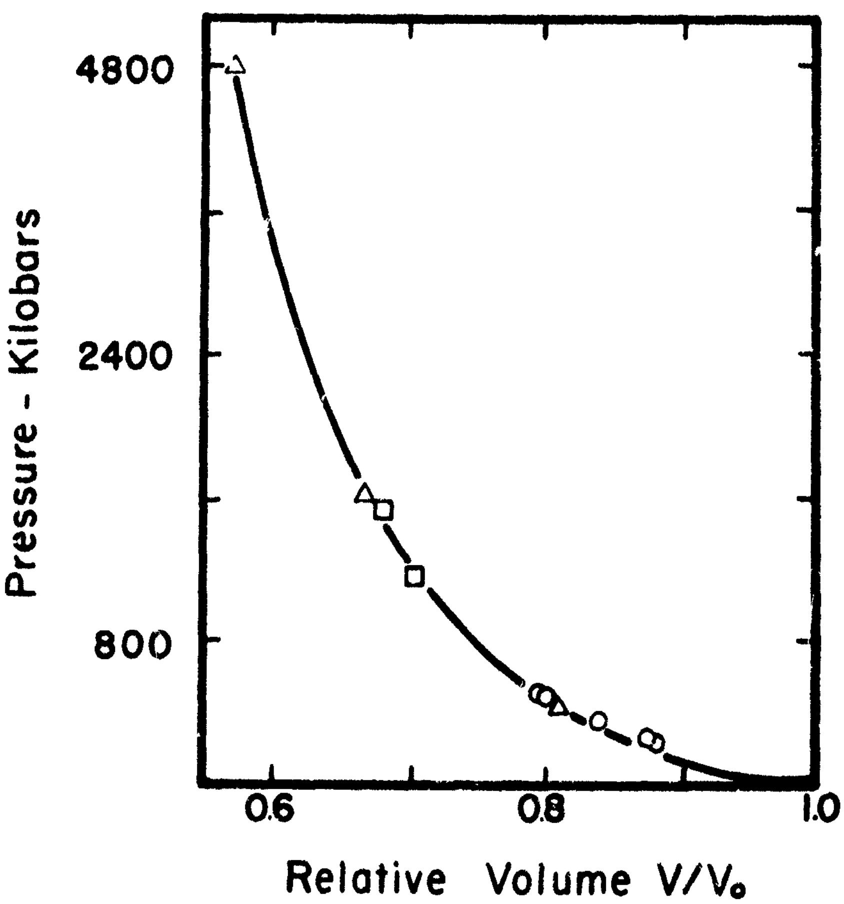
Source: Al'tshuler, Krupnikov and Brazhnik (1958)

SILVER

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.98	1.77	1107	0.705
5.96	1.78	1109	0.702
6.73	2.14	1512	0.681
6.63	2.17	1509	0.673
6.68	2.16	1510	0.677
6.72	2.17	1530	0.677

$\rho_o = 10.94$ Source: McQueen and Marsh (1960)


10
8
6
4
Shock Velocity
mm/μsec
2000
4000
Pressure - Kilobars


4800
2400
800
Pressure - Kilobars
0.6
0.8
1.0
Relative Volume V/Vo

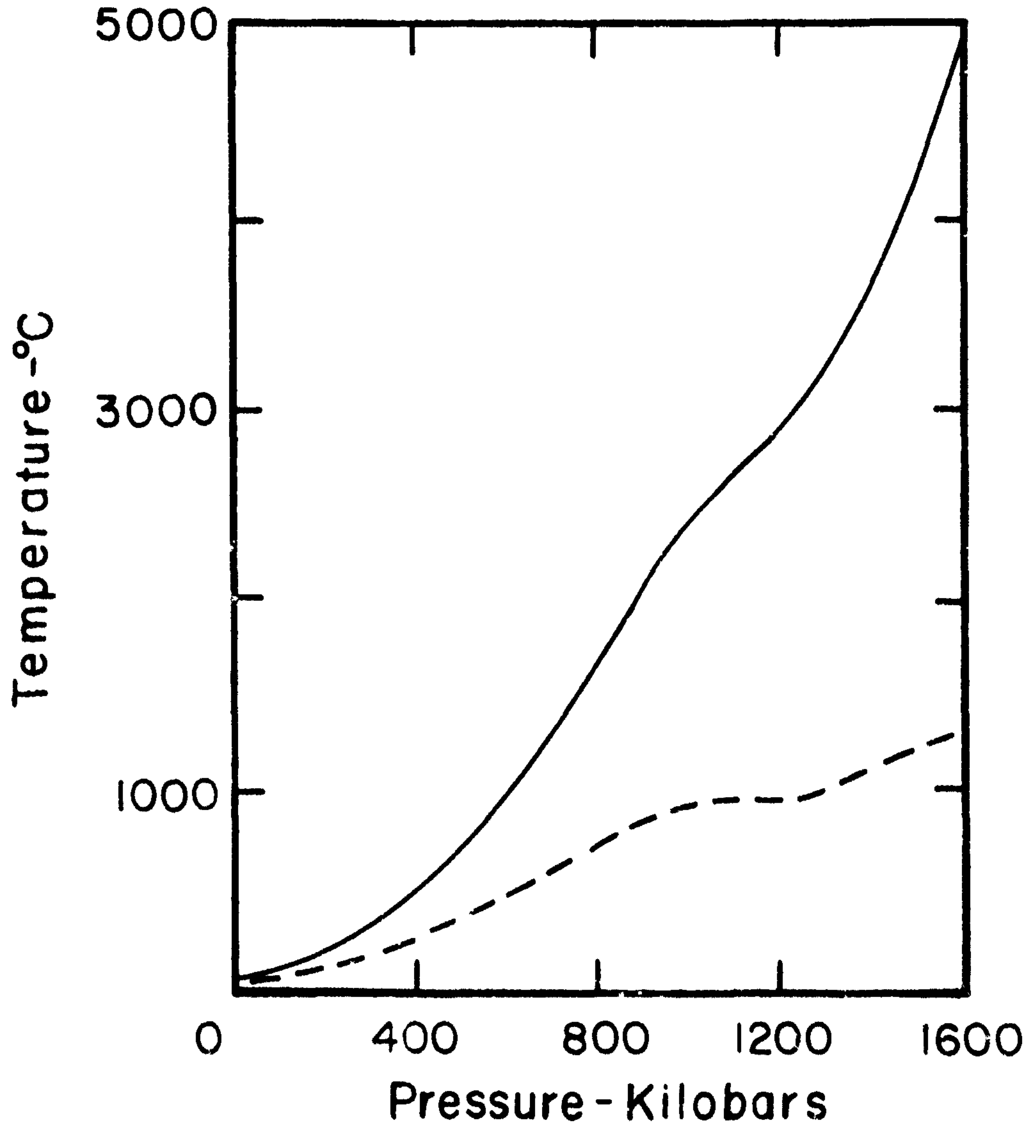
SILVER

Temperatures associated with shock

Silver

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	85	30
200	179	71
300	320	143
400	510	238
500	748	349
600	1029	470
700	1348	596
800	1701	725
900	2083	853
1000	2460	960
1100	2682	960
1200	2903	960
1300	3198	992
1400	3725	1117
1500	4285	1241
1600	4875	1364

Source: McQueen and Marsh, 1960


5000
3000
1000
Temperature -°C
0
400
800
1200
1600
Pressure - Kilobars

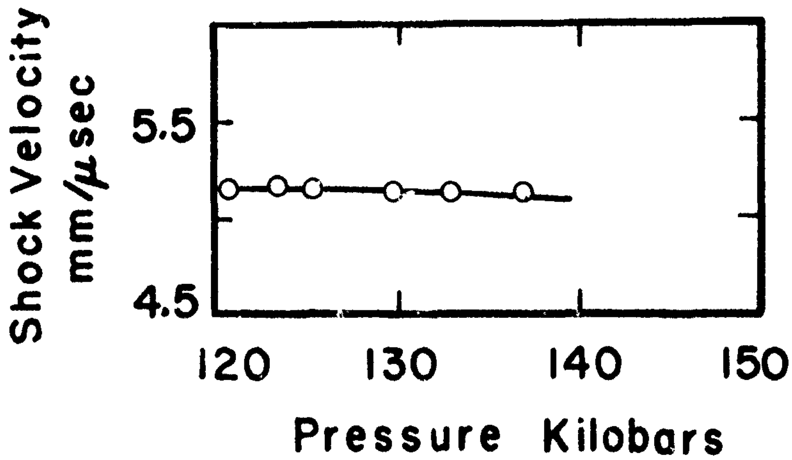
SILVER

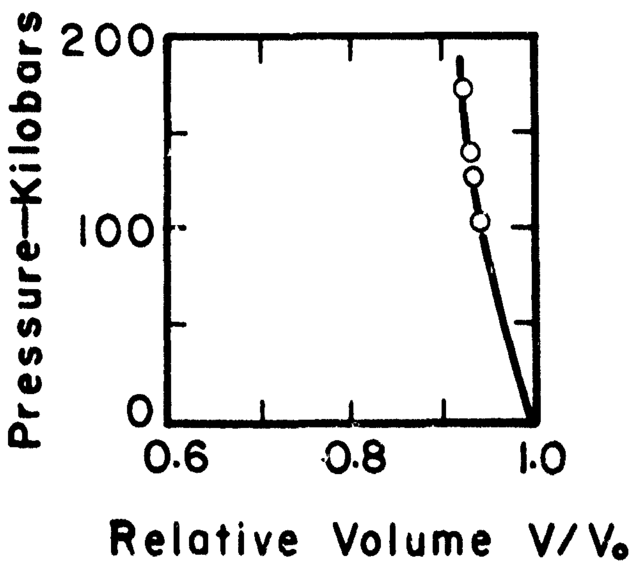
LOW CARBON STEEL

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.15	0.300	120.8	0.9418
5.16	0.305	123.5	0.9408
5.14	0.311	125.4	0.9394
5.15	0.316	127.7	0.9386
5.14	0.322	129.9	0.9373
5.155	0.329	132.9	0.9362
5.15	0.338	136.7	0.9343

$\rho_o = 7.8$

Source: Katz, Dorran and Curran (1959)





LOW CARBON STEEL

TACONITE

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Iron			
4.36	0.68	126	0.843
5.33	1.61	246	0.657
7.51	3.02	940	0.229 (?)
7.98	3.25	1140	0.593

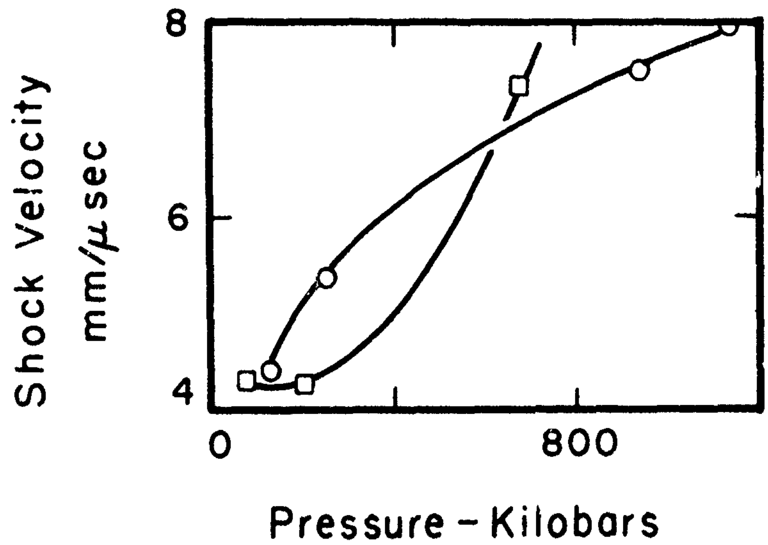
$\rho_o = 4.15 - 4.38$

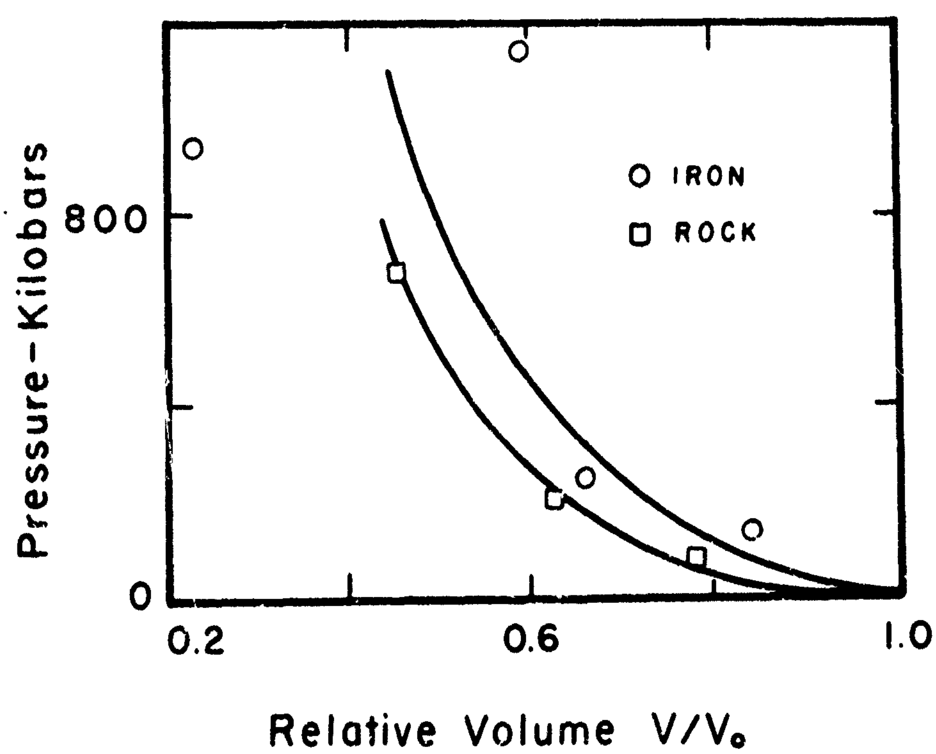
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
Rock			
4.29	0.95	74	0.780
4.23	1.59	200	0.624
7.41	4.05	679	0.453

$\rho_o = 1.82 - 2.41$

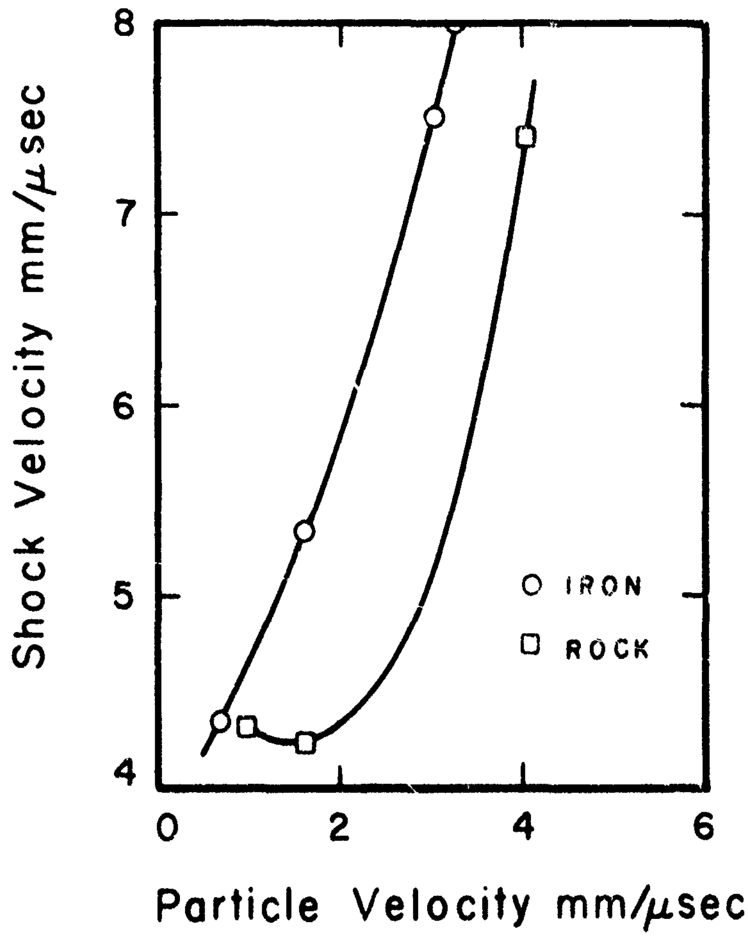
Source: Lombard (1961)

*Banded Mesabi Range, Erie formation. The banding was of the same dimensions as the sample, hence the "iron" samples are almost pure iron while the "rock" samples contain little iron.


8
6
4
0
800
Shock Velocity
mm/μsec
Pressure - Kilobars


IRON
ROCK
800
0
0.2
0.6
1.0
Pressure - Kilobars
Relative Volume V/V₀

TACONITE



8
7
6
5
4
0
2
4
6
Shock Velocity mm/μsec
Particle Velocity mm/μsec
IRON
ROCK

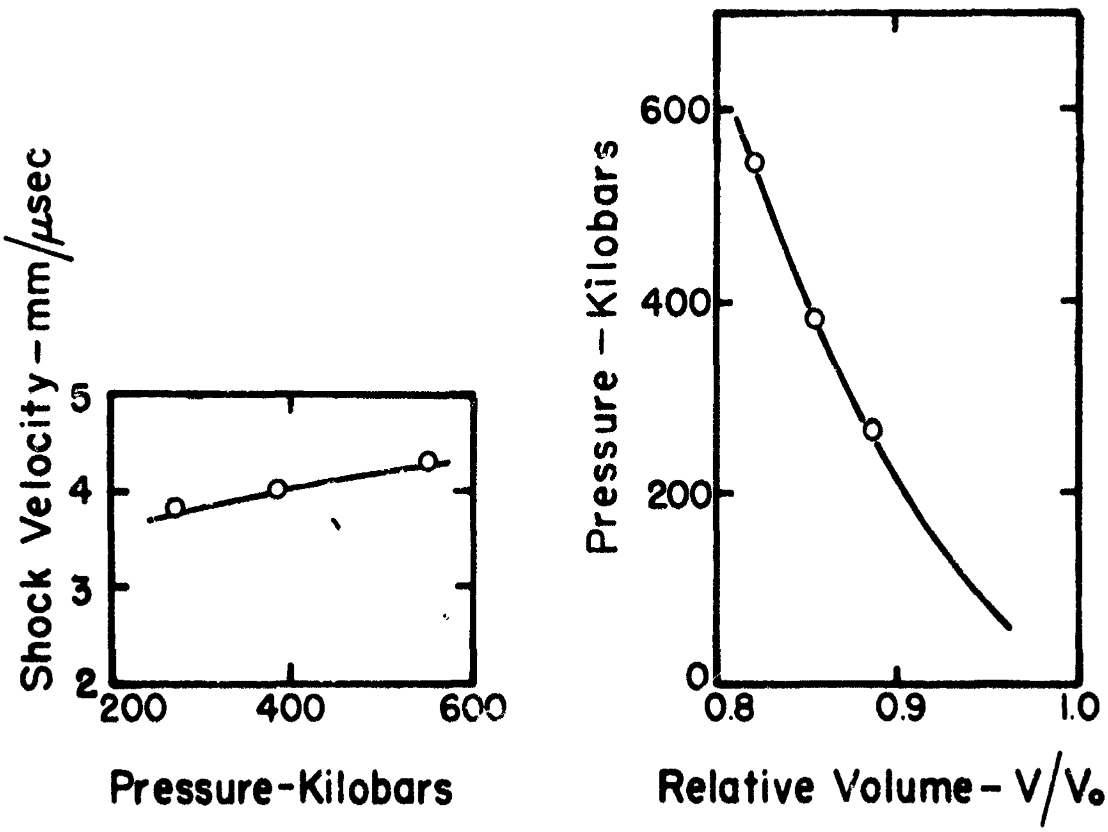
TACONITE

TANTALUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.811	0.4327	271.5	0.8865
4.010	0.5800	383	0.8554
4.323	0.7685	547	0.8222

$\rho_0 = 16.46$

Source: Walsh, Rice, McQueen and Yarger (1957)


Shock Velocity - mm/μsec
5
4
3
2
200
400
600
Pressure-Kilobars
Pressure - Kilobars
600
400
200
0
0.8
0.9
1.0
Relative Volume - V/V₀

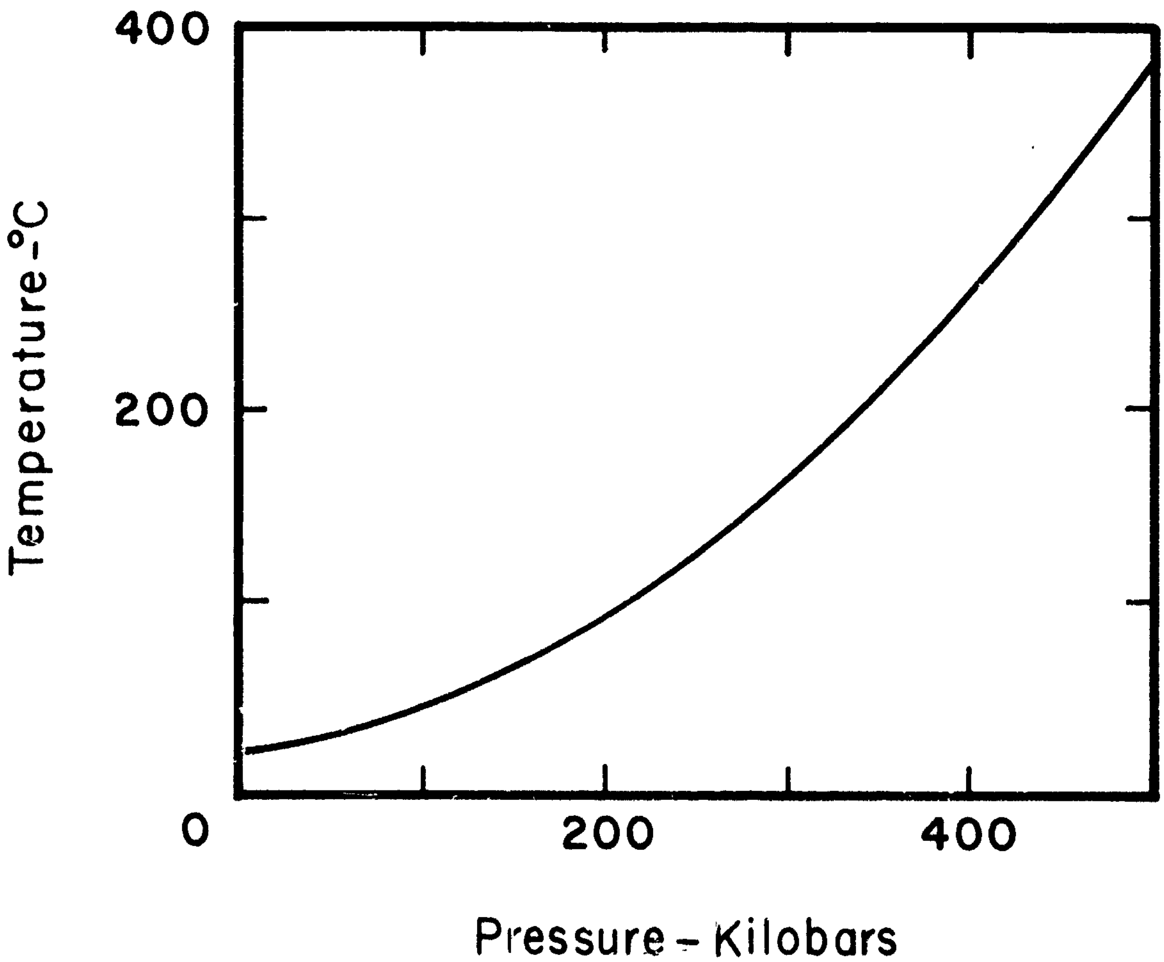
TANTALUM

Temperatures associated with shock

Tantalum

Pressure (kilobars)	Temperature behind shock (C^o)	Residual temperature (C^o)
0	20	
100	47	
150	69	
200	92	
250	121	
300	160	
350	207	
400	260	
450	315	
500	379	

Source: Rice, McQueen and Walsh, 1958



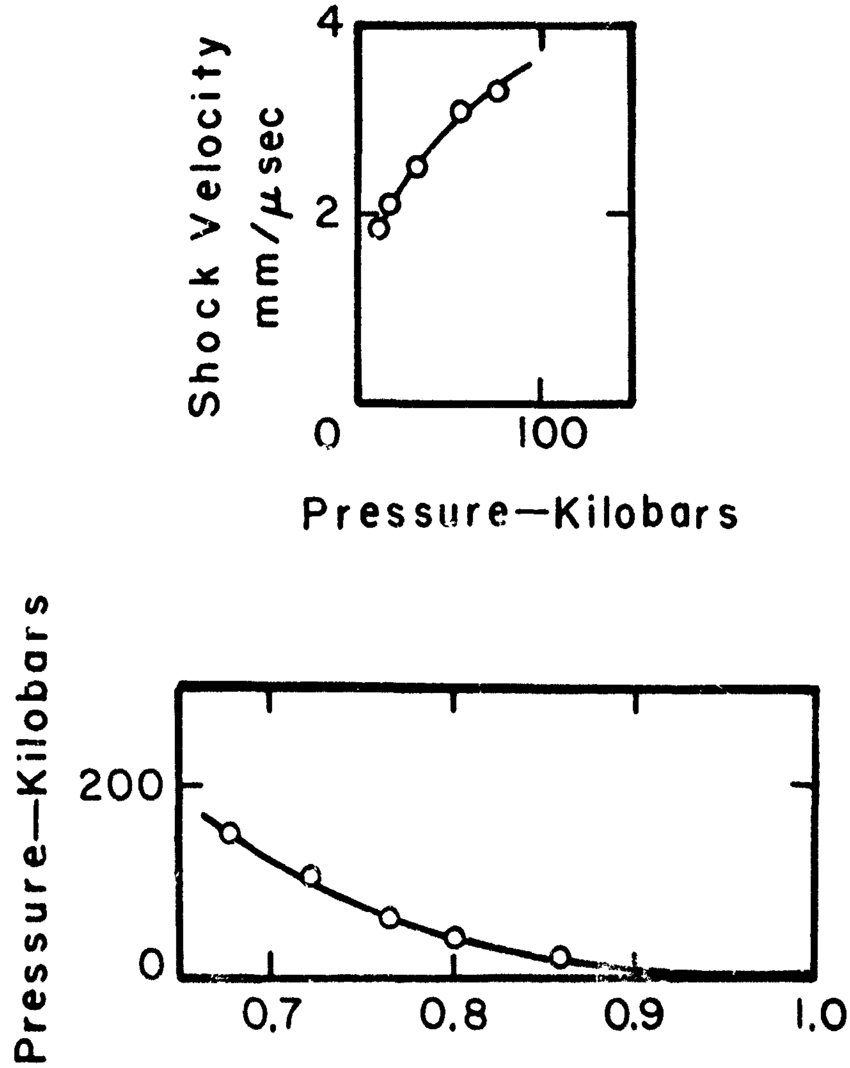
TANTALUM

TEFLON

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
1.85	0.263	10.5	0.859
2.08	0.410	18.4	0.803
2.49	0.578	31.1	0.767
3.03	0.837	54.8	0.723
3.32	1.06	76.4	0.679

$\rho_0 = 2.16$

Source: Wagner, Waldorf and Louie (1962)



Shock Velocity
mm/μ sec
4
2
0
100
Pressure—Kilobars
Pressure—Kilobars
200
0
0.7
0.8
0.9
1.0
Relative Volume V/V₀

TEFLON

THALLIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
2.804	0.6416	213	0.7712
2.817	0.6386	213	0.7733
3.120	0.8446	312	0.7293
3.145	0.8406	313	0.7327
3.538	1.090	456.5	0.6919
3.541	1.089	456.5	0.6925

$\rho_o = 11.84$

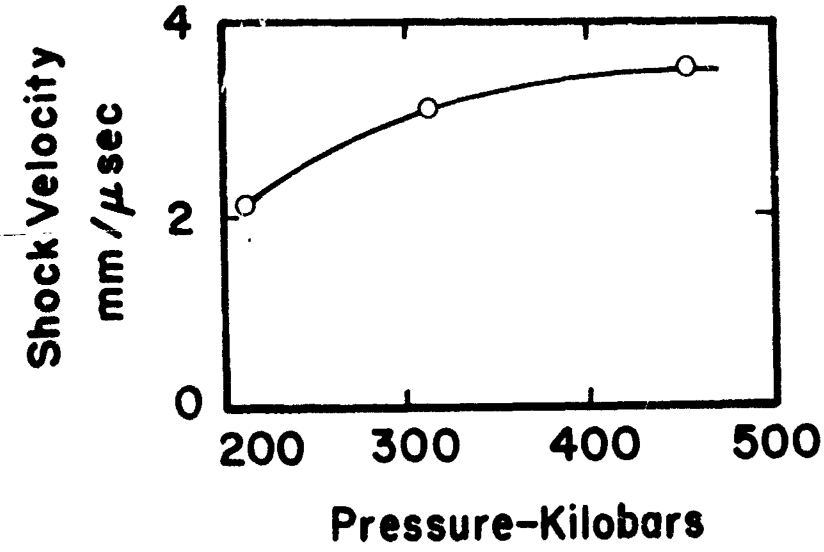
Source: Walsh, Rice, McQueen and Yarger (1957)

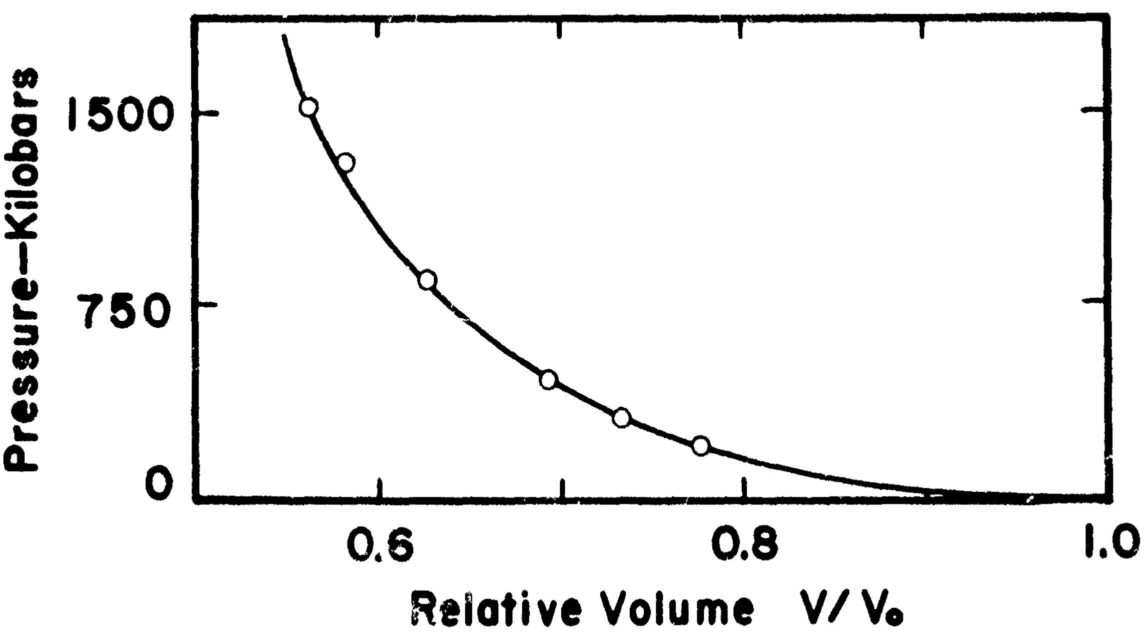
THALLIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.42	1.65	864	0.627
4.41	1.65	862	0.626
4.41	1.65	862	0.626
5.13	2.15	1306	0.581
5.39	2.37	1515	0.560
5.40	2.37	1516	0.561
5.40	2.37	1517	0.561

$\rho_o = 11.84$

Source: McQueen and Marsh (1960)


Shock Velocity
mm / μsec
4
2
0
200
300
400
500
Pressure-Kilobars


Pressure—Kilobars
1500
750
0
0.6
0.8
1.0
Relative Volume V/ V₀

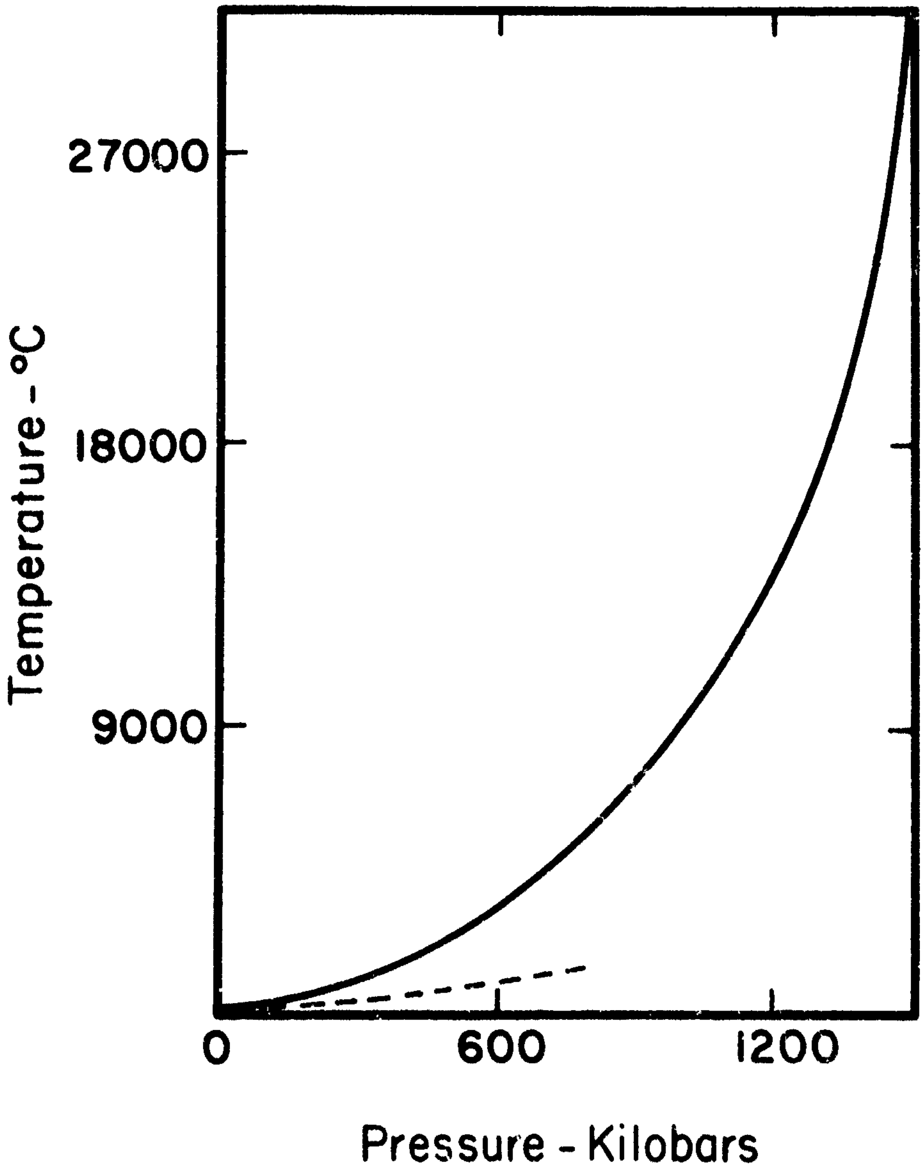
THALLIUM

Temperatures associated with shock

Thallium

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	211	78
200	587	245
300	857	303
400	1503	502
500	2374	723
600	3412	940
700	4614	1148
800	5988	1345
900	7552	-
1000	9340	-
1100	11417	-
1200	13897	-
1300	17067	-
1400	21607	-
1500	30627	-

Source: McQueen amd Marsh, 1960


27000
18000
9000
Temperature - °C
0
600
1200
Pressure - Kilobars

THALLIUM

THORIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
3.497	1.043	426.0	0.7017
3.192	0.812	302.7	0.7456
2.954	0.620	213.9	0.7901
2.900	0.571	193.4	0.8031

$\rho_0 = 11.68$

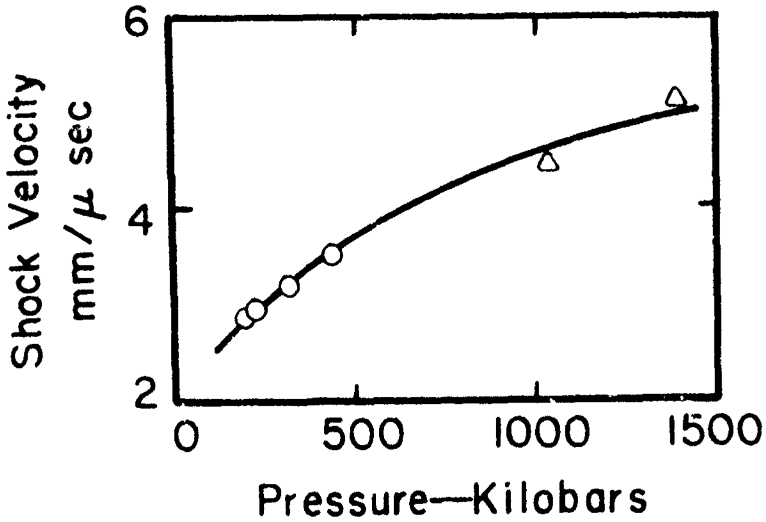
Source: Walsh, Rice, McQueen and Yarger (1957)

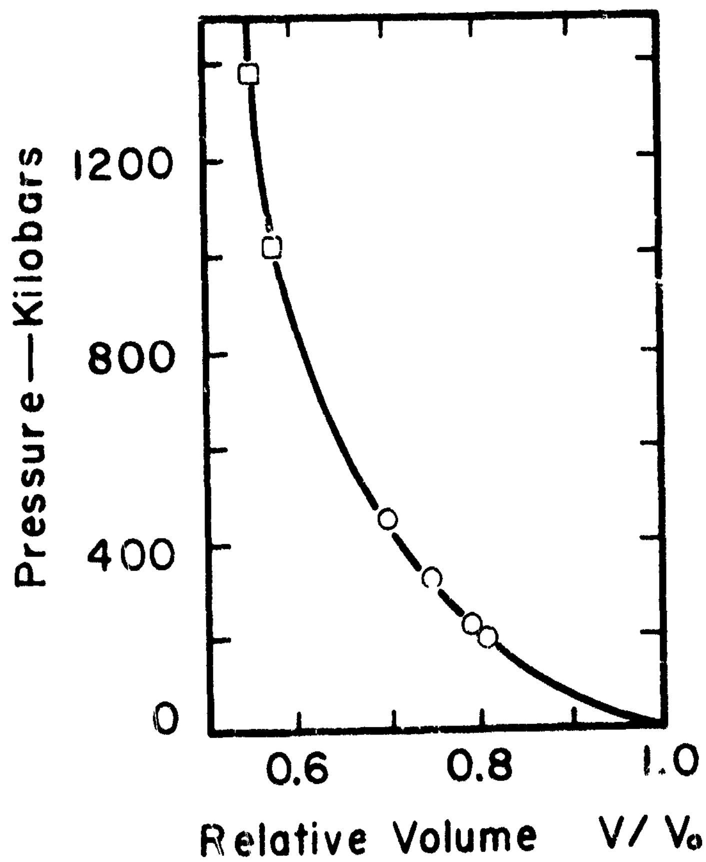
THORIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.51	1.90	1003	0.578
4.53	1.94	1026	0.572
5.16	2.32	1400	0.550
5.11	2.31	1378	0.548
5.09	2.33	1384	0.543
5.10	2.36	1405	0.538

$\rho_0 = 11.68$

Source: McQueen and Marsh (1960)


Shock Velocity mm/μ sec
6
4
2
0
500
1000
1500
Pressure—Kilobars


Pressure—Kilobars
1200
800
400
0
0.6
0.8
1.0
Relative Volume V/ V₀

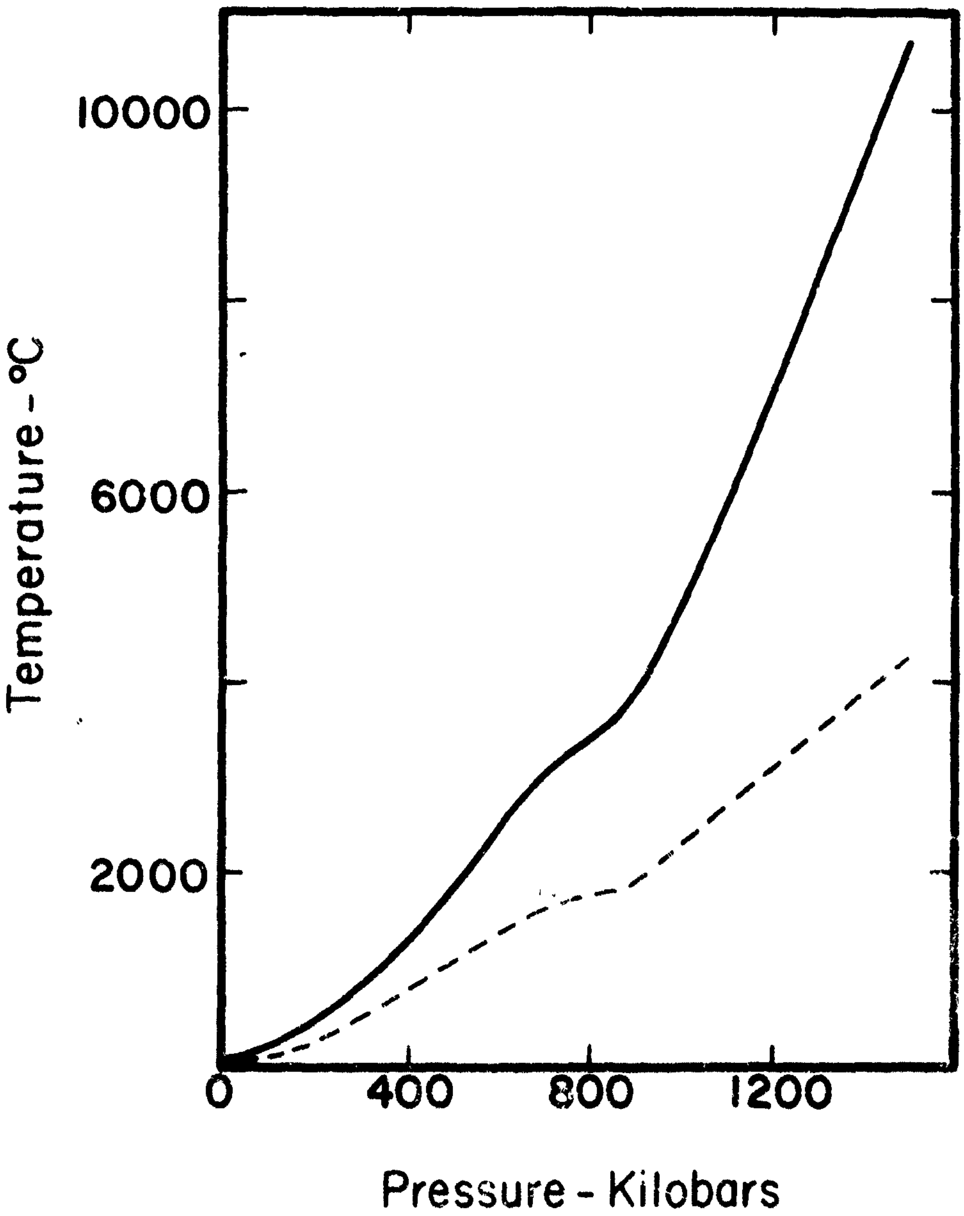
THORIUM

Temperatures associated with shock

Thorium

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	129	67
200	394	238
300	801	491
400	1304	781
500	1849	1079
600	2435	1366
700	3009	1632
800	3386	1750
900	3855	1895
1000	4818	2285
1100	5856	2677
1200	6966	3071
1300	8145	3464
1400	9393	3855
1500	10707	4243

Source: McQueen and Marsh, 1960


10000
6000
2000
Temperature - °C
0
400
800
1200
Pressure - Kilobars

THORIUM

TIN

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.555	1.290	427.8	0.7168
4.435	1.190	384.2	0.7317
4.004	0.925	269.6	0.7690
3.557	0.705	182.6	0.8018
3.524	0.670	171.9	0.8098

$\rho_0 = 7.28$

Source: Walsh, Rice, McQueen and Yarger (1957)

TIN

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.20	1.08	330	0.741
6.36	2.59	1200	0.833
9.02	4.73	3100	0.476

$\rho_0 = 7.28$

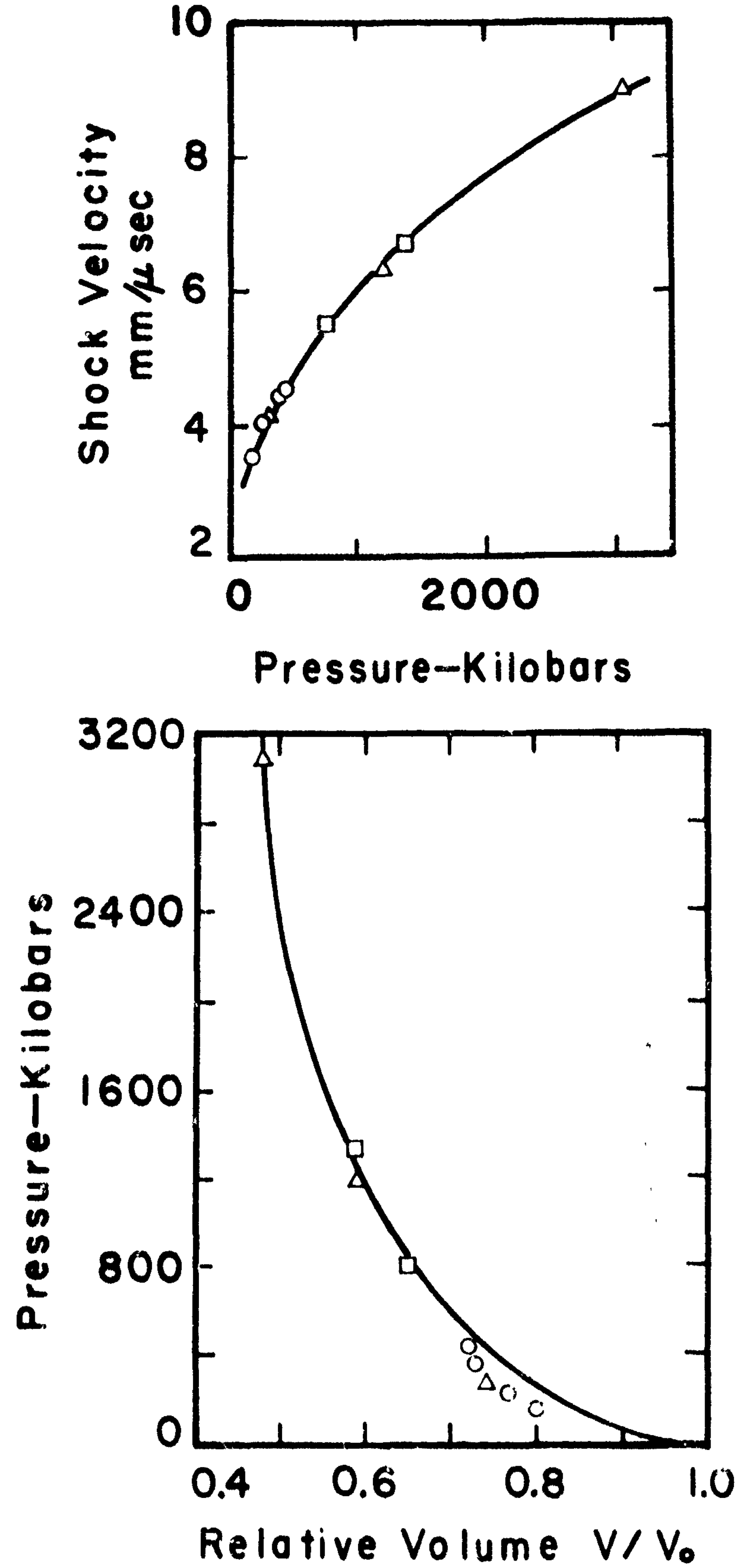
Source: Al'tshuler, Krupnikov and Brazhnik (1958)

TIN

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.57	1.95	790	0.651
6.71	2.80	1364	0.583
6.80	2.78	1377	0.591
6.75	2.81	1378	0.584

$\rho_0 = 7.28$

Source: McQueen and Marsh (1960)


10
8
6
4
2
Shock Velocity
mm/μ sec
0
2000
Pressure—Kilobars
3200
2400
1600
800
0
Pressure—Kilobars
0.4
0.6
0.8
1.0
Relative Volume V/ V₀

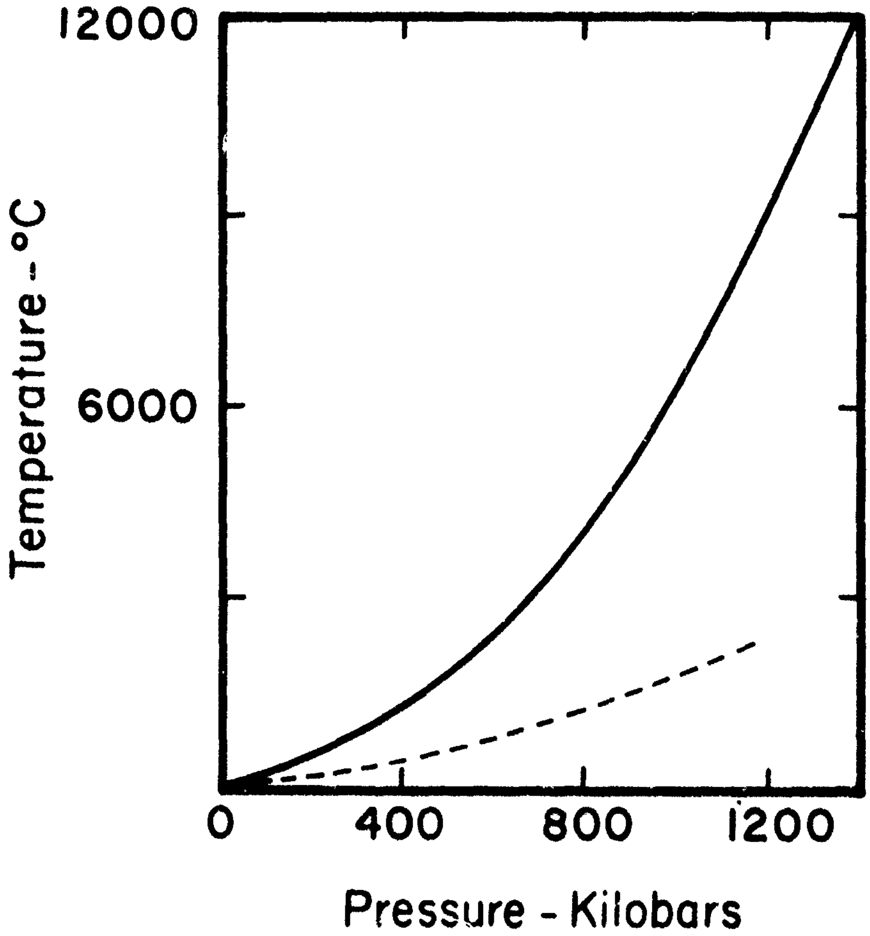
TIN

Temperatures associated with shock

Tin

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	162	63
200	436	198
300	598	232
400	924	341
500	1556	565
600	2312	795
700	3182	1025
800	4169	1252
900	5182	1476
1000	6357	1697
1100	7637	1921
1200	9017	2147
1300	10487	-
1400	12047	-

Source: McQueen and Marsh, 1960



TIN

TITANIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
6.329	1.370	390.8	0.7835
5.790	0.980	255.7	0.8307
5.501	0.723	179.3	0.8686
5.469	0.684	168.6	0.8749

$\rho_0 = 4.51$

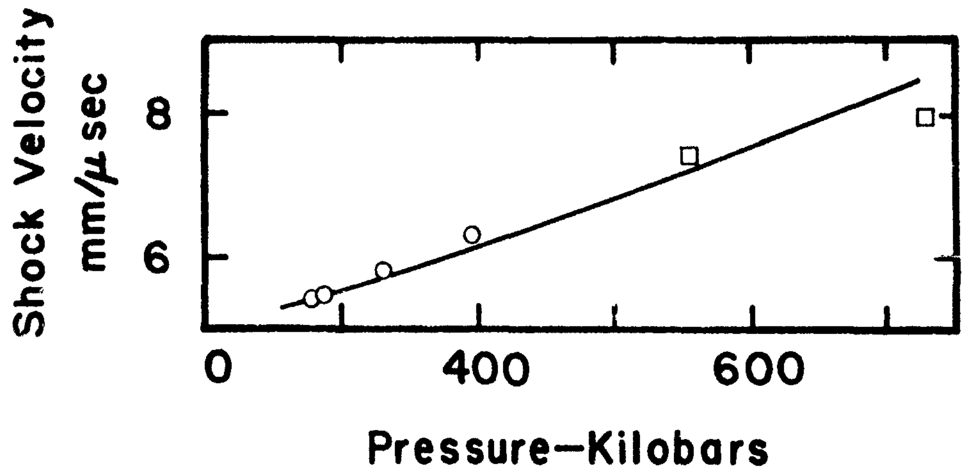
Source: Walsh, Rice, McQueen and Yarger (1957)

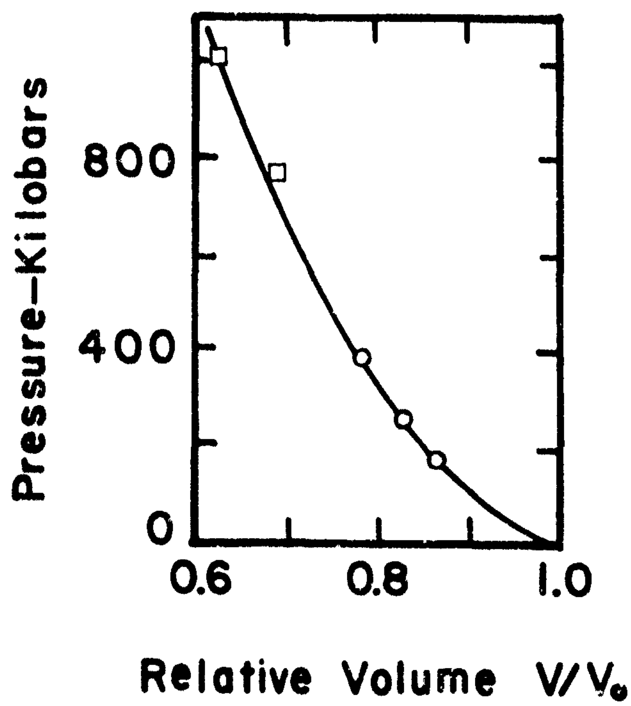
TITANIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
7.35	2.30	762	0.687
7.40	2.29	764	0.691
7.34	2.29	758	0.689
7.94	2.97	1063	0.626
7.92	2.97	1060	0.625

$\rho_0 = 4.51$

Source: McQueen and Marsh (1960)


Shock Velocity mm/μ sec
8
6
0
400
600
Pressure—Kilobars


Pressure—Kilobars
800
400
0
0.6
0.8
1.0
Relative Volume V/V₀

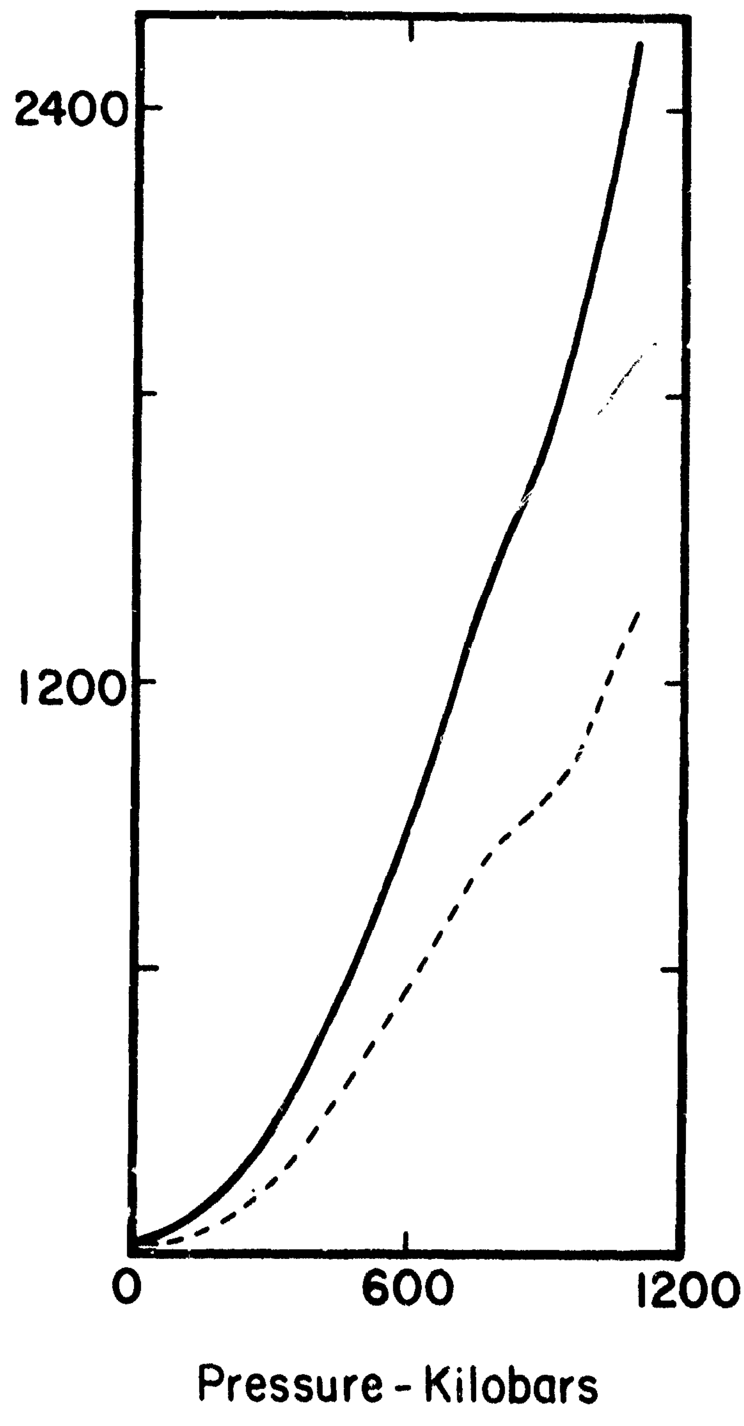
TITANIUM

Temperatures associated with shock

Titanium

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	30	29
200	133	73
300	262	154
400	441	268
500	664	406
600	926	561
700	1217	727
800	1503	877
900	1721	957
1000	2115	1154
1100	2550	1363

Source: McQueen and Marsh, 1960



TITANIUM

VOLCANIC TUFF

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
	Volcanic Tuff - Dry		
2.627	0.869	39	0.6695 (1)
3.33	1.340	74	0.598 (2)
3.433	1.329	77	0.613 (2)
3.78	1.73	105	0.542 (2)
3.71	1.72	109	0.536 (2)
4.299	1.626	132	0.6218 (1)
4.76	2.31	181	0.515 (2)
	Volcanic Tuff - Wet		
4.05	1.236	94	0.695 (2)
4.13	1.27	95	0.692 (2)
4.09	1.230	96	0.699 (3)
4.411	1.61	130	0.635 (2)
4.40	1.60	133	0.636 (2)
4.61	1.59	136	0.655 (2)
5.01	2.02	171	0.597 (2)
4.79	2.24	197	0.542 (2)
5.23	2.25	224	0.570 (2)

ρ_o = Dry - 1.60 - 1.88; Wet - 1.79 - 1.90

Source: Lombard (1961)

(1) Tunnel U12A, Nevada Test Site

(2) Tunnel U12B, Nevada Test Site, mined near Rainier

(3) Origin undetermined

VOLCANIC TUFF

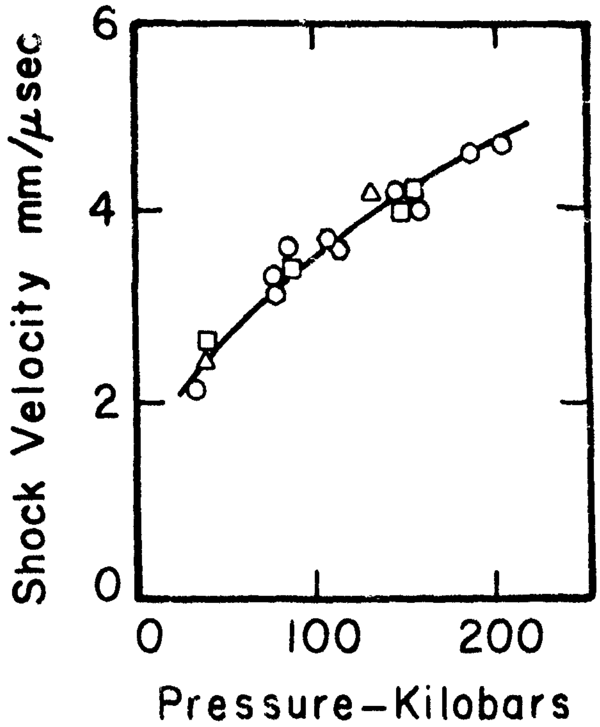
Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
	Dry Volcanic Tuff		
2.24	0.95	31	0.576 (5)
3.70	1.58	85	0.573 (5)
4.28	2.28	143	0.467 (5)
4.20	2.50	153	0.405 (5)
4.78	2.90	202	0.393 (5)
2.68	1.00	39	0.627 (4)
3.56	1.57	82	0.566 (4)
4.03	2.50	147	0.380 (4)
4.24	2.46	152	0.420 (4)
	Water-Saturated Volcanic Tuff		
3.42	0.90	53	0.737 (4)
4.26	1.45	108	0.660 (4)
5.49	2.81	270	0.488 (5)

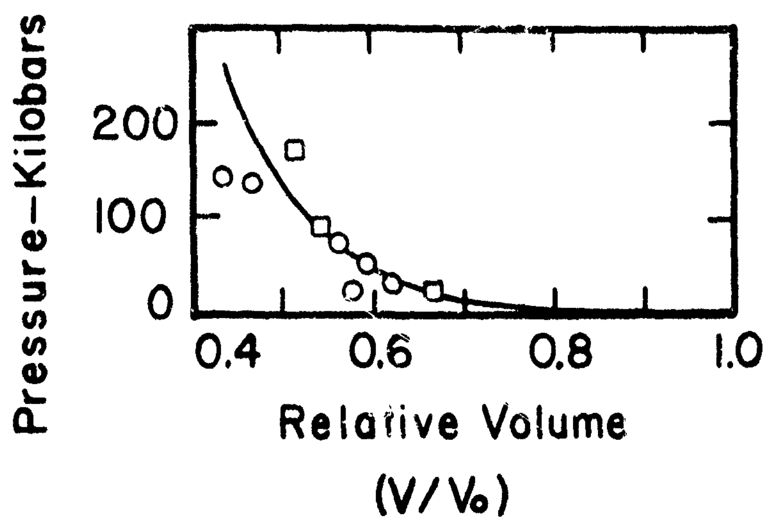
ρ_o = Dry - 1.46; Water-saturated - 1.74

Source: Bass, Hawk and Chabai (1963)

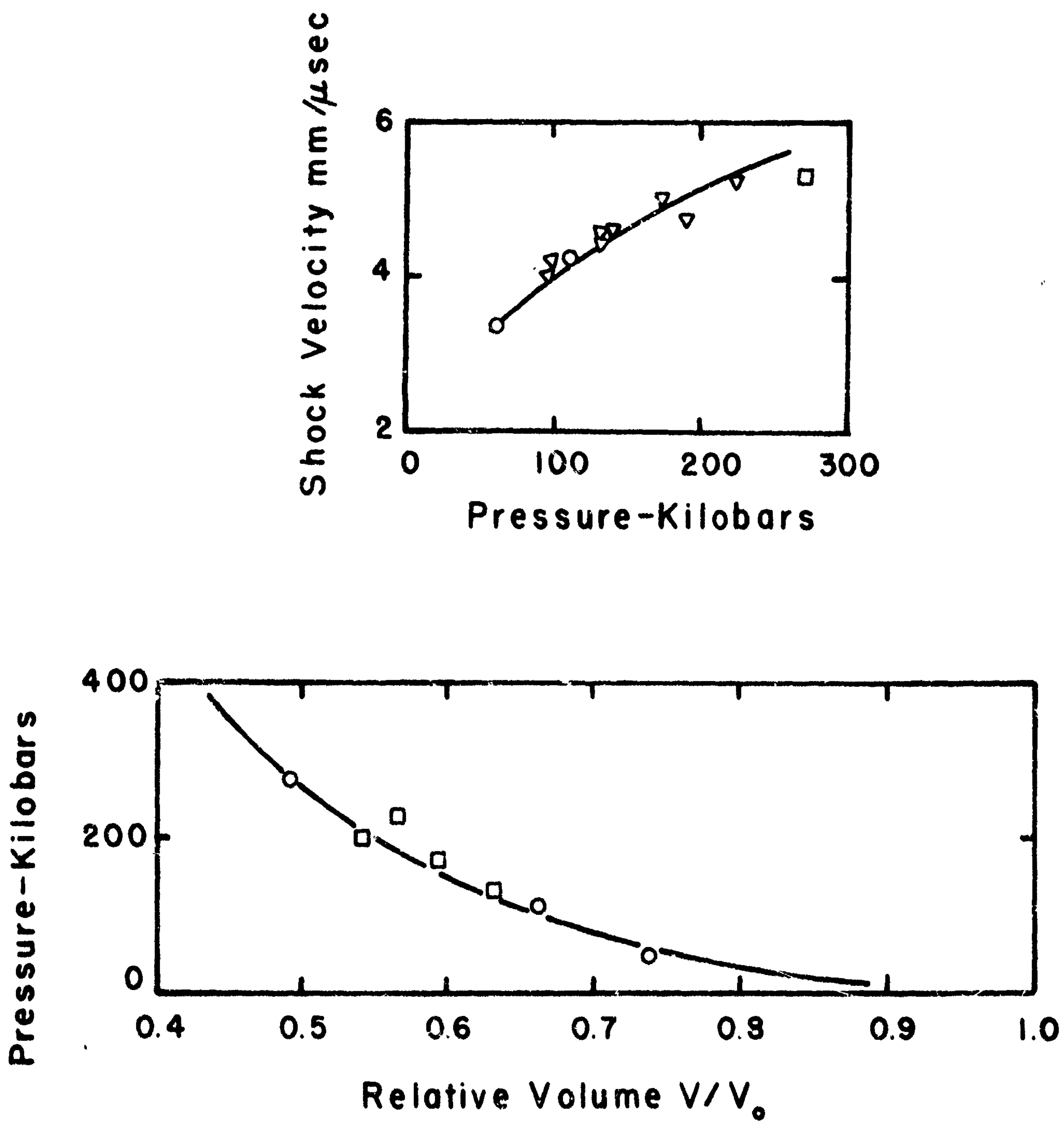
(4) Nevada Test Site Area 16

(5) Nevada Test Site Area 3





VOLCANIC TUFF - DRY



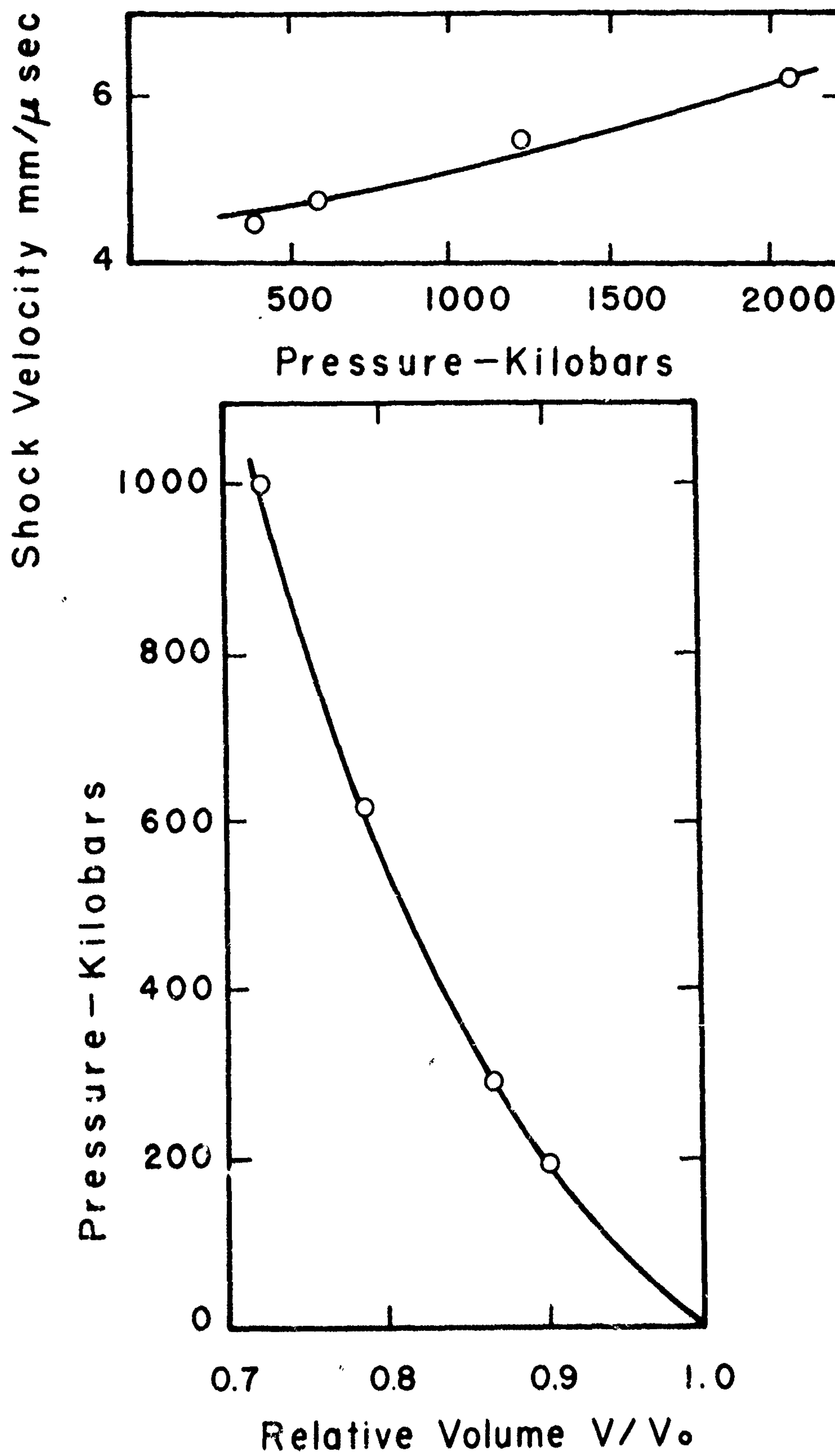
VOLCANIC TUFF—WET

TUNGSTEN

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.56	0.45	395	0.901
4.55	0.45	394	0.901
4.78	0.64	587	0.866
4.82	0.64	590	0.868
5.47	1.17	1225	0.786
5.49	1.17	1227	0.788
6.21	1.73	2061	0.721
6.19	1.73	2054	0.721
6.24	1.73	2074	0.723

$\rho_0 = 19.17$

Source: McQueen and Marsh (1960)


Shock Velocity mm/μ sec
6
4
500
1000
1500
2000
Pressure—Kilobars
1000
800
600
400
200
0
Pressure—Kilobars
0.7
0.8
0.9
1.0
Relative Volume V/Vo

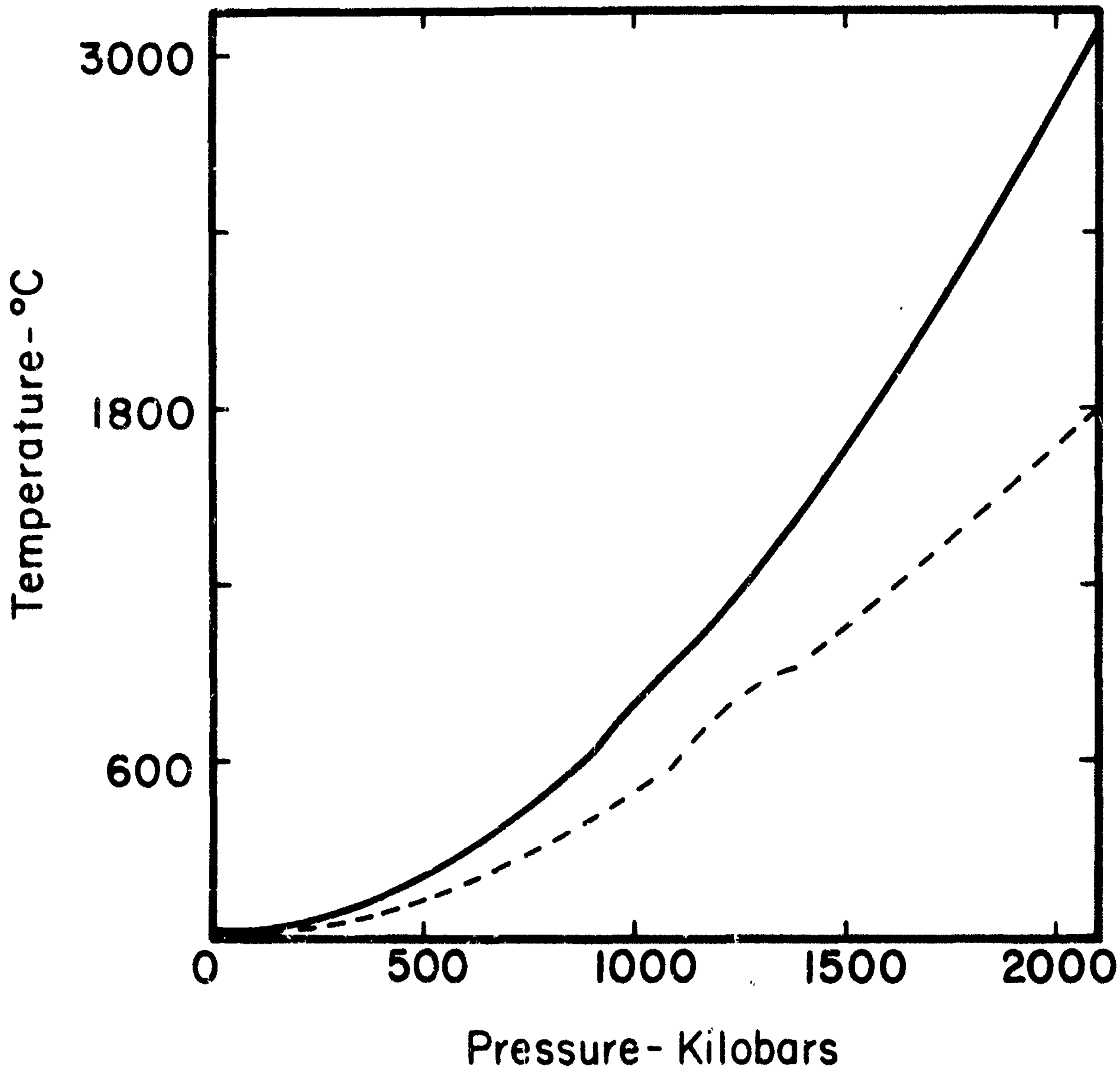
TUNGSTEN

Temperatures associated with shock

Tungsten

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	35	21
200	56	30
300	89	48
400	136	79
500	199	121
600	279	176
700	375	241
800	488	316
900	617	401
1000	761	494
1100	920	594
1200	1092	700
1300	1277	802
1400	1474	928
1500	1681	1048
1600	1898	1170
1700	2123	1295
1800	2356	1421
1900	2596	1547
2000	2841	1674
2100	3090	1800

Source: McQueen and Marsh, 1960


3000
1800
600
Temperature - °C
0
500
1000
1500
2000
Pressure - Kilobars

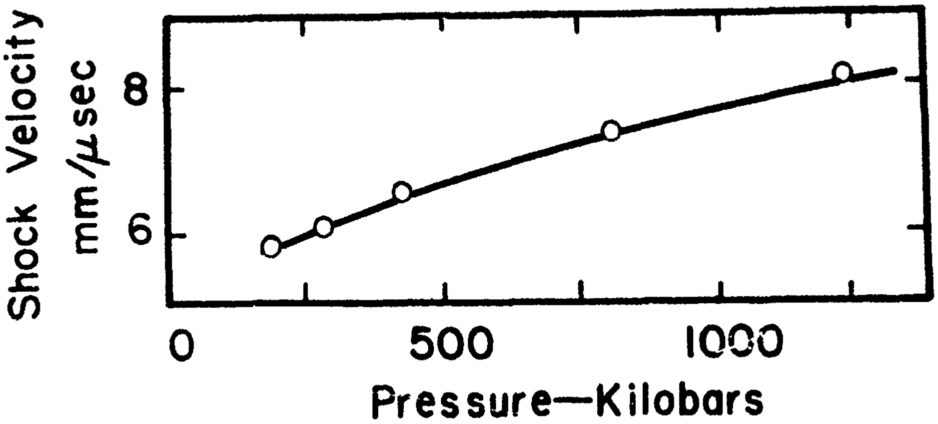
TUNGSTEN

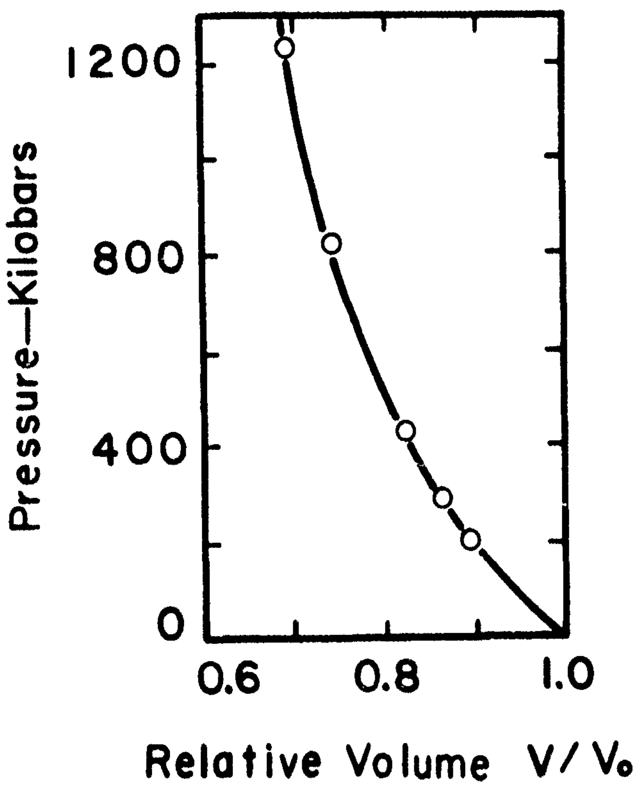
VANADIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.78	0.58	204	0.900
5.73	0.58	203	0.898
6.16	0.80	301	0.870
6.07	0.81	301	0.866
6.08	0.81	302	0.866
6.05	0.82	301	0.865
6.08	0.81	301	0.866
6.49	1.12	441	0.828
6.50	1.11	441	0.829
6.46	1.12	441	0.827
7.29	1.86	825	0.746
7.28	1.86	825	0.745
7.32	1.85	828	0.747
7.34	1.85	829	0.748
8.20	2.59	1244	0.697
8.17	2.49	1241	0.695

$\rho_0 = 6.1$

Source: McQueen and Marsh (1960)


Shock Velocity
mm/μsec
8
6
0
500
1000
Pressure—Kilobars


1200
800
400
0
Pressure—Kilobars
0.6
0.8
1.0
Relative Volume V/V₀

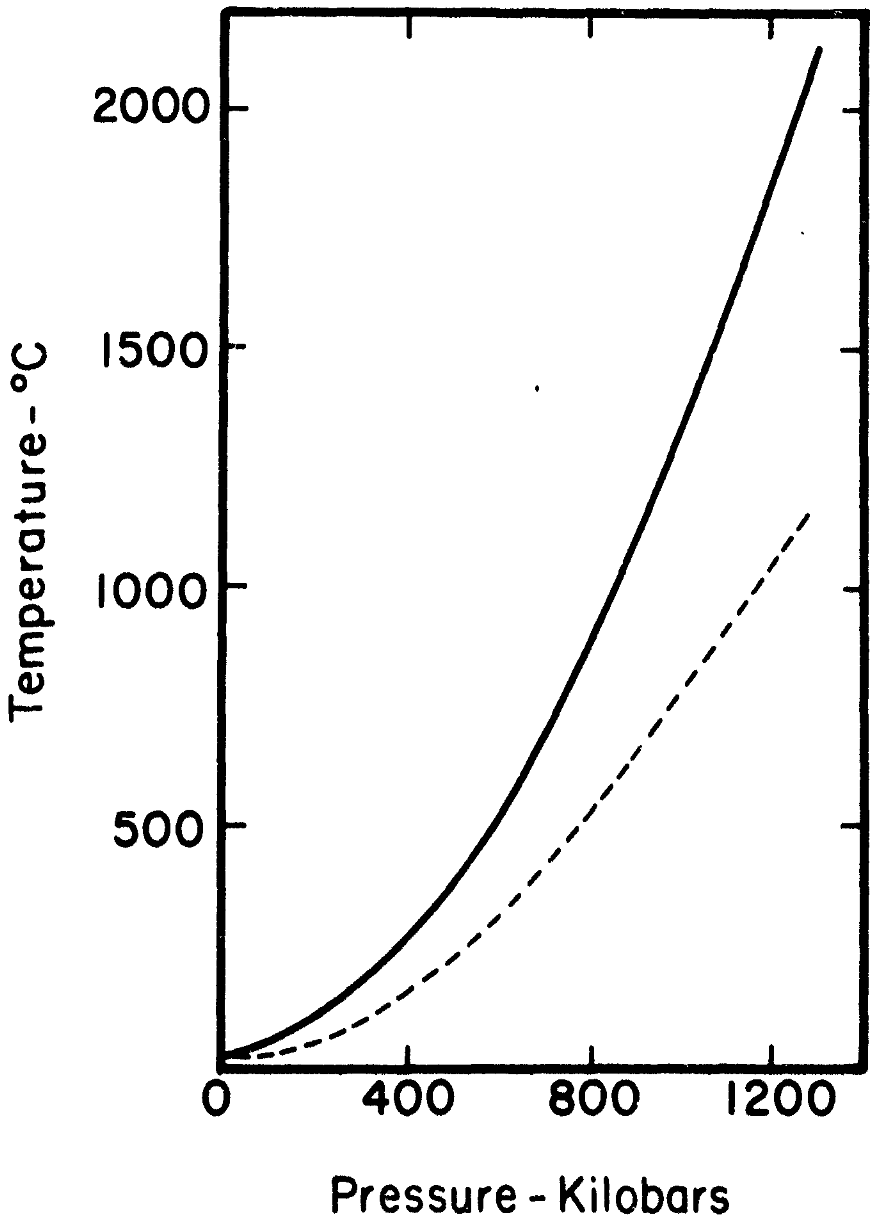
VANADIUM

Temperatures associated with shock

Vanadium

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	45	24
200	87	44
300	155	84
400	251	144
500	374	222
600	523	314
700	697	419
800	892	533
900	1106	655
1000	1338	783
1100	1584	913
1200	1841	1046
1300	2109	1178

Source: McQueen and Marsh, 1960


2000
1500
1000
500
Temperature - °C
0
400
800
1200
Pressure - Kilobars

VANADIUM

ZINC

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.019	0.673	193.0	0.833
3.850	0.615	169.1	0.840
4.418	0.842	265.6	0.809
4.663	1.008	335.6	0.784
4.684	1.043	348.7	0.777
4.791	1.121	383.5	0.766
4.792	1.172	401.0	0.755
4.815	1.197	411.5	0.751

$\rho_0 = 7.14$

Source: Walsh and Christian (1955)

ZINC

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.81	1.80	745	0.690
5.82	1.80	747	0.691
5.78	1.80	743	0.688
7.22	2.71	1394	0.625
7.34	2.71	1416	0.631
7.30	2.69	1403	0.631

$\rho_0 = 7.14$

Source: McQueen and Marsh (1960)

ZINC

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
5.014	1.250	447	0.7507
4.870	1.190	414	0.7556
4.481	0.88	281.4	0.8036
4.450	0.894	283.9	0.7991
4.053	0.650	188	0.8396
4.13	0.673	198.3	0.8370
4.022	0.630	180.8	0.8434

$\rho_0 = 7.135$

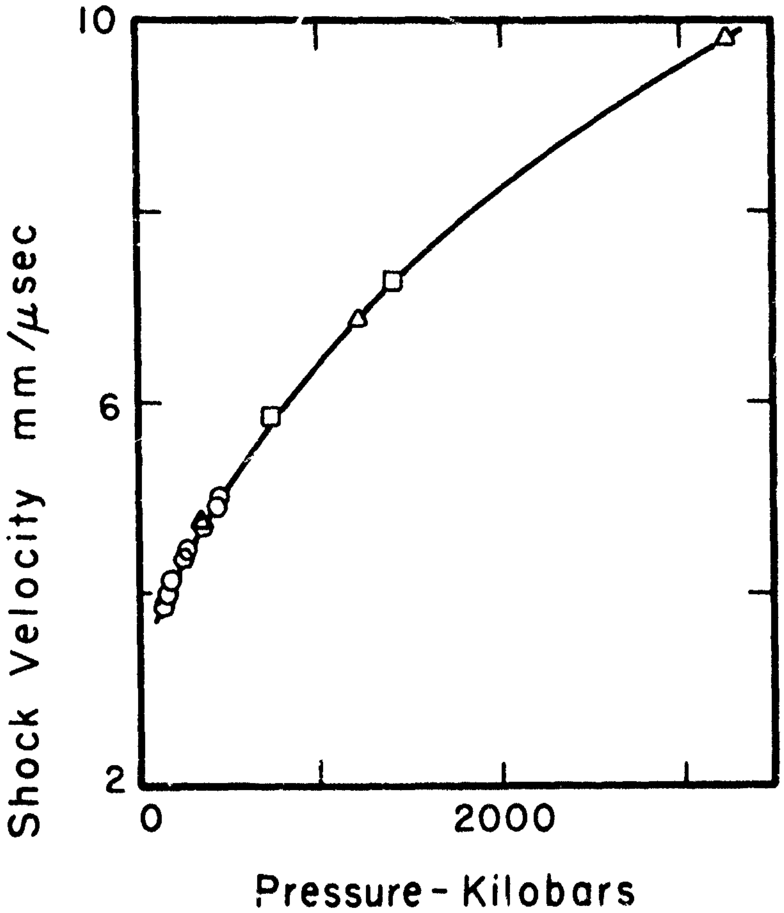
Source: Walsh, Rice, McQueen and Yarger (1957)

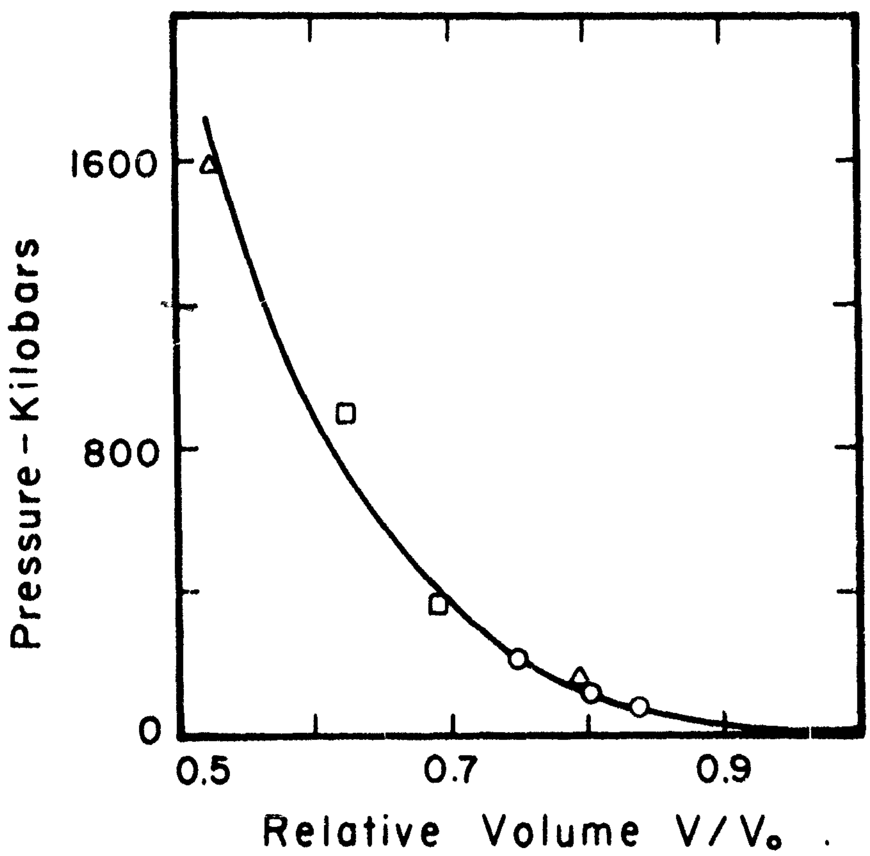
ZINC

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.70	1.04	350	0.781
6.85	2.54	1240	0.629
9.90	4.61	3260	0.535

$\rho_0 = 7.14$

Source: Al'tshuler, Krupnikov and Brazhnik (1958)


10
6
2
0
2000
Shock Velocity mm/μsec
Pressure - Kilobars


1600
800
0
0.5
0.7
0.9
Pressure - Kilobars
Relative Volume V/V₀

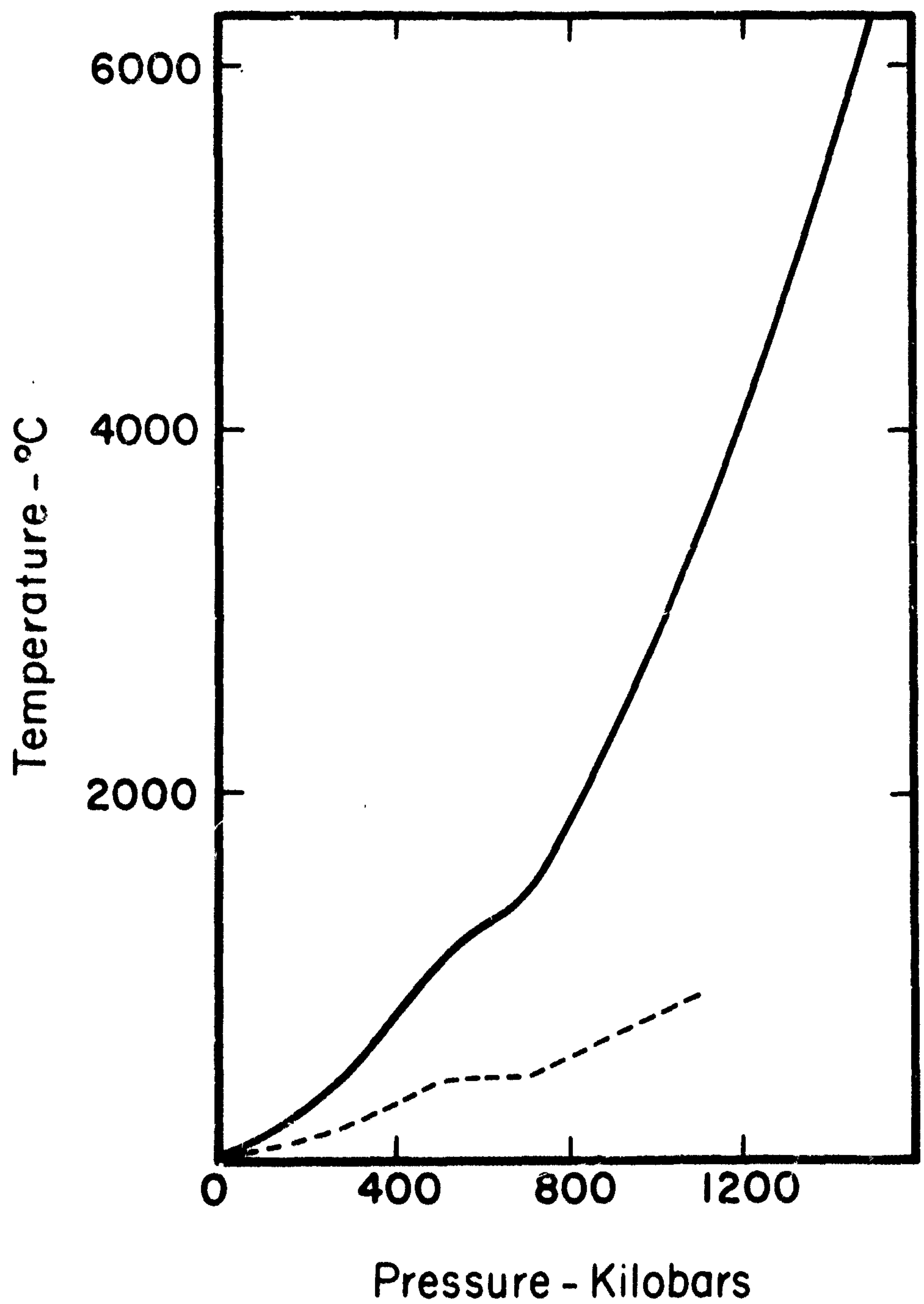
ZINC

Temperatures associated with shock

Zinc

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	20
100	122	37
200	274	101
300	495	197
400	780	310
500	1102	419
600	1223	419
700	1363	426
800	1810	544
900	2305	660
1000	2846	774
1100	3431	885
1200	4060	-
1300	4734	-
1400	5454	-
1500	6225	-

Source: McQueen and Marsh, 1960


6000
4000
2000
Temperature - °C
0
400
800
1200
Pressure - Kilobars

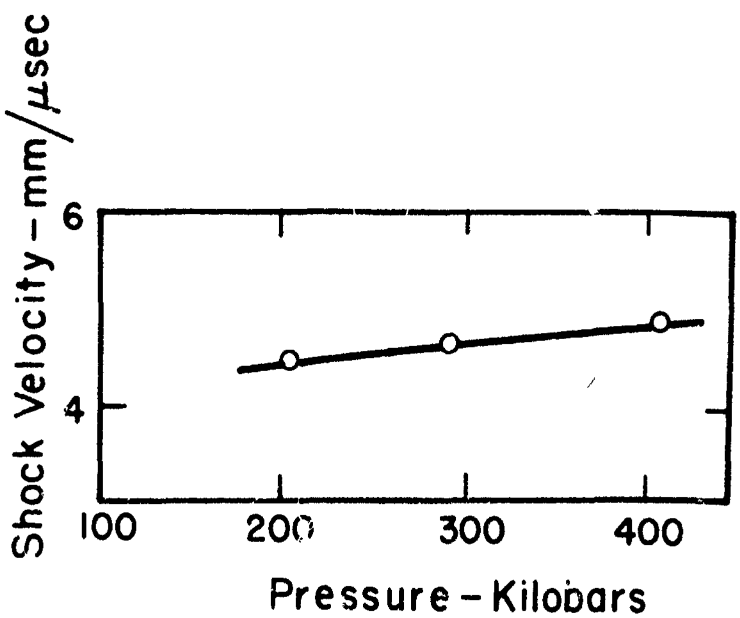
ZINC

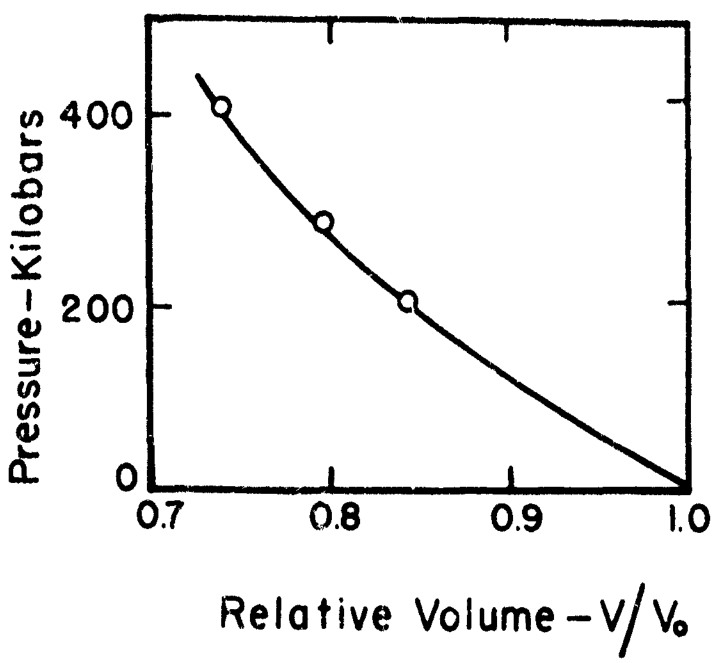
ZIRCONIUM

Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)	Relative Volume
4.494	0.7117	207.5	0.8416
4.674	0.9563	290	0.7954
4.920	1.275	407	0.7408

$\rho_0 = 6.49$

Source: Walsh, Rice, McQueen and Yarger (1957)


Shock Velocity - mm/μsec
6
4
100
200
300
400
Pressure - Kilobars


Pressure - Kilobars
400
200
0
0.7
0.8
0.9
1.0
Relative Volume - V/Vo

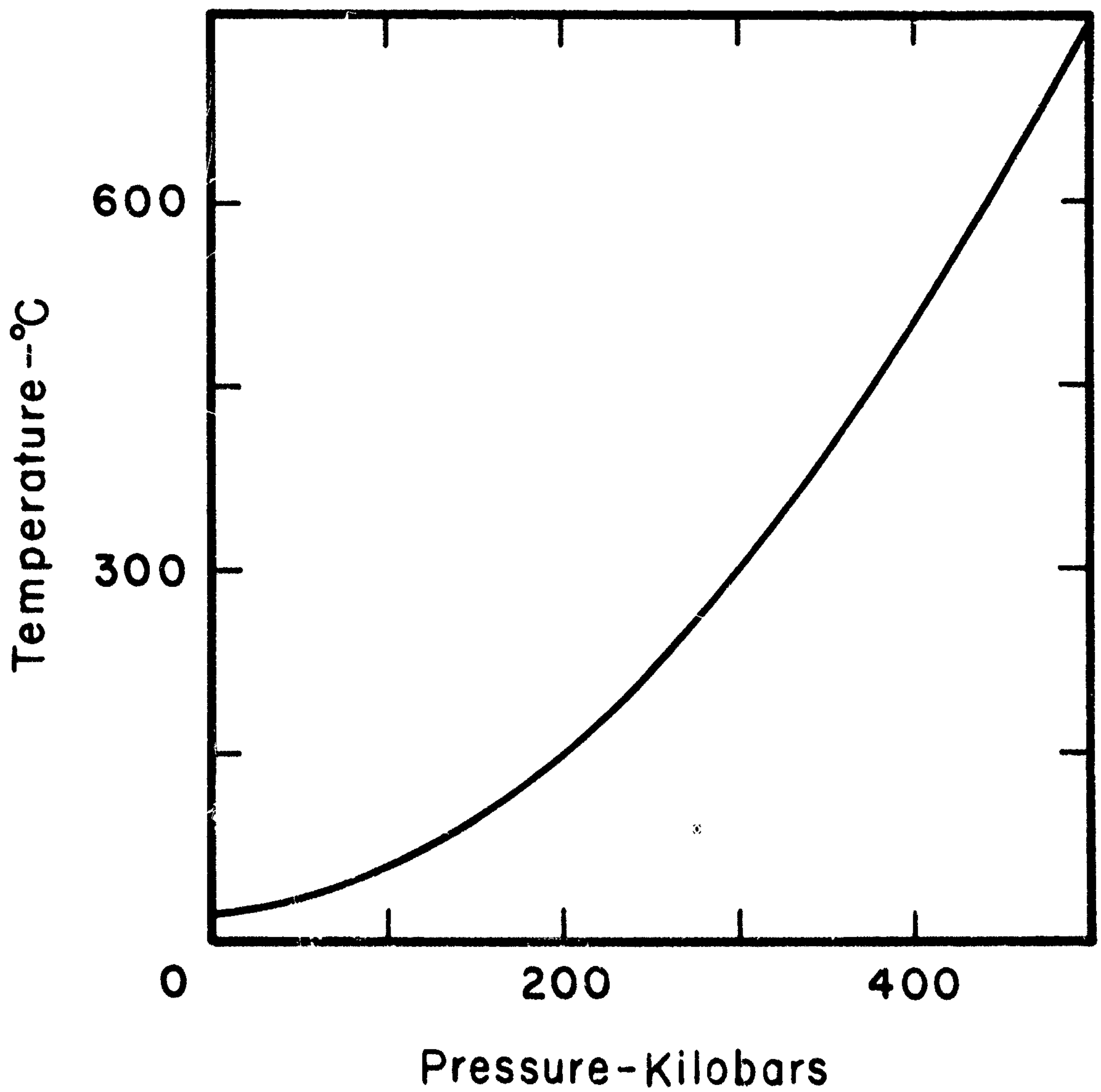
ZIRCONIUM

Temperatures associated with shock

Zirconium

Pressure (kilobars)	Temperature behind shock (C°)	Residual temperature (C°)
0	20	
100	55	
150	92	
200	143	
250	214	
300	298	
350	395	
400	503	
450	616	
500	737	

Source: Rice, McQueen and Walsh, 1958



ZIRCONIUM

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