CLEARINGHOUSE FOR FEDERAL SCIENTIFIC AND TECHNICAL INFORMATION CFSTI
DOCUMENT MANAGEMENT BRANCH 410.11

LIMITATIONS IN REPRODUCTION QUALITY

ACCESSION # 605 020

☒ 1. WE REGRET THAT LEGIBILITY OF THIS DOCUMENT IS IN PART UNSATISFACTORY. REPRODUCTION HAS BEEN MADE FROM BEST AVAILABLE COPY.

☐ 2. A PORTION OF THE ORIGINAL DOCUMENT CONTAINS FINE DETAIL WHICH MAY MAKE READING OF PHOTOCOPY DIFFICULT.

☐ 3. THE ORIGINAL DOCUMENT CONTAINS COLOR, BUT DISTRIBUTION COPIES ARE AVAILABLE IN BLACK-AND-WHITE REPRODUCTION ONLY.

☐ 4. THE INITIAL DISTRIBUTION COPIES CONTAIN COLOR WHICH WILL BE SHOWN IN BLACK-AND-WHITE WHEN IT IS NECESSARY TO REPRINT.

☐ 5. LIMITED SUPPLY ON HAND: WHEN EXHAUSTED, DOCUMENT WILL BE AVAILABLE IN MICROFICHE ONLY.

☐ 6. LIMITED SUPPLY ON HAND: WHEN EXHAUSTED DOCUMENT WILL NOT BE AVAILABLE.

☐ 7. DOCUMENT IS AVAILABLE IN MICROFICHE ONLY.

☐ 8. DOCUMENT AVAILABLE ON LOAN FROM CFSTI (TT DOCUMENTS ONLY).

☐ 9.

NBS 9/64

PROCESSOR: PM

THE IMPACT OF LARGE METEORITES

J. J. Gilvarry and J. E. Hill

P-836

3 April 1956

The RAND Corporation
1700 MAIN ST. • SANTA MONICA • CALIFORNIA

ABSTRACT

The impact of large meteorites on the moon or earth is discussed, on the basis of a one-dimensional idealization of the flow problem, in which a plane shock wave in both meteorite and impact surface is considered. Conditions are discussed under which such a model can yield physically valid estimates of pressure and temperature generated on explosive impact of meteorites. Computations are carried out for an equation of state and internal energy from the statistical Thomas-Fermi atom model; departures from complete degeneracy are taken into account by means of results of a first-order perturbation with respect to temperature. It is assumed that the meteorite and impact surface are composed of the same pure element, taken as Si, Fe, and an average element (in a sense defined) for meteorites. The range of impact velocity considered goes up to the limit possible for meteorite origin in the solar system, which is well in excess of Whipple's estimates of mean atmospheric velocity for meteorite falls. Over this range, values of compression ratio, pressure, and temperature behind the shocks, and of shock velocities, are exhibited as a function of impact velocity; at the lowest and the highest velocities, results are only qualitative. Shock temperatures computed for Fe agree reasonably with extrapolation of experimental data of Walsh and Christian for Cu at lower pressures. The results yield pressures and temperatures of explosive magnitude behind the shock waves, in confirmation of the views of Gifford and Baldwin.

THE IMPACT OF LARGE METEORITES

I. INTRODUCTION

The original suggestion that the craters of the moon were formed by explosions associated with the impact of large meteorites on the lunar surface can be credited to Gilbert (1893) and to Gifford (1924, 1930). In an extensive monograph, Baldwin (1949) has put the hypothesis on a strong foundation. He presents powerful arguments against other modes of origin, such as volcanism. Further, he demonstrates that the curve of diameter vs depth for the lunar craters shows a continuous variation, through the analogous curve for the terrestrial meteoritic craters, into the corresponding curve for explosion craters on the earth (due to artillery shells and bombs at low energy and accidental chemical explosions at high energy). The prescription, within a certain error, of diameter as a function of depth for all these craters by one analytic function, corresponding to the Baldwin curve, yields a strong argument for a common genesis in an explosion.

To justify fully the empirical arguments of Gifford and Baldwin, it remains to show by direct computation from physical laws that impact of large bodies on the moon or the earth with astronomically possible velocities actually produces temperatures and pressures of explosive magnitude. The explosion that forms a large lunar or terrestrial meteoritic crater arises from the high pressures and temperatures behind shock waves generated on meteorite impact. To solve the associated problem in shock hydrodynamics to any approximation, it is necessary to assume an equation of state (and a corresponding form of the internal energy) for the material of the meteorite and the impact surface. Gold (1955) has made computations based on an equation of state corresponding to an ideal gas of dissociated nuclei and electrons. However, the compressions and temperatures one expects (at least for the lower impact velocities) are such that the electron gas should be relatively degenerate, since this gas is strongly degenerate in a metal under standard conditions. The purpose of this paper is to present computations of the pressures and temperatures attained in the impact of large meteorites, based on an equation of state (Gilvarry 1954a; Gilvarry and Peebles 1955) obtained from the statistical Thomas-Fermi model of the atom. In this equation of state, departure of the electrons from complete degeneracy is taken into account by means of a first-order perturbation with respect to temperature; provided the absolute temperature is less than a certain degeneracy limit, the model should be physically applicable for pure elements if the pressure exceeds a limit in the order of megabars. A preliminary description (Gilvarry and Hill 1956) of results has been given. Previous discussions (Baldwin 1949; Urey 1952; Kuiper 1954) of the impact of large meteorites have ignored shock formation in any analytic treatment given.

For simplicity, the meteorite and the lunar surface will be assumed to be composed of the same pure element. As reasonable average values of atomic number, Z = 14 (silicon) and Z = 26 (iron) have been selected, corresponding to stone and iron meteorites, respectively. A hypothetical element "averagium" can be defined by determining the average atomic number of the elements, weighted by their gross relative abundance by mass over the silicate, sulfide, and metal phases of meteorites. From data of Brown (1949), the atomic number of averagium is 18.5. Results are presented for this element in some cases also. Conclusions for averagium should be representative in some average sense, since thermodynamic functions on the Thomas-Fermi model scale with, and thus vary smoothly as, the atomic number Z. Note that thermodynamic functions on this model are insensitive to the physical state of the uncompressed material (presumably pumice-like in the case of the moon).

As a gross simplification to reduce the problem to one-dimensional form, the meteorite will be considered as a right cylinder whose base impinges upon the surface of the moon or earth. A plane shock wave enters the cylinder along its axis, and a plane shock wave enters the surface of the moon or earth. This idealized model will apply to the impact of a large meteorite of roughly spherical shape, for a time sufficiently short so that the distances traversed by the shocks in the meteorite and impact surfaces are small compared to a linear dimension of the impinging mass. For times sufficiently long so that the shock in the meteorite reaches the rear surface (from which a rarefaction wave arises in this case), the idealization loses physical validity, since appreciable lateral motion of the meteoritic material can exist, and the shock wave can no longer be regarded as plane. A basic assumption which will be made is that the shock pressure exceeds the yield stress of the material, so that the colliding masses can be treated as fluid. The validity of this assumption is borne out by the experimental work of Walsh and Christian (1955) and of Minshall (1955) on shock waves in metals.

The maximum velocity of a meteorite before impact on the moon or earth will be taken as the sum of the heliocentric parabolic limit (42.2 km/sec) corresponding to the mean distance of the earth-moon system, and the orbital velocity (29.7 km/sec) of the earth-moon system about the sun, or about 72 km/sec. In the case of the earth, this figure neglects the small accelerating effect (contributing about 1 km/sec) of the earth's gravitational field and the decelerating effect of the atmosphere; in the case of the moon, it neglects the effect of the moon's gravitational field and its orbital velocity about the earth. The limit in question is in agreement with the general results (Lovell, 1954) of measurements of meteor velocities in the earth's upper atmosphere by photographic and radio techniques. If the bodies that caused the lunar and terrestrial meteoritic craters were members of the solar system, it follows that this approximate figure represents the maximum selenocentric or geocentric velocity possible; this limit may be reduced substantially if it is established that meteorites come from orbits similar to those of the observed minor planets (Whipple 1955). The choice made here of upper limit on the velocity carries no implication on the mean value. In the absence of an atmosphere, the minimum velocity for impact normal to the surface is the escape velocity (2.4 km/sec and 11.2 km/sec for the moon and earth, respectively). The effects of atmospheric retardation for the earth, and of obliquity of impact for both moon and earth, reduce the lower limit on the normal velocity. In what follows, the impact will be assumed to correspond to a normal plane shock.

It should be emphasized that the results presented here are valid only when shock formation is the dominant mechanism of energy transfer, that is, for relatively large velocities of impact. To obtain an idea of a possible lower limit on velocity, one can note that Allen, Rinehart, and White (1952) have accelerated steel pellets with masses of a few grams to velocities of 6 km/sec by a shaped-charge technique; they observed severe deformation of the impinging pellets but no certain evidence of explosive impact, in agreement with previous results (Rinehart 1950; Rinehart and White 1952) at somewhat lower velocites. The figure of 6 km/sec noted seems to be the upper limit on velocity obtained to date under laboratory conditions for small solid projectiles. For the same velocity, however, experiments with pellets may not necessarily be representative of conditions for impact of the large masses responsible for production of the larger craters. An efficiency question may enter for smaller bodies, in the sense that the instantaneous pressure generated on impact may not have sufficient time to overcome the inertia of the material and explode the body, before the pressure is relieved by rarefactions from the rear and sides. For plane shocks obtained by an explosive lens system, Walsh and Christian (1955) determined particle velocities of the order of 1 km/sec for shock pressures up to about 500 kilobars; thus impact velocities of this order may be sufficient for explosive impact if the meteorite is large enough to yield a sustained plane shock.

The most one can say, therefore, is that the lower limit on impact velocity for validity of the treatment given possibly lies between 1 and 10 km/sec and may depend on meteorite size; one can note that the velocity at which the kinetic energy per unit mass equals the energy release (about 5×10^{10} erg/gm) of TNT is about 3 km/sec. Consequently, collision of a meteorite with the surface of the earth does not necessarily result in an explosion, since geocentric velocities down to low values are possible as a result of atmospheric deceleration. A continuous gradation must exist, from energy transfer by shock formation at the higher velocities, to transfer by plastic yield or elastic strain at the lower velocities (Whiffen 1948; Minshall 1955). The likelihood of survival of a meteorite to impinge with low fractional mass loss at high velocity must be strongly favored by large initial size, since the decelerating, melting, volatilizing, and ablating effects of the atmosphere vary as the surface area, while the mass and energy vary as the volume.*

II. EQUATION OF STATE

On the first-order temperature-perturbed Thomas-Fermi model for a pure element, the pressure P and internal energy U per atom for a volume v of the atom are

$$P = p\left[1 + (5/2)(\sigma + 2\tau)\zeta(kT)^2\right] , \tag{1a}$$

$$U = u + (15/2)pv(\sigma + 2\tau + 3\omega)\zeta(kT)^2 , \tag{1b}$$

respectively, where the leading terms p and u are the corresponding values for the volume v at zero value of the absolute temperature T. Values of p and u depend on

---

*The large fractional mass losses predicted for <u>large</u> meteorites by computations (Thomas and Whipple 1951) based on values of the coefficient of heat transfer corresponding to an accommodation coefficient of the order of unity, should be accepted only with hesitation. A meteoroid large enough to survive the domain of long mean free path enters a region in which hydrodynamic flow sets in and a detached shock (head wave) forms in front of the body. The hot compressed air behind the head wave furnishes an additional sink for the energy which, in the domain of long mean free path, is largely absorbed by the meteoroid. This effect can reduce the coefficient of heat transfer and the resulting mass loss by orders of magnitude, as shown by C. Oasley, Jr. (unpublished).

the solutions of the zero-temperature Thomas-Fermi equation, and can be obtained as a function of v from fitted functions given by Gilvarry (1954a). In the temperature-perturbation terms of order T^2, k is Boltzmann's constant, and ζ is a quantity having dimensions of the reciprocal square of an energy and depending only on the atomic number Z. The perturbation parameters σ, τ, and ω depend on the solutions of the first-order temperature-perturbed and the zero-temperature Thomas-Fermi equations, and they can be obtained in terms of v from fitted functions given by Gilvarry and Peebles (1955). For validity of this temperature-perturbed Thomas-Fermi model, the absolute temperature T must satisfy $T \ll T_o$, where the degeneracy limit T_o is a function of v defined in terms of the Thomas-Fermi variables ϕ_b and x_b by

$$Z^{-4/3}\, kT_o/R = 8(2/9\pi^2)^{1/3} \phi_b/x_b \quad , \tag{2}$$

in which R is the Rydberg. The quantity kT_o is the chemical potential of the atom at zero temperature. Perturbation terms of higher order can be included by means of a general perturbation method (Gilvarry 1954a; 1954b), to permit correspondingly greater relaxation of the condition $T \ll T_o$.

As will appear, the parameter which characterizes to large extent the effect of the first-order temperature-perturbation terms in the shock transition is

$$\gamma_e = \frac{1}{3}\,(\sigma + 2\ )/(\sigma + 2\ + 3\omega) \quad , \tag{3}$$

which is a function only of the volume v of the atom. From equations (1), one obtains

$$U - u = \gamma_e^{-1}(P - p)v \tag{4}$$

as a relation connecting the energy and pressure which is independent of the temperature.

On the Thomas-Fermi model, the atom showing zero pressure at its boundary has an infinite radius. Hence, the value v_o of the volume v per atom corresponding to normal density implies a fairly high pressure p_0. The values of v_0 taken were 19.3 and 11.8 $Å^3$ for Z = 14 and Z = 26, respectively*, from densities given by Forsythe (1954); the corresponding values of p_0 are 0.71 and 4.0 megabars for Z = 14 and Z = 26, respectively. One could remove this artificial feature of the Thomas-Fermi model by fairing the pressure-volume curve into that corresponding to the equation of state of Bridgman (1949) at low pressure. In this paper, however, the pressure p_0 implied by the Thomas-Fermi model at normal density will be taken as the initial pressure of the material (at temperature T = 0) before shock; for consistency, the internal energy for the atom at the normal volume v_0 will be taken as the Thomas-Fermi value u_0. Thermodynamic quantities behind the shock will be computed on this basis, except that the final curve for the pressure below 5 p_0 will be corrected by extrapolating it into the value zero for zero impact velocity. Pressures greater than 5 p_0 are high enough to make thermodynamic variables behind the shock approximately independent of the choice of initial pressure, and correspond roughly to the range of high pressure for which the Thomas-Fermi model is physically valid.

III. SHOCK DYNAMICS

On the one-dimensional idealization made, the analytic description of the impact is equivalent to that for normal collision of two plane slabs, which are semi-infinite in opposing directions. Behind the shock in each slab, the flow pattern and the distribution of pressure and temperature are uniform up to the interface between material of the two slabs. Continuity of flow velocity at the interface requires the flow velocity to be constant in the region between the two shocks, and

---

* For averagium, an average v_0 and an average mass per atom for Si and Fe were taken; curves of compression ratio, pressure, and temperature given for this case by Gilvarry and Hill (1956) differ somewhat from those given here because of a slightly different choice of v_0.

continuity of pressure at the interface for the same composition of the two slabs implies that thermodynamic functions are the same behind both shocks. If one slab (referred to as the impact surface) is at rest, and the other (referred to as the meteorite) possesses the velocity V, a Galilean transformation from a frame in the impact surface to one located in the interface at time of impact shows that, in this frame, the interface remains at rest and the particle velocity behind the shock in each slab vanishes, by virtue of the symmetry. By transforming back to the frame fixed in the impact surface, one obtains the result that the particle velocity behind the shock wave in the impact surface and in the meteorite is V/2 (directed into the impact surface in both cases), which likewise is the velocity of the interface between meteoritic material and that of the impact surface. The velocity C' (directed away from the impact surface) of the shock wave in the meteorite is related in magnitude by the equation

$$C' = C + V \qquad (5)$$

with the velocity C (directed into the impact surface) of the shock wave in the impact surface; C represents also the speed of the shock wave in the meteorite with respect to the undisturbed material of the meteorite ahead of it.

Since thermodynamic variables are the same behind the shocks in both media, it is necessary to satisfy the Rankine-Hugoniot equations explicitly only for the shock wave in the impact surface, which moves with velocity C into undisturbed material and imparts to it a velocity V/2. The Rankine-Hugoniot equations (Courant and Friedrichs 1948) corresponding to conservation of mass, momentum and energy at this shock front are

$$(C - V/2)/v = C/v_o, \qquad (6a)$$

$$(P - p_o)v_o = \frac{1}{2}\, m\, CV, \qquad (6b)$$

$$U - u_o = \frac{1}{2}\,(P + p_o)(v_o - v), \qquad (6c)$$

respectively, where m is the mass of an atom. The initial state ahead of the shock corresponds to T = 0 and $v = v_o$ with the initial pressure and energy per atom chosen as the values p_o and u_o, respectively, as discussed previously. The final state behind the shock corresponds to a volume v per atom, a pressure P, and an energy U per atom which are connected with the non-vanishing temperature T behind the shock by the Thomas-Fermi equations (1).

The mechanical shock conditions (6a) and (6b) yield

$$C^2 = m^{-1}V^2(P - p_o)/(v_o - v) \tag{7}$$

as an expression for the shock velocity, and also provide the relation

$$(P - p_o)(v_o - v) = \frac{1}{4} m V^2, \tag{8}$$

in which the shock velocity and energy U per atom do not enter. In addition to the last equation, conjunction with the thermodynamic shock condition (6c) of the constitutive equation (4) from the Thomas-Fermi model yields a second relation in which the shock velocity and the energy U per atom do not enter. The eliminant of these two relations with respect to P is

$$Q(v) = \frac{1}{4} m V^2, \tag{9}$$

where

$$Q = \frac{(p - p_o)(v_o - v) + \gamma_e \left[p_o(v_o - v) - (u - u_o)\right] (v_o - v)/v}{1 - \frac{1}{2} \gamma_e (v_o - v)/v}$$

In addition to dependence on thermodynamic variables v_o, p_o, and u_o associated with the initial state, Q depends on the final state behind the shock only through v, p, u, and γ_e, which are all functions only of v; hence equation (9) fixes the volume v per atom behind the shock uniquely as a function of impact velocity V.

The method of solution of the shock equations used in this paper is to plot Q(v) from equation (10) for a particular atomic number Z against the volume v per atom. The value of v behind the shock for a particular impact velocity V is obtained graphically as the one satisfying equation (9). The corresponding temperature T behind the shock is determined by

$$\zeta(kT)^2 = (2/3)(\sigma + 2\gamma)^{-1} \left[Q/p(v_o - v) + p_o/p - 1\right] , \tag{11}$$

which follows from equations (8) and (9) with use of equation (1a) for P. With the temperature known, the pressure P behind the shock is fixed by the Thomas-Fermi equation (1a), and the relation (8) is available as a check.

IV. NUMERICAL RESULTS

On the basis of the preceding theory, the corresponding compression ratio $\eta = v_o/v$ is shown in Figure 1 for Z = 14, 18.5, and 26 as a function of meteorite velocity V up to the maximum value 72 km/sec noted above. The pressure P (in megabars) behind the shocks is shown likewise; the dashed portions of the curves (for pressures below 5 p_o) were extrapolated into the origin. For comparison with P, values of p obtained in the course of solution of the shock equations are shown (dot-dashed) in Figure 1 for Z = 14 and Z = 26; p is the pressure the material behind the shock would have at the corresponding compression ratio if its temperature were zero. It is clear from the order of magnitude of the pressures shown in Figure 1 that the yield stresses of the materials are exceeded by a wide margin, in general.*

The absolute temperature T behind the shocks is shown in Figure 2 as a function of impact velocity for Z = 14, 18.5, and 26. The degeneracy limit T_o of equation (2), relative to which T must be small for validity of the temperature-perturbed Thomas-Fermi model, is shown likewise. It is seen that the condition $T \ll T_o$ is satisfied reasonably well at the lower impact velocities, but that T tends to become comparable to T_o at the higher velocities. No reason exists, however, to believe that the pressures of Figure 1 and the temperatures of Figure 2 shown for the region of higher impact velocity are not qualitatively correct, as follows from a comparison (Latter 1955) of results of the temperature-perturbed theory with

---

*Whiffen (1948) finds a pressure of about 6.4 kilobars for the dynamic compressive yield stress of mild steel, and Minshall (1955) reports comparable values.

numerical results of the Thomas-Fermi theory as generalized to arbitrary temperature by Feynman, Metropolis, and Teller (1949). The comparison shows that pressures from the temperature-perturbed theory are qualitatively correct so long as the total pressure P does not exceed about twice the zero-temperature pressure p; one notes from Figure 1 that this criterion is met reasonably for the cases Z = 14 and Z = 26 where p is given.

As a check on the computed shock temperatures, the only experimental data available are those of Walsh and Christian (1955) on Al, Cu, and Zn for shock pressures up to about 500 kilobars. The curve of shock temperature vs pressure for Cu (Z = 29) should be reasonably close to that for Fe (Z = 26) in the range of very high pressure where the Thomas-Fermi model becomes physically valid, since thermodynamic functions on this model scale with atomic number Z (which differs only by about 10 per cent for the two cases in question). At low pressure, the coefficients a and b in the Bridgman (1949) isothermal equation of state, $-(v - v_0)/v_0 = aP - bP^2$, are roughly the same for the two metals (Slater 1949). Thus, the curve of shock temperature vs pressure for Cu should be close to that of Fe at the lower pressures, since values of the density, the volume coefficient α of thermal expansion, the parameter $(\partial P/\partial T)_v = \alpha/a$, and the heat capacities, which enter (Walsh and Christian 1955) in determining the difference between the isothermal equation of state and the Hugoniot relation, are approximately the same for the two metals under normal conditions (Forsythe 1954). Hence, one expects the data of Walsh and Christian for Cu, when extrapolated, to fair smoothly into the computed curve of shock temperature for Fe, and Figure 3 shows that such is actually the case when the extrapolation is carried out against pressure. The dashed line through the data points of Walsh and Christian has been terminated in a point of tangency on the curve (full) of computed shock temperature, at a pressure of 5 p_0. To determine the curve of shock temperature for Fe down to the low temperatures shown, it was necessary to extrapolate temperatures given by equation (11) into those given by the Taylor expansion at small compression.

The velocities C and C' of the shock wave in the impact surface and the meteorite, as defined by equations (7) and (5), respectively, are shown in Figure 4 for Z = 14 and Z = 26 as a function of impact velocity V. Both shock velocities are of the same order of magnitude as the impact velocity. The sonic speed c behind the shock is shown (dashed) in Figure 4 for Z = 14 and Z = 26; the values are determined by

$$c = (\epsilon_o pv/m)^{1/2} \left\{ 1 + (5/2) \left[\epsilon_o^{-1} \gamma_e(\sigma + 2\tau) - \frac{1}{3} \epsilon_o^{-1} d\sigma/d\ln v + \frac{1}{5}\tau + \frac{1}{2}\sigma \right] \zeta(kT)^2 \right\} , \quad (12)$$

where ϵ_o is defined (Gilvarry 1954a) as $-d \ln p/d \ln v$. On the Thomas-Fermi theory, the value c_o of c at V = 0 represents the sound speed in the undisturbed material ahead of the shock; the values of c_o shown are roughly of the correct order of magnitude for sound speeds in solids under normal conditions.* One notes that $C > c_o$ for $V > 0$, so that the material velocity relative to the shock front is correctly supersonic ahead of the shock in both the impact surface and the meteorite, as demanded by the Bethe-Weyl conditions (Courant and Friedrichs 1948).

V. DISCUSSION AND CONCLUSIONS

It is clear from the preceding discussion that the results obtained are merely qualitative for the region of high impact velocity, because of the poor approximation entailed in this domain by the first-order temperature-perturbed theory. If one takes a difference between P and p of p/3 as corresponding to tolerable validity of the temperature-perturbed model, the pressures and temperatures of Figures 1 and 2 respectively should be reasonably valid below an impact velocity of about 27 km/sec for Z = 14 and 37 km/sec for Z = 26. The range of lower velocity for a pressure behind the shock of less than 5 p_o corresponds to V < 16 and V < 20 km/sec for Z = 14

---

*Thus c_o for iron is 11 km/sec from the data of Figure 4, as against a sound speed of about 5.9 km/sec measured by Minshall (1955) in steel.

and Z = 26, respectively; in this region, the results are subject to uncertainties arising from incipient departure of the model from physical validity. Thus, only a relatively narrow range exists, from extremes depending on Z of 16 to 37 km/sec in impact velocity, over which the results are relatively unqualified. However, this range includes the values estimated by Whipple (1955) of 16.5 km/sec (from his own data) and 21.3 km/sec (from the data of Astapovich) for the mean atmospheric velocity of meteorite falls, and of 32.2 km/sec for the atmospheric velocity of the minor planet (1566) Icarus if this planet encountered the earth. In any event, the orders of magnitude obtained permit one to draw significant conclusions on the premises of Gifford (1924, 1930) that the impacts are explosive and that they yield circular craters even when oblique.

One sees immediately from Figure 1 that the highest pressures possible are over 100 megabars; in general, the pressures attained are of the order of those reached in the explosion of an atomic bomb (Glasstone 1950). Similarly, the higher temperatures shown in Figure 2 reach values larger than 100,000° C, but they are below the value (1,000,000° C) estimated by Gold (1955); in general, the temperatures shown are above the range (of the order of 5,000° C) corresponding to a chemical explosion, but are below the range (of the order of 10,000,000° C or higher) attained in an atomic explosion (Brickwedde 1955). For the mean atmospheric velocities given by Whipple, the pressures and temperatures are clearly of explosive magnitude. The possibility of such high pressures and temperatures stems from the fact, of course, that the kinetic energy per unit mass of a body moving at the higher speeds considered is far in excess of the explosive energy per unit mass of TNT, as stressed by Gifford (1924). As further emphasis, one can note that a method (Hill and Gilvarry 1956) of scaling dimensions of explosion craters of the earth from that of a prototype crater of known energy release, yields an energy expenditure for the Arizona crater of about 2×10^{23} erg, or about 4 megatons of TNT equivalent, which is comparable with that possible from a thermonuclear explosion.

Minshall, S. 1955, J. Appl. Phys., 26, 463.

Rinehart, J. S. 1950, Pop. Astr., 58, 458.

Rinehart, J. S., and White, W. C. 1952, Am. J. Phys., 20, 14.

Slater, J. C. 1940, Phys. Rev., 57, 744.

Thomas, R. N. and Whipple, F. L. 1951, Ap. J., 114, 448.

Urey, H. C. 1952, The Planets (New Haven: Yale University Press), pp. 26-39.

Walsh, J. M., and Christian, R. H. 1955, Phys. Rev., 97, 1544.

Whiffen, A. C. 1948, Proc. R. Soc. London, A 194, 300.

Whipple, F. L. 1955, in T. R. Kaiser (ed.), Meteors (London: Pergamon Press).

Initially, these pressures and temperatures subsist in a volume which is of the order of the initial volume of the impinging meteorite, if one takes into account the volume swept out by the shock wave in the impact surface, noting the values of compression ratio indicated in Figure 1. The explosive release of the energy initially confined in this volume blasts out the lunar crater. Gifford's conclusion that oblique impacts can yield circular craters then follows if the flow velocities generated by the explosive release exceed any component of velocity parallel to the impact surface which the material may have acquired as a consequence of oblique impact. The initial phase of the release is intractable to calculation because the process occurs at an interface between two different media; as an added difficulty, results of Figure 2 show that the material is relatively degenerate initially, but the equation of state will tend to approach that of an ideal gas under adiabatic release.

Since Figure 4 shows that the velocity C of the shock wave in the meteorite relative to the meteorite itself is of the order of the impact velocity, it follows that the explosive pressures and temperatures are created in a time of the order of that required for the impinging mass to traverse a distance equal to its diameter. Hence, the effective center of the explosion must lie within a depth below the impact surface of the order of a linear dimension of the impinging mass. This fact is of importance in a practical application made (Hill and Gilvarry 1956) of the Baldwin crater relation to the scaling of dimensions of explosion craters in the earth as a function of energy release. As emphasized by Gifford and Baldwin, the original volume of the exploding material will be small relative to the volume of the crater.

By means of a reformulation (Gilvarry 1956a) of the Lindemann law of melting, a method of estimating the fusion temperature at high pressure has been given by Gilvarry (1956b). The method depends on the assumption that the critical ratio of root-mean-square amplitude of thermal vibration to nearest-neighbor distance in the solid at fusion is a constant independent of pressure. On this basis, Figure 5 exhibits as a function of impact velocity the melting temperature T_m behind the shock corresponding to the compression ratio η of Figure 1, for Z = 14 and Z = 26; also shown is the melting temperature T_m' behind the shock corresponding to the pressure P of Figure 1.* One notes that the shock temperatures shown exceed the fusion temperatures corresponding either to the same compression or the same pressure. This method of estimating the melting temperature does not permit any reliability at the lower impact velocities, because of the uncertainties arising from the use of the Thomas-Fermi model. However, the corresponding extrapolation (shown dashed below a velocity corresponding to a pressure of 5 p_0 behind the shock) of the fusion curves shows no inconsistency with the postulated mechanism of Urey (1952) for formation of the lunar maria, by large planetesimals impinging with normal components of velocity low enough so that the temperature of the material merely reaches the fusion temperature. Although this result lends some plausibility to Urey's mechanism, different impact processes have been suggested by Baldwin (1949) and Kuiper (1954), and the possibility of a subsidence mechanism has been stressed by Alter (1956).

In this paper, the explosive nature of meteorite impacts at high velocity has been shown from the laws of hydrodynamics and quantum statistical mechanics, rather than by the empirical considerations of Gifford and Baldwin. In spite of their qualitative nature, the results bear out the fundamental correctness of the picture of the origin of lunar and terrestrial meteoritic craters, as given by Gifford and Baldwin.

The authors wish to acknowledge valuable discussions of this problem with Dr. R. B. Baldwin, and with Dr. A. Latter, Dr. W. G. McMillan, and Dr. C. Gasley. Thanks are due Dr. H. K. Kallman and particularly Dr. F. R. Gilmore for critical discussion of the manuscript.

---

*The parameter Ω appearing in the equation for the melting temperature given by Gilvarry (1956b) was assigned the average value 0.012 justified in that paper.

REFERENCES

Allen, W. A., Rinehart, J. S., and White, W. C. 1952, J. Appl. Phys., 23, 132.

Alter, D. 1956, P. A. S. P., 68, 38.

Baldwin, R. B. 1949, The Face of the Moon (Chicago: University of Chicago Press).

Brickwedde, F. G. 1955, in H. C. Wolfe (ed.), Temperature, Volume 2 (New York: Reinhold Publishing Corporation).

Bridgman, P. W. 1949, The Physics of High Pressure (London: G. Bell and Sons, Ltd.) p. 169.

Brown, H. 1949, Revs. Modern Phys., 21, 625.

Courant, R., and Friedrichs, K. O. 1948, Supersonic Flow and Shock Waves (New York: Interscience Publishers), pp. 121, 141.

Feynman, R. P., Metropolis, N., and Teller, E. 1949, Phys. Rev., 75, 1561.

Forsythe, W. E. 1954, Smithsonian Physical Tables (Washington: Smithsonian Institution), pp. 145, 155, 291.

Gifford, A. C. 1924, N. Zealand J. Sci. Tech., 7, 129.

_____, 1930, ibid., 11, 319

Gilbert, G. K. 1893, Bull. Phil Soc. Washington, 12, 241.

Gilvarry, J. J. 1954a, Phys. Rev., 96, 934.

_____, 1954b, ibid., 96, 944.

_____, 1956a, ibid., in press.

_____, 1956b, ibid., in press.

Gilvarry, J. J., and Hill, J. E. 1956, P.A.S.P., in press.

Gilvarry, J. J., and Peebles, G. H. 1955, Phys. Rev., 99, 550.

Glasstone, S. 1950, The Effects of Atomic Weapons (Washington: Combat Forces Press), p. 25

Gold, T. 1955, public lecture, University of California, Los Angeles.

Hill, J. E., and Gilvarry, J. J. 1956, to be published.

Kuiper, G. P. 1954, Proc. Nat. Acad. Sci., 40, 1096.

Latter, R. 1955, Phys. Rev., 99, 1854.

Lovell, A. C. B. 1954, Meteor Astronomy (Oxford: Clarendon Press), chaps. 11, 12.

Figure Legends

Figure 1.- Compression ratio η and pressure P behind the shock waves as a function of impact velocity of the meteorite. The quantity p is the pressure the material behind the shock would have at the corresponding compression ratio if its temperature were zero.

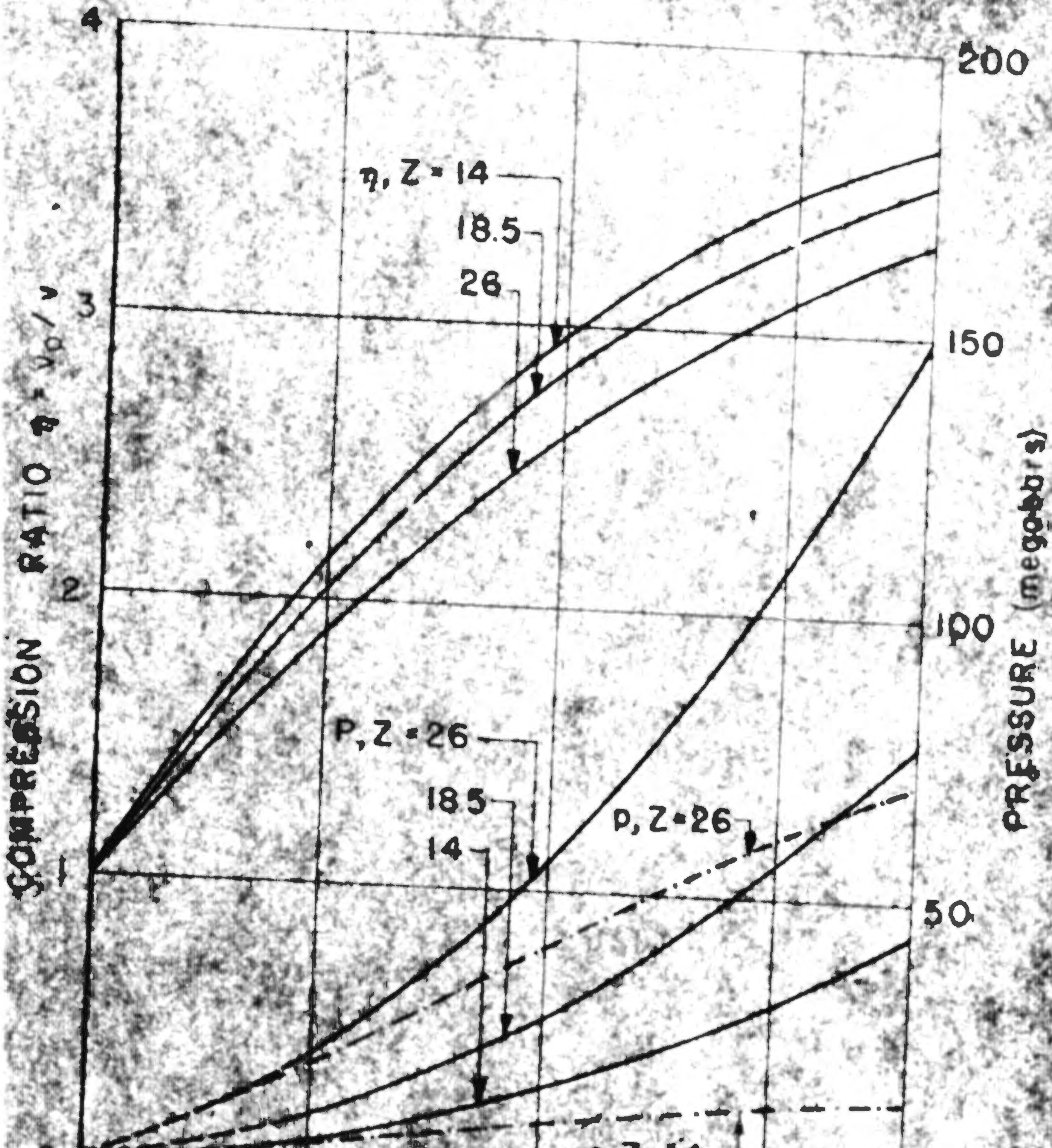
Figure 2.- Absolute temperatures behind the shock waves as a function of impact velocity, with the degeneracy limit for comparison.

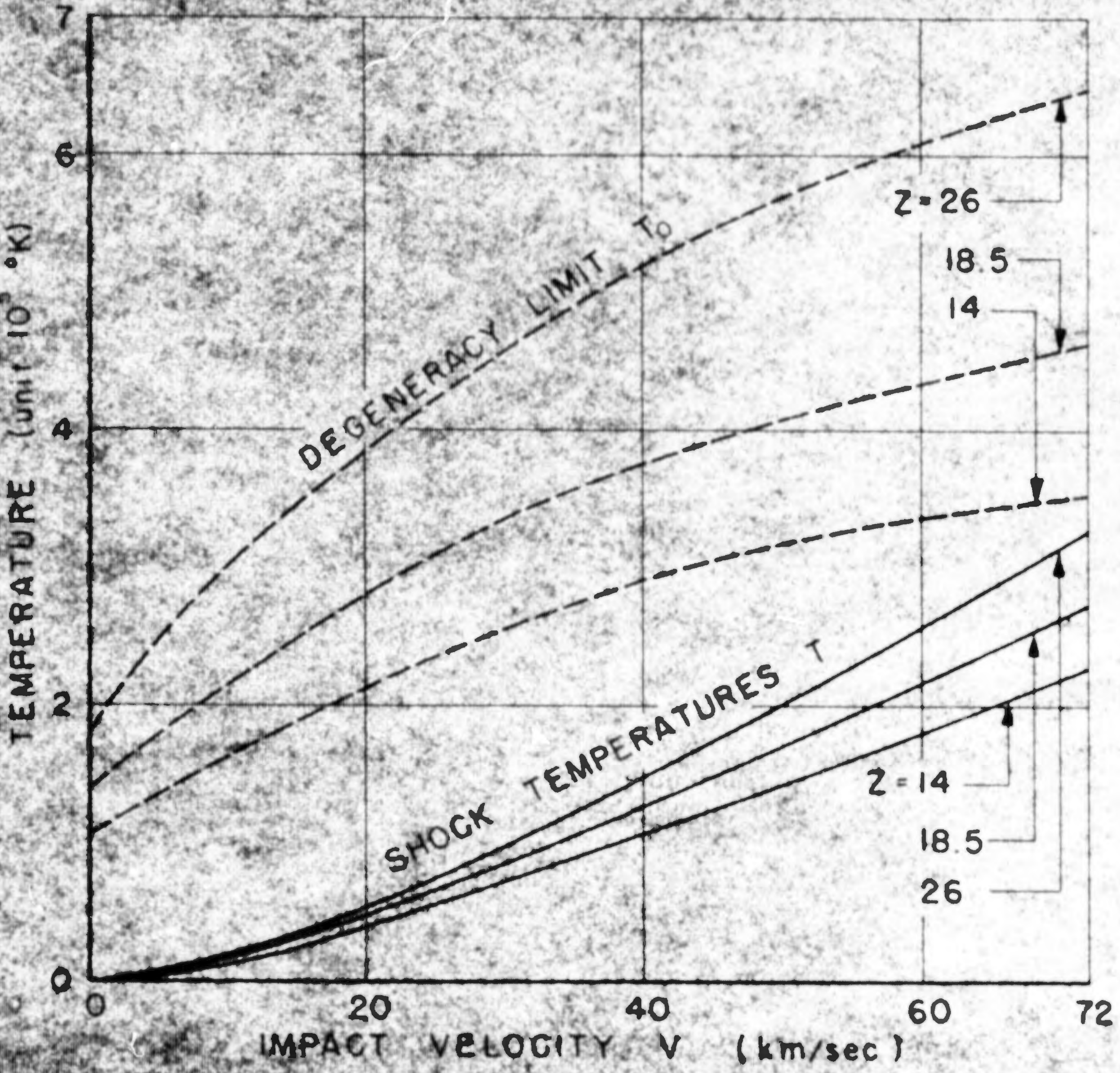
Figure 3.- Centigrade temperatures behind the shock wave as a function of shock pressure for iron, as compared to extrapolation of the data of Walsh and Christian for copper.

Figure 4.- Velocities C and C' of the shock wave in the impact surface and the meteorite, respectively, as a function of impact velocity; c is the corresponding sound speed for the material behind the shock.

Figure 5.- Shock temperatures as a function of impact velocity, for comparison with the fusion temperatures T_m and T_m' corresponding to the compression ratio and pressure, respectively, of Figure 1.

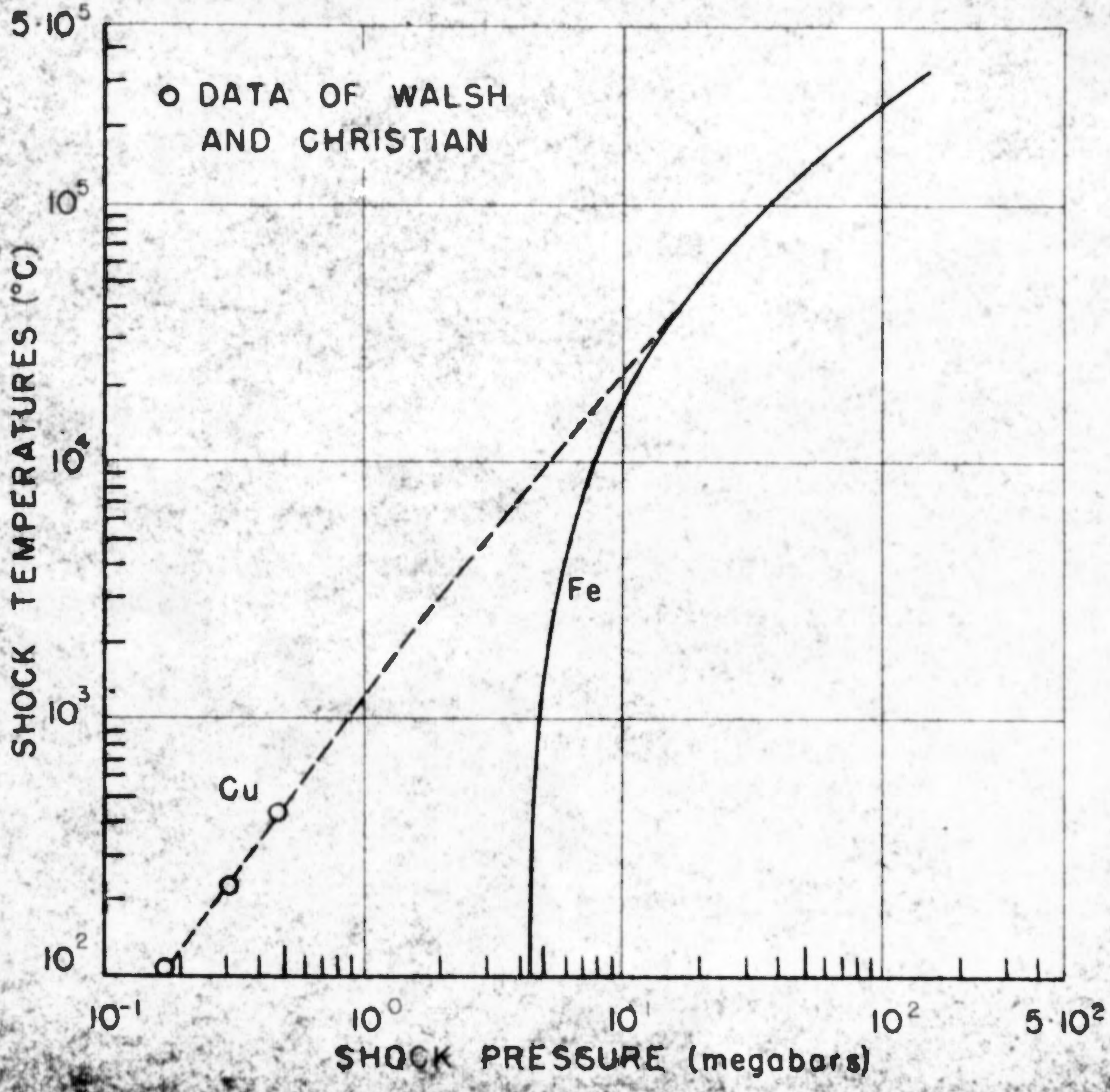
BLANK PAGE


COMPRESSION RATIO η = v₀ / v
PRESSURE (megabars)
IMPACT VELOCITY V (km/sec)
η, Z = 14
18.5
26
P, Z = 26
18.5
14
p, Z = 26
p, Z = 14
0
1
2
3
4
0
20
40
60
72
0
50
100
150
200



TEMPERATURE (unit 10^5 °K)
IMPACT VELOCITY V (km/sec)
DEGENERACY LIMIT T_0
SHOCK TEMPERATURES T
Z = 26
18.5
14
Z = 14
18.5
26
0
2
4
6
7
0
20
40
60
72

Fig 2


5·10^5
10^5
10^4
10^3
10^2
SHOCK TEMPERATURES (°C)
o DATA OF WALSH
AND CHRISTIAN
Cu
Fe
10^-1
10^0
10^1
10^2
5·10^2
SHOCK PRESSURE (megabars)

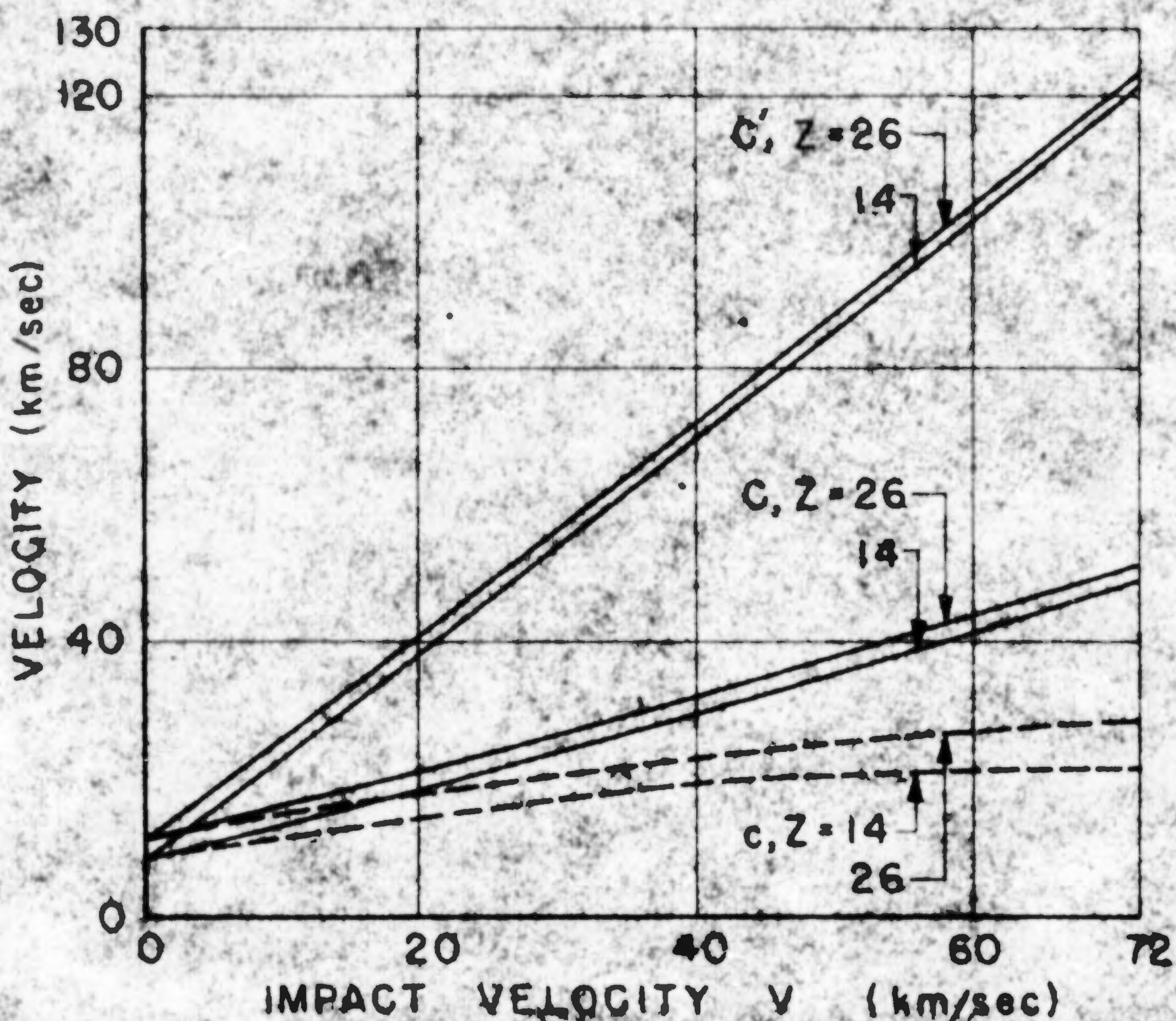
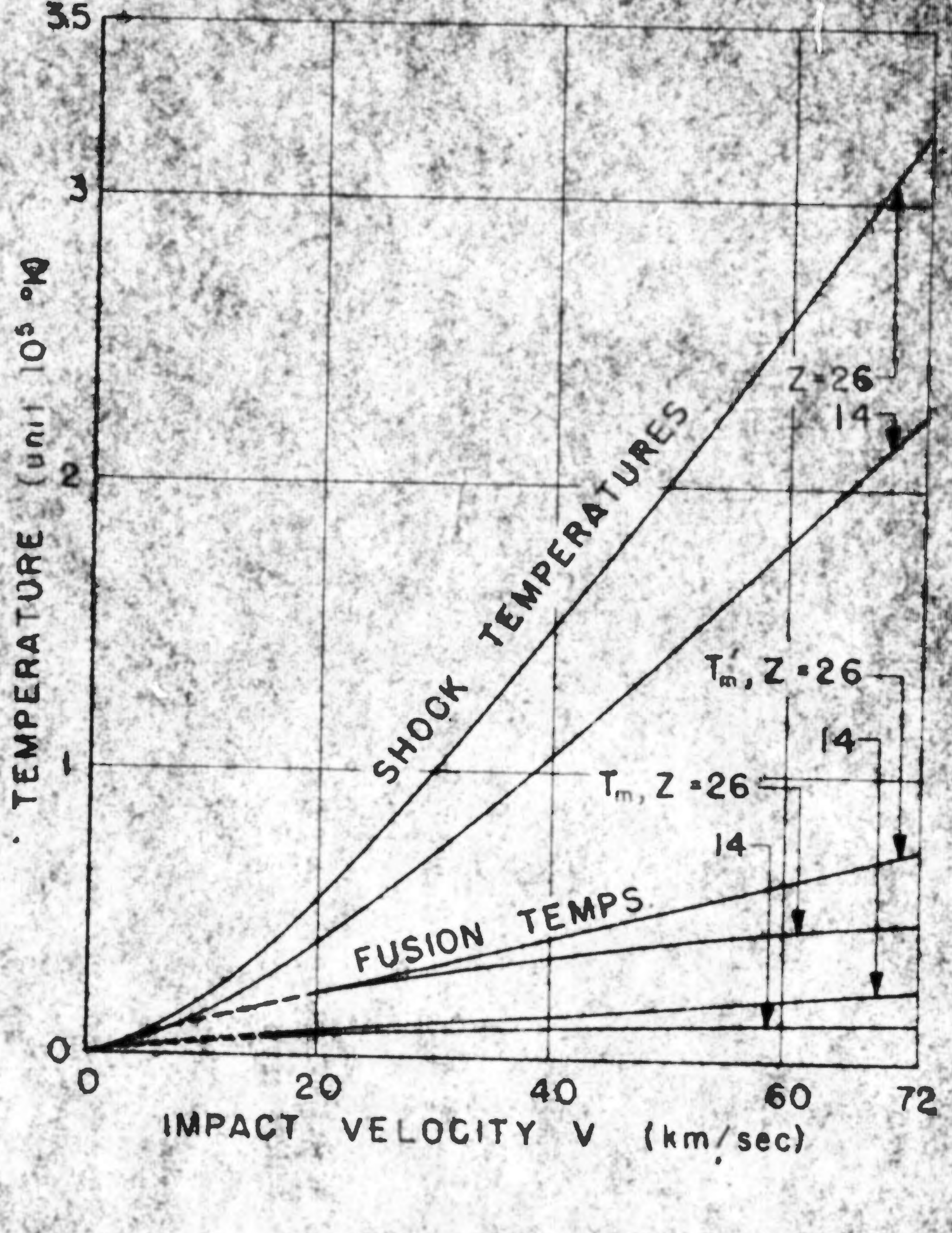


FIG-4

D-836
4-3-56
-22-



TEMPERATURE (unit 10^5 °K)
3.5
3
2
1
0
SHOCK TEMPERATURES
Z = 26
14
FUSION TEMPS
T'm, Z = 26
14
Tm, Z = 26
14
0
20
40
60
72
IMPACT VELOCITY V (km/sec)