

## Shock Melting and Vaporization of Metals \*†

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The effect of initial porosity on shock induction of melting and vaporization is investigated for Ba, Sr, Li, Fe, Al, U, and Th. For the less compressible of these metals, it is found that for a given strong shock-generation system (explosive in contact, or flyer-plate impact) an optimum initial specific volume exists such that the total entropy production, and hence the amount of metal liquid or vapor, is a maximum. Initial volumes from 1.4 to 2.0 times crystal volumes, depending on the metal sample and shock-inducing system, will result in optimum postshock entropies.

The use of explosively induced plane shocks can efficiently and rapidly produce large-volume flows of melted or vaporized metals. In this paper the shocks produced in initially solid and porous metals, which up-

on shocking will result in melting or vaporization, are discussed.

It is shown that for a given strong shock-generating

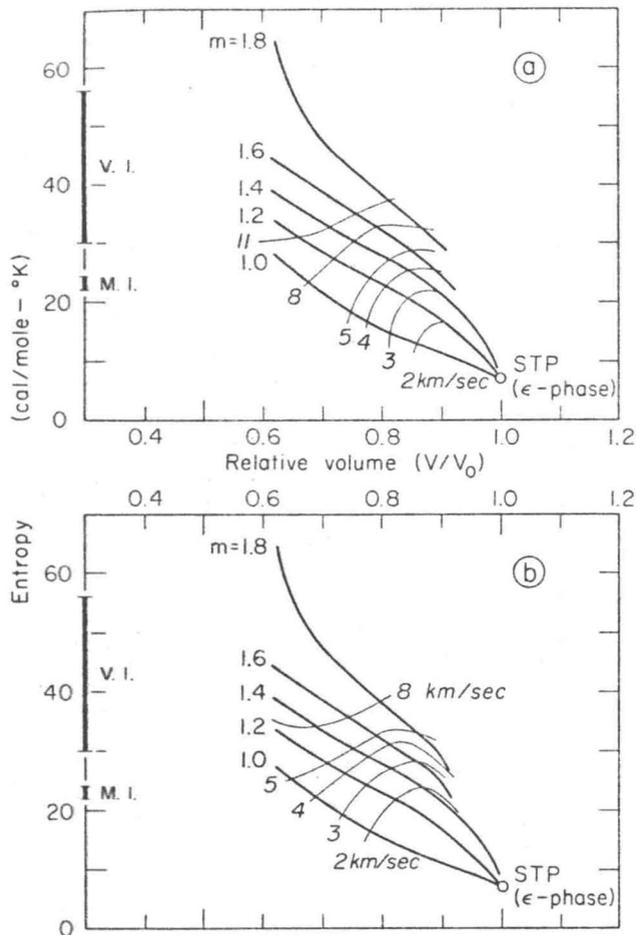


FIG. 1. Shock-induced entropy vs compression for different distention ( $m=1.0$  to  $m=1.8$ ) iron samples. (a) 2024-Al flyer plates; (b) tungsten flyer plates. M.I. and V.I. are the melting interval (Ref. 3) and vaporization interval (Ref. 3), respectively. STP entropy of  $\epsilon$ -phase taken from Andrews (Ref. 10). Entropy data from JANAF tables (Ref. 3).

system (explosive or flyer-plate impact) an optimum initial sample porosity exists for several metals, such that total entropy production, hence liquid or vapor production, is a maximum.

To determine the extent to which a metal may be melted or vaporized upon first being brought to a high-pressure Hugoniot state by a shock and then released to ambient pressure by the following rarefaction wave, it is convenient to calculate the entropy increase due to the shock.<sup>1</sup> The assumption is made that, during the rarefaction phase of the shock and rarefaction process, the specific entropy remains constant (isentropic expansion). The tactic followed is to calculate the entropy increases resulting from shock compression of both initially single-crystal-density nonporous and porous metals and comparing these to entropy-vs-temperature data<sup>2-4</sup> at ambient pressure.

Using the pressure  $p_h$ , volume  $V_h$ , and temperature  $T_h$ , reported for the principal Hugoniot (centered at STP at crystal density) states for the metals,<sup>5-8</sup> the entropies along these Hugoniots, and theoretical Hugoniots centered at a series of initial distentions, are calculated.

It is assumed that the metal's Gruneisen ratio depends only on volume. This Mie-Gruneisen assumption is known to break down<sup>1</sup> both at extremely high temperature ( $\sim 10\,000$  °K) where electrons take on a significant fraction of the thermal energy and, in the context of the Gruneisen equation, at pressure states above which the condition  $\partial p_h/\partial V = -\infty$ , or

$$V/V_0 = \gamma m / (2 + \gamma), \quad (1)$$

occurs. Here  $m$  is the distention, indicating the factor by which the initial specific volume is increased by porosity and  $V_0$  is the crystal specific volume at standard conditions, i.e.,  $m=1$ .

Using the published calculations of shock temperature, the entropy at any point on the Hugoniot is

$$\Delta S_h = \int_0^{T_h} \frac{C_v(\theta_D/T) dt}{T}. \quad (2)$$

By calculating  $\theta_D$  at each Hugoniot volume, from the published Gruneisen parameters, and assuming a Debye-like dependence for  $C_v$ , the specific heat at constant volume, the entropy is obtained from the tabulation of Eq. (2).<sup>9</sup> (Although actual deviations from the Debye assumption will only slightly affect the calculation of entropy, the validity of assumptions regarding the function  $\gamma(V)$ , made by various authors in calculating  $T_h$ , will control the values of entropy which are calculated.) The pressure  $p_m$  and temperature  $T_m$  along porous Hugoniots, from the Mie-Gruneisen equation, are

$$p_m = p_h [1 + (m-1)V_0/V(2/\gamma - mV_0/V + 1)^{-1}], \quad (3)$$

$$T_m = (p_m - p_h)V/3R\gamma + T_h. \quad (4)$$

In Eq. (4), the DuLong-Petit value for  $C_v$  is assumed. At each  $V$ , the entropy increase represented by  $T_m$  along the porous Hugoniots is calculated using the Eq. (2) form. A series of simple calculations [outlined in Eqs. (2)–(4)] were carried out for Fe, Al, Ba, Sr, U, Li, and Th in which the entropy generated by various metal flyer plates impacting specimens, having distentions in the range  $1 \leq m \leq 2$ , at speeds of 1–8 km/sec, were examined. Since for compressible metals (i.e.,

TABLE I. Entropy generation for solid and porous Li and Th for 2024-Al flyer impact.

Element (melting range boiling range) (cal/mole °K)	Flyer- plate velocity (km/sec)	Distention					
		1.0	1.2	1.4	1.6	1.8	2.0
Li							
(9.7–11.3, <sup>a</sup> 20.1–41.5)	2	8.4 <sup>b</sup>	9.7 <sup>c</sup>	8.6	...	...	...
	3	10.2	12.6	13.3 <sup>c</sup>	12.4	...	...
	4	12.1	14.6	15.9	16.3 <sup>c</sup>	...	...
	5	14.0	16.3	17.8	18.6 <sup>c</sup>	...	...
Th							
(29.2–31.1, <sup>a</sup> 41.1–66.0)	2	16.4	22.8	23.6 <sup>c</sup>	20.9	...	...
	3	20.1	26.8	29.3	30.0 <sup>c</sup>	28.0	18.9
	4	23.1	29.1	32.0	33.6	34.0 <sup>c</sup>	30.6
	5	25.6	31.0	33.7	35.7	37.9 <sup>c</sup>	36.1

<sup>a</sup>Reference 2.

<sup>b</sup>(cal/mole °K).

<sup>c</sup>Optimum distention value.

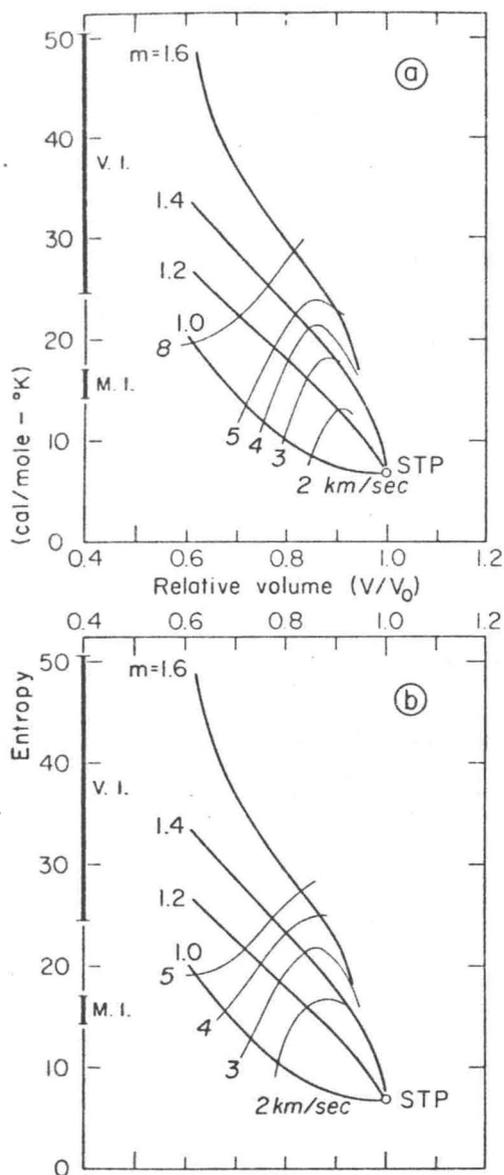


FIG. 2. Shock-induced entropy vs compression for different distention ( $m = 1.0$  to  $m = 1.6$ ) pure aluminum samples. (a) 2024-Al flyer plates; (b) tungsten flyer plates. Symbols are defined in Fig. 1.

Sr, Ba), Eq. (1) is satisfied at relatively low pressures, within the bounds of the Mie-Grüneisen theory the optimum distention for maximum entropy production was not defined. Both Sr and Ba ( $m = 1.0$  and  $m = 1.2$ ) will be completely melted, and partially vaporized upon impact by 3- and 5-km/sec iron flyer plates, respectively. For the less compressible metals the present results are interesting in that, for a given flyer-plate material and impact velocity, an optimum distention exists which will result in a maximum entropy production and hence maximum postshock temperature. This maximum occurs as a result of the competing effects of increasing entropy production and decreasing shock impedance with increasing distention. The significance

in recognizing this extreme can be illustrated by considering the 2- and 4-km/sec impact velocity curves of Fig. 1(b). At 2 km/sec, the impact of a tungsten plate with a single-crystal-density ( $m = 1.0$ ) specimen will not induce melting; however, impact with a  $m = 1.2$  sample will induce incipient melting. Impact with a  $m = 1.4$  sample will produce nearly complete melting. Increasing the distention to  $m = 1.6$  will again result in no shock-induced melting. (See note added in proof.) In the case of a 4-km/sec impact, only an iron sample with a distention near  $m = 1.6$  will undergo partial vaporization. Results for Li and Th are given in Table I. Uranium, although melted by impact of 2-km/sec tungsten flyer plates, will not be vaporized even upon being impacted with a 5-km/sec plate at distentions up to 1.4.

In the case of Fe and Al (Figs. 1 and 2) as well as for the other metals studied, the maxima in the entropy-vs-compression functions are observed to be sharper, with respect to initial distention, at lower impact velocity and flyer-plate shock impedance. Also the distention for which maximum entropy is generated, at a given flyer-plate velocity, occurs at higher distentions with increasing impact velocity.

*Note added in proof.* Beckett has pointed out that  $\theta_0$  for  $\epsilon$ -iron is  $\sim 38^\circ\text{K}$  [G. L. Stepakoff and L. Kaufman, *Acta Met.* 16, 13 (1968)] and not  $175^\circ\text{K}$ , as used in the original shock wave reduction (Ref. B). This will have the effect of lowering the calculated shock-induced entropies.

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<sup>1</sup>Y. B. Zeldovich and Y. B. Raizer, *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena*, (Academic, New York, 1967), Vol. II.

<sup>2</sup>R. Hultgren, R. L. Orr, P. D. Anderson, and K. K. Kelly, *Selected Values of the Thermodynamic Properties of Metals and Alloys* (Wiley, New York, 1963), also revised data addendum, 1970.

<sup>3</sup>JANAF *Thermochemical Tables*, edited by D. R. Stull, Clearinghouse for Federal Scientific and Technical Information, PB 168-370 (Dow Chemical Corp., Midland, Michigan, 1965).

<sup>4</sup>D. R. Stull and G. C. Sinke, *Thermodynamic Properties of the Elements*, Advances in Chemistry Series No. 18 (American Chemical Society, Washington, D. C., 1956).

<sup>5</sup>R. G. McQueen and S. P. Marsh, *J. Appl. Phys.* 31, 1253 (1960).

<sup>6</sup>R. Grover, R. N. Keeler, F. J. Rogers, and G. C. Kennedy, *J. Chem. Phys.* 30, 2091 (1969).

<sup>7</sup>R. G. McQueen and S. P. Marsh, Los Alamos Scientific Laboratory (unpublished data reduced by F. Rogers, Lawrence Livermore Laboratory).

<sup>8</sup>R. G. McQueen, S. P. Marsh, J. W. Taylor, J. N. Fritz, and W. J. Carter, in *High-Velocity Impact Studies*, edited by R. Kinslone (Academic, New York, 1970), pp. 294-419.

<sup>9</sup>G. T. Furukawa and T. B. Douglas, in *American Institute of Physics Handbook*, edited by D. E. Gray (McGraw-Hill, New York, 1963), pp. 4-47 to 4-63.

<sup>10</sup>D. J. Andrews, Ph.D. thesis (Washington State University, 1970) (unpublished).