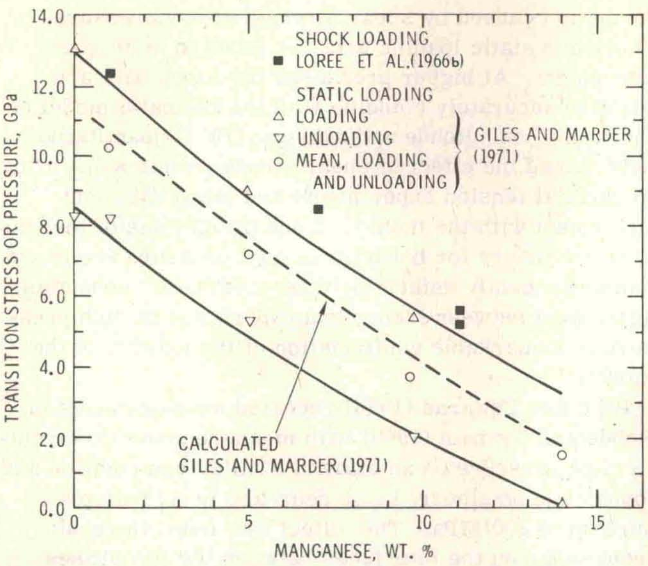

FIG. 21. The effect of alloying iron with manganese is to lower the transition stress or pressure as indicated from static and shock loading measurements. For static loading, the pressure for the reverse transition on unloading is significantly lower than for loading, while the equilibrium pressure taken as the mean of loading and unloading is found to be in good agreement with equilibrium thermodynamic calculations. After Giles and Marder (1971).

found for iron (Giles and Marder, 1971). Their results are compared with shock data (Loree *et al.*, 1966b) in Fig. 21. Agreement between static and shock transition pressures on loading is reasonably good and would be improved if a correction for shear were applied. (An HEL measurement on 10 wt% Mn alloy by Graham with a quartz gauge shows an HEL of 1.0 GPa.) The calculated mean between loading and unloading pressure is shown to agree well with equilibrium pressures calculated by Kaufman's thermodynamic theory. The agreement between calculation and experiment indicates that thermodynamic calculations may prove useful in identifying other pressure-induced iron alloy transitions.

Shock-induced transition measurements in ternary Fe–Ni–Cr alloys are reported by Fowler *et al.* (1961) and by Gust and Royce (1970). Static high-pressure x-ray diffraction measurements on this alloy system are reported by Giles and Marder (1971) and Jamieson (1963a).

Shock demagnetization measurements on a 3.25 wt% SiFe commercial alloy, Silectron, have revealed considerable detail on initiation of the transition, the mixed phase region, and the input pressure at which a single shock wave is formed (Graham, 1968). The detail derived from these measurements results from use of a projectile impact technique to apply input pressures in small increments over a wide range of pressure. The shock-induced demagnetization is shown in Fig. 22. At high pressure the material is in a nonferromagnetic state. Onset of transition stress is at 14.5± 0.5 GPa and transition is complete at 22.5± 1 GPa. Other data indicated that a single shock wave is formed at input pressures greater than 37.5 GPa. According to data in Fig. 22 the transformation does not proceed linearly with pressure in the mixed phase region; initial increments of pressure above 14.5 GPa appear to produce larger amounts of the nonferromagnetic phase than higher pressures. Completion of the mixed phase region at 22.5 GPa is in good agreement with the pressure–volume (R–H) data of Zukas *et al.* (1963). Changes in magnetization below the transition are due to stress-induced magnetic anisotropy (inverse magnetostriction) and pressure dependence of magnetization of the bcc phase.

Christou and Brown (1971) have examined Fe–Mn alloys recovered after shock loading for evidences of retained high-pressure phases. Interpretations by Christou (1972) of the role of defects, determined from annealing studies of shock-loaded Fe–Mn alloys, have been criticized by Schumann (1973).

Investigations of the pressure-induced martensite-to-austenite transition in a low carbon 28.4% Ni–Fe alloy have provided an unusually complete test of the use of thermodynamic data taken at atmospheric pressure to predict a pressure-induced transition. A well-annealed sample of this alloy is stable in the fcc, austenitic, phase at room temperature and atmospheric pressure. Cooling the sample to liquid nitrogen temperatures for many hours transforms it to a metastable, mostly martensite (bcc) phase that is retained indefinitely when temperature is subsequently raised to room temperature. Thus an alloy of fixed chemical composition is available for study in both the bcc and fcc phases, and thermodynamic properties can be determined for both phases. Furthermore, the transition from bcc to fcc in the vicinity of 675 K is accessible for study in a purely hydrostatic apparatus. The transition can also be readily studied with quartz gauge under impact loading in both fcc and bcc phases. Time-resolved wave profile measurements provide information for detailed pressure–volume de-

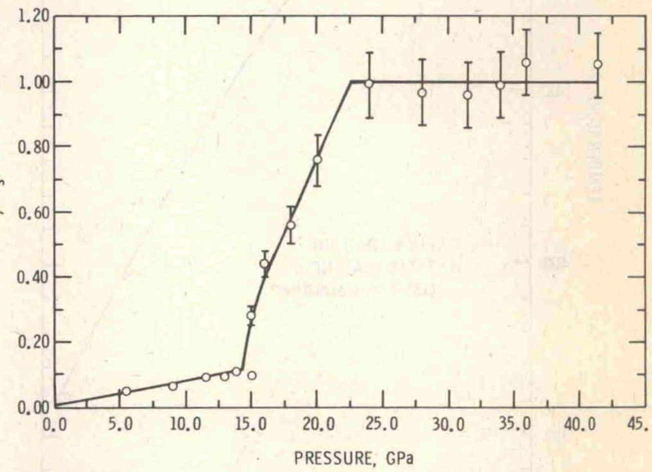

FIG. 22. The indicated relative change in magnetization, M_s, for various shock loading pressures for Fe–3.25 wt% Si shows a phase transition to a nonferromagnetic phase beginning at about 14 GPa. The data indicate that the transition is complete at 22.5 GPa. The apparent magnetization change below the transition is that expected from stress-induced magnetic anisotropy and the change in magnetization with pressure for the bcc phase. The figure illustrates how experiments conducted at closely spaced input pressure can provide independent data on details of ferromagnetic to nonferromagnetic transitions. From Graham (1968).

terminations. These happy circumstances have led to an opportunity to predict and study details of a pressure-induced transition under both static and shock loading.

Stress wave profiles in an impact-loaded bcc 28.4% Ni–Fe alloy measured by Graham *et al.* (1967) showed a region of unusual compressibility from a few hundred MPa to 2.0 GPa. Subsequent investigations of shock-loaded samples by Rohde *et al.* (1968) showed that shear stress resulting from the shear strength was responsible for partial transformation to the fcc phase. Measurements of pressure dependence of the austenite start temperature A_s (the temperature at which bcc martensite begins to revert to fcc austenite under increasing temperature) under static loading by Rohde and Graham (1969) to 2.0 GPa show a large decrease in A_s with pressure. The observed decrease in A_s agrees well with predictions from a simple isothermal model in which transition pressure is determined by free energy and volume differences between the two phases. Predictions from an adiabatic model were not significantly different from the isothermal model. Rohde (1970) extended the investigation on this same alloy to impact loading at temperatures between 298 and 663 K to test the thermodynamic model to higher pressure. His data are shown in Fig. 23. When a correction is made for partial transformation caused by shear strength at low pressure, shock and static loading data are found to be in good agreement. At higher pressures the shock data are found to accurately coincide with the adiabatic model of the transition. Rohde and Albright (1971) quantitatively determined the effect of shear stress on this same alloy in uniaxial tension experiments and found excellent agreement with the theory. Since predictions of thermodynamic theory for behavior at high pressure are based on independently determined thermodynamic constants, agreement between theory and experiment at high pressure is remarkable confirmation of the validity of the models.

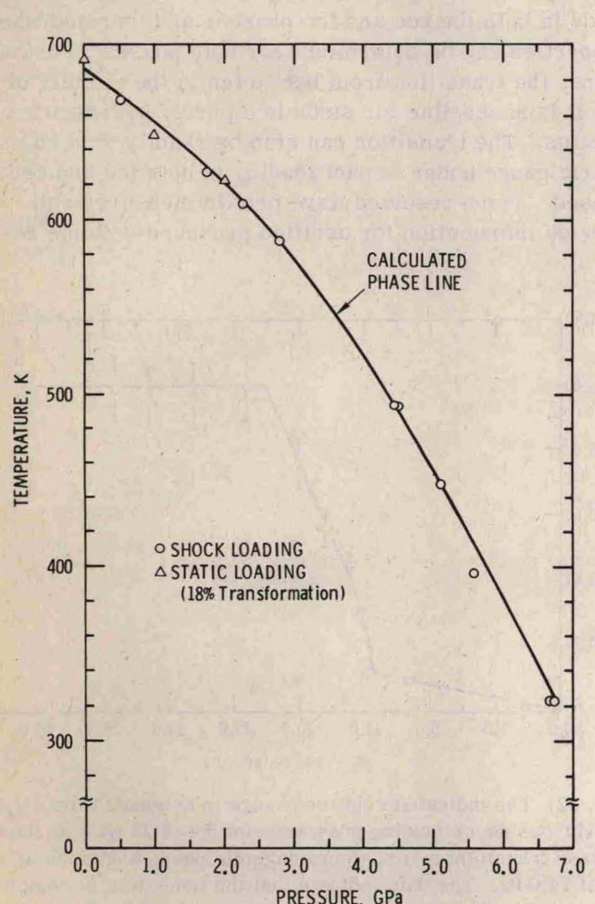

FIG. 23. The calculated and observed phase line for a low carbon Fe–28.4 at. % Ni alloy whose thermodynamic properties can be studied in both the bcc and fcc phases. The behavior under both static and shock loading is found to be in excellent agreement with the phase line calculated from the thermodynamic properties of the two phases. After Rohde (1970).

Pope and Edwards (1973) repeated measurements of Rohde and Graham (1969) with measurements under static high pressure on an alloy of similar composition and found an anomalously large decrease in A_s with pressure up to 200 MPa. This effect was found to result from shear on the interfaces between the two phases (Pope and Warren, 1974). The appreciable effects of shear stresses on the transformation can apparently be modeled well enough under shock loading that accurate predictions of transition pressures can be made from thermodynamic data.

Later work on Fe–Ni alloys by Christou (1973) was found to disagree with previous experimental observations and with previous thermodynamic predictions. A critique of this work has been given by Rohde and Graham (1973).

D. Antimony

Duff and Minshall (1957) referred to shock loading experiments on antimony which showed a transition characterized by an unusually pronounced decay of p_x^{TL} with sample thickness. [The detailed data are reported by McQueen (1964).] Katz *et al.* (1959) confirmed the existence of a multiple wave structure in antimony. A detailed study of the transition was reported by Warnes (1967), whose p_x^{TL} values measured at different sample thickness are shown in Fig. 24. Transition pressure decreases strongly with sample thickness to 20 mm, then decreases more slowly to 50 mm. Based on an extrapolation to thicker samples, Warnes assigned an equilibrium p_x^{TL} of 8.8 GPa. This value is probably a few hundred MPa high, since it is based on average shock velocity determinations. Application of a shear strength correction yields a mean pressure lower by about 100 MPa.

Static high-pressure data indicate a rhombohedral to simple cubic transition completed in the vicinity of 7.0 GPa (Vereshchagin and Kabalkina, 1965), followed by a cubic to hcp transition in the vicinity of 8.3 to 8.8 GPa (Vereshchagin and Kabalkina, 1965; Bridgman, 1942). More recent work by McDonald *et al.* (1965) and Kabalkina *et al.* (1970) indicates that the high-pressure phase is not hcp. Considering the errors in both shock and static loading experiments, the observed transition pressures are in good agreement.

The lower-pressure transition apparently involves little or no volume change (Kabalkina *et al.*, 1970), and Warnes saw no evidence of it in the wave profile. The R–H curve below the transition showed softening which