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SHOCK TEMPERATURES AND THE MELTING POINT OF IRON

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New measurements of the ratio of Fe to LiF and Al₂O₃ anvil thermal diffusivities are used to obtain revised shock temperatures for Fe. New results match Brown and McQueen's (1) calculations of the temperatures of 5000 and 5800K at the 200 and 243 GPa transitions in Fe. New sound speed measurements along the Hugoniot of γ -Fe, centered at 1573K, demonstrate that this phase melts at ~ 70 GPa and ~ 2800 K and the γ phase does not occur above ~ 93 GPa. At higher pressures, perhaps over the entire pressure range of the Earth's molten outer core (132 to 330 GPa), the β (dhcp) phase, and not the ϵ phase, appears to be the solidus phase of pure Fe.

INTRODUCTION

The melting point of iron (Fe) at the pressures of the outer (liquid) core-inner (solid) core (330 GPa) at a depth in the Earth 5150 km was suggested (2) to provide a constraint on the absolute temperature. Initial work on the melting relations in the Fe-Ni-O-S system below 20 GPa (3) indicated that geochemically plausible iron alloys drastically lowered the solidus of Fe from 2200 to 1150K. However, recent measurements (4; 5) indicate a decrease of eutectic melting depression in the Fe-FeO-FeS system at core pressures (>130 GPa).

Brown and McQueen (1) conducted pioneering measurements of the longitudinal wave velocity behind shock waves along the principal Hugoniot (Fig. 1) of Fe and interpreted the 5 and 3.5% decreases at 200 and 234 GPa to the intersection of the Hugoniot with the ϵ to γ , and γ to liquid phase lines. Assumption dependent temperature calculations gave 4100 to 5300 K and 4900 to 6900 K, for the 200 and 243 GPa transitions, respectively.

SHOCK TEMPERATURE MEASUREMENTS

Urtiew and Grover (6) laid the theoretical basis for shock temperature measurements in metals. In

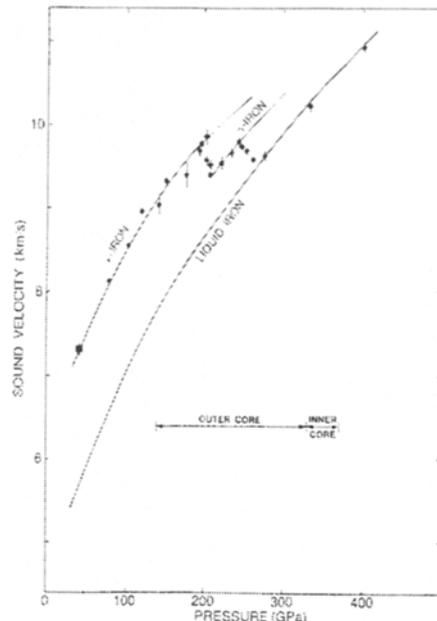


FIGURE 1. Rarefaction velocities for iron along principal Hugoniot as a function of pressure. Circles are present data. The square is from Barker and Hollenbach (7). Brown and McQueen (1) suggested these two phase transitions are related to the temperatures in the Earth as shown in Fig. 2. Copyright 1986, American Geophysical Union.

our experiments a film of metal is deposited upon a transparent anvil material and a shock wave is driven from the metal sample into the transparent anvil.

Lyzenga and Ahrens (8) first reported radiance versus time measurements for such an experimental assembly, for a 51 μm -thick Ag sample sputtered onto a Al_2O_3 anvil shocked to 185 GPa. These experiments demonstrated that the steady interface temperatures predicted by Urtiew and Grover (8) could be obtained via spectral measurements of the grey-body Planck function. Urtiew and Grover (8) showed that the metal Hugoniot temperatures are related to the interface temperatures by

$$T_i = T'_H + (T_a - T'_H)/(1 + \alpha) \quad (1)$$

where T'_H is the Hugoniot temperature of the metal (in the case where the metal and anvil have the same shock impedance), T_a is the Hugoniot temperature of the anvil material and α a correction factor involving the ratio of thermal properties of both media is given by

$$\alpha = \left\{ (\kappa_m \rho_m C_m) / (\kappa_a \rho_a C_a) \right\}^{1/2} \quad (2)$$

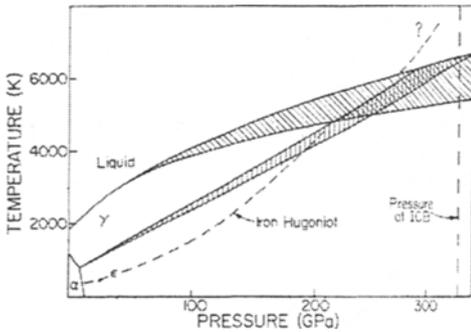


FIGURE 2. Phase diagram for pure iron proposed by Brown and McQueen (9) Reprinted with permission.

where κ_m and κ_a , ρ_m and ρ_a , and C_m and C_a are the thermal diffusivities, densities, and specific heats for the metal and anvil at the compressed interface state, respectively. If the shock impedance of the anvil is lower than the sample (as in our experiments on Fe using Al_2O_3 or LiF anvils), the value of T'_H is replaced by T_R . The temperature achieved upon wave reflection and partial release at the metal film-anvil interface, T_R , is related to Hugoniot temperature by

$$T_R = T'_H \exp \left[\frac{V_H}{V_R} \int \frac{\gamma}{V} dV \right] \quad (3)$$

Similarly, the shock compressed volume is slightly increased upon partial decompression by an amount given by

$$V_R - V_H = \Delta V \cong \frac{(u_R - u_H)^2}{P_H - P_I} \quad (4)$$

where V_H and V_R , and u_R and u_H are the Hugoniot and release states specific volume and particle velocity, respectively. Here γ is the metal's Grüneisen ratio. It appears from Eqs. 1, 2, and 3, that thermal parameters of the metal and anvil are required to relate T_i to T_H . However, if the anvil and sample are even approximately matched in shock impedance, then T_a and T'_H are of the same order, and for iron samples, and LiF and Al_2O_3 anvils, since α is ~ 10 , the second term of Eq. 1 makes only a 10-15% contribution to T_i . Moreover, adiabatic decompression prescribed by Eq. 3, results in T_R being ~ 85 -90% of T_H . Thus, Eqs. 1-4 allow correcting the measured value of T_i and providing for uncertainties in the EOS parameters for the thermal properties of even $\sim 50\%$, affects the resulting values of T_H by only some 10%.

SHOCK TEMPERATURES FOR IRON

Measured (10) values of κ_m/κ_a of Eq. 3, are some 12 to 32% greater than that calculated using the Weidemann-Franz law for κ_m (11) and Debye theory for κ_a (12-14). Revised values of T_H for Fe (Fig. 2) allow a smooth curve to be drawn through the data (of Fig. 6 of Bass et al. (15)) with an addi-

tional two data at 178 and 194 GPa (10). The temperature along the principal Hugoniot below 100 GPa are from Table 3 (1). Points at 200 and 243 GPa correspond to $T_H = 5000$ (4410, 5300) K and $T_H = 5800$ (5620, 6990) K. The uncertainties plotted in Fig. 3 correspond to $\gamma/V = \text{constant} = 20 \text{ Mg/m}^3$ of Table 4 (cases a and b) (1).

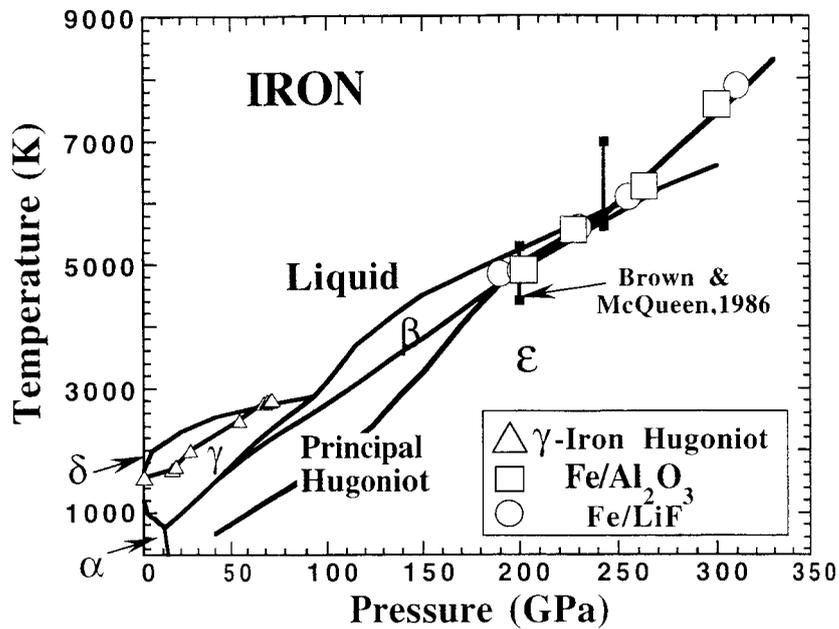


FIGURE 3. Pressure-temperature principal and γ -iron (centered at 1573K) Hugoniot states relative to phase diagram based on Boehler (4) and Saxena et al. (16) Phase transitions of Brown and McQueen (1) now agree closely with the revised shock temperature data for Fe.

PHASE DIAGRAM OF IRON

Fig. 3, also shows the states achieved in our study of preheating γ -Fe (Hugoniot centered at 1573 K) where we measured longitudinal elastic unloading velocities. We find a sharp, 19.7% decrease in compressional wave velocity from 7.71 km/sec upon melting of the initial γ phase at 70 ± 2 GPa and 2800 ± 30 K. This agrees with the phase diagram of Saxena et al. (16) and Boehler (4). Our results are consistent with the γ phase terminating at a γ - ϵ -liquid triple point at ~ 2900 K and ~ 93 GPa (Fig. 3).

CONCLUSIONS

We agree with Boehler (4) that the 200 GPa transition of Brown and McQueen (1) corresponds to the ϵ to β phase change and the 243 GPa transition represents the onset of melting of the β phase. Thus, the solidus iron phase at pressures of the outer core in the 133 to 243 GPa range is probably the β phase. Finally, as shown in Fig. 3, the extent of the pressure stability regime of the β phase is unknown. This phase's field of stability may extend to the pressures of the outer to inner core boundary at 330 GPa or, even to higher pressures, or there may exist a β - ϵ -liquid triple point between 243 and 330 GPa.

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