TABLE II. Critical transformation conditions for iron in the vicinity of 300 K.[a]

	$\alpha \to \epsilon$ (loading)				$\epsilon \to \alpha$ (unloading)		average	
	p_x^{TL} GPa	$\bar{p}^T$ GPa	P^{TL} GPa	η_{TL} %	p_x^{TU} GPa	P^{TU} GPa	P_e^T or $p_x^T\eta_T$ GPa	%
Shock loading								
Bancroft *et al.* (1956)	13.0[b]	⋯	⋯	6.4	⋯	⋯	⋯	⋯
Loree *et al.* (1966a)	12.9	12.5	⋯	6.4	⋯	⋯	⋯	⋯
Barker *et al.* (1974)	12.8	12.4	⋯	6.3	9.8 ± 0.4	⋯	11.3 ± 0.5[c]	10.0
Static loading								
Giles *et al.* (1971)	⋯	⋯	13.3	6.6	⋯	8.1	10.7 ± 0.8	10.3
Mao *et al.* (1967)	⋯	⋯	13	6.8	⋯	⋯	⋯	⋯
Drickamer (1970)	⋯	⋯	11–12	⋯	⋯	⋯	⋯	⋯
Bundy (1975)	⋯	⋯	11.2	⋯	⋯	⋯	⋯	⋯

[a] p_x^T is the observed value of p_x at the transition; $\bar{p}^T$ is the mean pressure calculated from $\bar{p}^T = p_x^{TL} - (2/3)(1-2\nu)/(1-\nu)(\mathrm{HEL})$; ν = Poisson's ratio = 0.28, P^T is the pressure at the initiation of the transition under quasihydrostatic conditions, $\eta_T = 1 - V_{TL}/V_0$, where V_{TL} is the specific volume at the initiation of the transition and V_0 is the initial specific volume ($= 1.27 \times 10^{-4}$ m^3/kg); P_e^T is taken as the mean of P^{TL} and P^{TU}.

[b] Based on lowest pressure input, thickest sample.

[c] Uncorrected for shear strength effects.

scribed earlier by Rinehart and Pearson (1954).

Identification of the high-pressure phase as hcp (ϵ) was suggested from static high-pressure x-ray diffraction measurements of Jamieson and Lawson (1962) and Jamieson (1963a) on the basis of a single diffraction line. Confirmation of the ϵ phase resulted from full x-ray diffraction patterns obtained by Takahashi and Bassett (1964) and Clendenen and Drickamer (1964). Bundy (1965) confirmed general features of the phase diagram with static resistance measurements of the $\alpha \to \epsilon$ and $\epsilon \to \gamma$ phase boundaries to 18 GPa. These he connected directly to the Johnson *et al.* (1962) triple point. The temperature–pressure phase diagram indicated by present measurements and theory is summarized in Fig. 17.

X-ray diffraction studies of α and ϵ phases at high pressure have been used to determine compressibility of both phases and volume change at the transition. Recent work by Mao *et al.* (1967) and Giles *et al.* (1971) shows different results from earlier work by Clendenen and Drickamer (1964).

Evidence that the $\alpha \to \epsilon$ transition pressure measured on static loading is not an equilibrium value has been obtained from x-ray diffraction measurements. (Similar nonequilibrium behavior under shock loading will be noted later.) Giles *et al.* (1971) established an equilibrium pressure of 11.0 GPa for the transition, based on the mean of $\alpha \to \epsilon$ and $\epsilon \to \alpha$ transition pressures observed in a static loading–unloading cycle. This mean pressure is in better agreement with the triple point at 9.2 GPa and 750 K calculated by Blackburn *et al.* (1965) and the high-pressure Mössbauer effect measurements of Millet and Decker (1969) than are the loading measurements. Furthermore, the recent measurement of 5.4% for volume change at the transition (Giles *et al.*, 1971) appears to be in good agreement with thermodynamic conditions at the triple point proposed by Blackburn *et al.* (1965).

Barker and Hollenbach (1974) have recently reported an unusually complete study of wave profiles in impact-loaded iron using projectile impact loading and the VISAR interferometer system. They were able to examine both loading and unloading profiles. Critical values characterizing the transition obtained by Barker and Hollenbach are compared with other shock and static compression measurements in Table II.

Several different features of the various measurements shown in Table II are of interest. Among shock data there is remarkable consistency concerning transition stress and volume. This is especially notable when the difference between early and recent experiments is considered. Early experiments used plane-wave explosive loading while recent ones used projectile impact loading. Early experimenters detected wave arrivals with pins, and recent ones used the VISAR to record surface velocities continuously. Although the measurements of Barker and Hollenbach show considerable detail not observed by Bancroft *et al.*, the best assignments of transition pressure and volume are in excellent agreement. This produces confidence that the value of loading stress at transition is close to 12.8 GPa, which, after a correction for shear strength effects, corresponds to a mean loading pressure of 12.4 GPa.[6]

Shear strength corrections are somewhat uncertain because of our lack of knowledge of modeling plastic deformation in shock-loaded metals, as described in Sec. II.E. However, the correction for iron is carefully considered on the basis of experimental observations of a common volume compression at the transition, independent of the various HEL values observed in low carbon steels (Jones and Graham, 1971). Nevertheless, unloading measurements of Barker and Hollenbach (1974) at stresses below the transition provide evidence that the 0.4 GPa shear strength correction may be too large.

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[6] This excellent agreement among shock loading investigators was recently broken by a report of the transition at 15 GPa by Anan'in *et al.* (1973), as determined with an *in situ* Manganin gauge. Because of reported difficulties with calibration of such gauges the measurements are open to some question. Vereshchagin *et al.* (1969b) have also reported the transition at 15.3 GPa in static loading experiments.

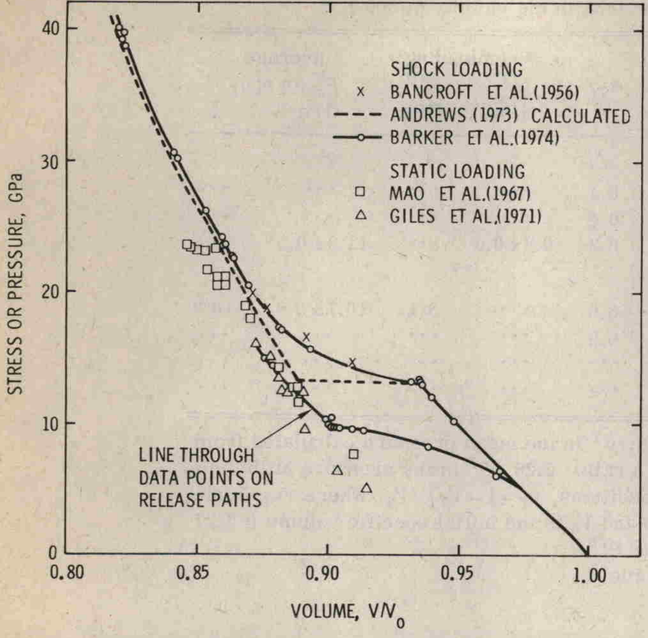

FIG. 18. The stress or pressure versus relative volume for iron is shown as determined by shock and static loading investigations. The dashed line represents the calculated equilibrium curve for shock loading. Shock loading data in mixed phase region between 13 and 20 GPa show a significantly lower compressibility than expected for equilibrium thermodynamic conditions.

The value of the mean pressure of 12.5 GPa is in reasonable agreement with the loading pressure of 13.3 GPa obtained from x-ray diffraction studies [especially when the pressure distribution problems of *in situ* static pressure markers are considered (Jamieson and Olinger, 1971)]; however, the difference between resistance measurements of Drickamer (1970) and Bundy (1975) and shock data are possibly outside experimental errors.

Barker and Hollenbach (1974) measured wave profiles resulting from controlled release of pressure. From these measurements a pressure–volume curve for release of pressure was determined. Their data, shown for loading and unloading in Fig. 18 along with the data of Giles *et al.* (1971), establish the $\epsilon \rightarrow \alpha$ reversal pressure as 9.8 ± 0.4 GPa. This value is in remarkably good agreement with the observations of Giles *et al.* and appears to confirm the concept of a martensitic transition with different forward and reverse pressures as proposed by Giles *et al.* The equilibrium pressure, taken as the mean of loading and unloading transition pressures, is 10.7 ± 0.8 GPa from static x-ray diffraction measurements and is 11.3 ± 0.5 GPa based on shock loading measurements. Measurements of Barker and Hollenbach show complete reversion to α at 5.5 GPa, compared to 4.9 GPa for the static experiments. Thus shock and static data on reversion of $\epsilon \rightarrow \alpha$ on release of pressure are in good agreement. Equilibrium pressure established by Giles *et al.* and by Barker and Hollenbach are in reasonable accord with the calculated triple point of Blackburn *et al.* (1965), as shown in Fig. 17.

Finite transformation rates associated with the iron transition have been recognized for some time. Duvall and Horie (1965) used observed compressibilities in the mixed phase region to calculate equilibrium values of the slopes of phase lines and found poor agreement. Horie and Duvall (1968a) developed a finite transformation rate model (described in Sec. II.F) to calculate wave profiles for iron shocked above the transition pressure. Their calculations indicated need for more detailed wave profile measurements and for further calculations to define appropriate relaxation times. Novikov *et al.* (1965) indicated the need for finite transformation rates to explain their wave profile measurements in iron.

Based on Eq. (55) the most apparent manifestation of finite transformation rate are p_x^{TL} values which depend on sample thickness and input pressure. Loree *et al.* (1966a) recognized "overdrive pressure" and sample thickness effects and reported an equilibrium value of p_x^{TL} based on thick samples and input pressures not far above 13 GPa. Input pressure and sample thickness effects are also apparent in the work of Bancroft *et al.* (1956) and Minshall (1961). Forbes and Duvall (1975) observed thickness effects in samples varying in thickness from 1 to 25 mm.

Barker and Hollenbach (1974) also obtained data to test the dependence of p_x^{TL} on input pressure and sample thickness. Their data, shown in Fig. 19, can be well fitted by Eq. (55) with $t_0 = 0.18\ \mu$s. Although this agreement between the simple transformation rate model and experiments is gratifying, the relaxation time obtained apparently does not correctly predict rise time of the Plastic II wave, $P_{\rm II}$, nor does it correctly predict change in time of arrival of p_x^{TL} with input pressure. Barker and Hollenbach concluded that a fixed transformation rate model may be too simple to fully describe all data for iron; it is, nevertheless, remarkably successful in describing thickness and input pressure effects.

Barker and Hollenbach also observed that the $\epsilon \rightarrow \alpha$ reversal is at least as fast as the $\alpha \rightarrow \epsilon$ transition. They found no evidence for relaxation in stress behind the Plastic I wave as observed by Novikov *et al.* (1965). Rise times of $P_{\rm II}$ waves were about the same in both investigations.

Further evidence for thermodynamic nonequilibrium in iron shock-loaded into the mixed phase region between 13 and 22.5 GPa is obtained from the difference between the observed pressure-volume curve in Fig. 18 and the calculated Hugoniot of Andrews (1973) based on self-consistent equations of state for α and ϵ iron. As previously indicated, hysteresis on static loading and unloading indicates similar nonequilibrium behavior. The observation of thermodynamic nonequilibrium under shock loading in the mixed phase region will be noted for other shock-induced transitions.

Electrical resistance and demagnetization measurements associated with the shock-induced 13 GPa transition have been used to probe the transition. Fuller and Price (1962) measured resistance of iron wires shock-loaded below and above the transition and found an increase in resistance by a factor of about 2.5 in the vicinity of 15 GPa. Wong *et al.* (1968) made similar measurements on iron and interpreted irregularities in the observed resistance below the transition as evidence for partial transformation below 13 GPa. Above 13 GPa their data agreed with those of Fuller and Price. The