Fig. 2—Effect of manganese on the transfor-
mation pressures of iron.

tion back to bcc as the pressure is reduced is evi-
denced by the low intensity of the 1 and 3 lines at 0
kbar. These diffraction patterns clearly demonstrate:
a) the bcc ⇌ hcp nature of the transformation, b) the
gradual increase in the amount of the hcp phase as
pressure is increased, and c) the transformation of
most of the hcp back to bcc as pressure was released.

In the case of the Fe-17.7 pct Mn sample, this basic
transformation pattern exhibits some interesting vari-
ations. This sample initially has a structure which is
about 50 pct fcc and 50 pct hcp in the annealed condi-
tion. The diffraction pattern in Fig. 4 (Fe-17.7 pct Mn
alloy) taken at 18 kbar nominal pressure (33 kbar ac-
tual pressure) shows this untransformed crystallo-
graphic structure. The data show that the transforma-
tion starts at 26 kbar actual pressure. In Fig. 4, the
increase in the intensity of the number three line
(1.92Å -hcp) at 30 kbar nominal pressure (47.5 kbar
actual pressure) indicates that the transformation
then proceeds as pressure is increased until the sam-
ple is 100 pct hcp at 50 kbar nominal (120 kbar actual).
Upon release of pressure, the hcp structure is re-
tained. Since the sample contains no bcc prior to the
beginning of transformation, the transformation which
occurs is either a $\gamma \rightarrow \epsilon$ transformation or is due to
a $\gamma \rightarrow (\alpha) \rightarrow \epsilon$ type transformation where the fcc first
shears to bcc. This bcc then transforms immediately
to hcp because the bcc is unstable at this pressure.
The necessary $\gamma \rightarrow \alpha \rightarrow \epsilon$ martensitic transformation
associated with deformation has been proposed for
stainless steels[21-22] and Schumann[19] has observed both
a $\gamma \rightarrow \alpha$ and $\gamma \rightarrow \epsilon$ martensitic transformation in
Fe-Mn alloys containing 0 to 10, and 14.5 to 27 pct
manganese, respectively.

As in the case of pure iron,[10] the transformations
for the Fe-Mn alloys are "abaric," i.e., the extent of
completion of the transformation is determined by the
difference between the applied pressure and the pres-
sure necessary to initiate the transformation. Also,

there is a hysteresis between the pressures required
to initiate the forward and reverse transformations.
These observations again indicate that the transfor-
mation may be of the martensitic type.

Plotted in Fig. 2 is a P_0 curve, or the equilibrium
$\alpha \rightleftharpoons \epsilon$ transformation line, determined from the follow-
ing equation:[10]

$$P_0 = \frac{P_{M_s}^{a \rightarrow \epsilon} + P_{M_s}^{\epsilon \rightarrow a}}{2} \qquad [1]$$

This equation is the analogue of the Kaufman and
Cohen[24] equilibrium temperature equation, T_0, derived
for the martensite transformation. Also shown in Fig.
2 is the calculated P_0 line for Fe-Mn alloys.[29] This
line was determined from the free energy equation:

$$\Delta F^{a \rightarrow \epsilon}[T_1 P_1 x] = (1-x)\Delta F_{Fe}^{a \rightarrow \epsilon} + x \Delta F_{Mn}^{a \rightarrow \epsilon}$$
$$+ x(1-x)(E-A)_{FeMn} + 23.9 P \Delta V^{a \rightarrow \epsilon} \qquad [2]$$

where x = atomic fraction Mn

at 300°K $\Delta F_{Fe}^{a \rightarrow \epsilon}$ = +1010 cal per g-atom

$\Delta F_{Mn}^{a \rightarrow \epsilon}$ = +1080 cal per g-atom

interaction parameter $(E-A)$

= −6990 cal per g-atom

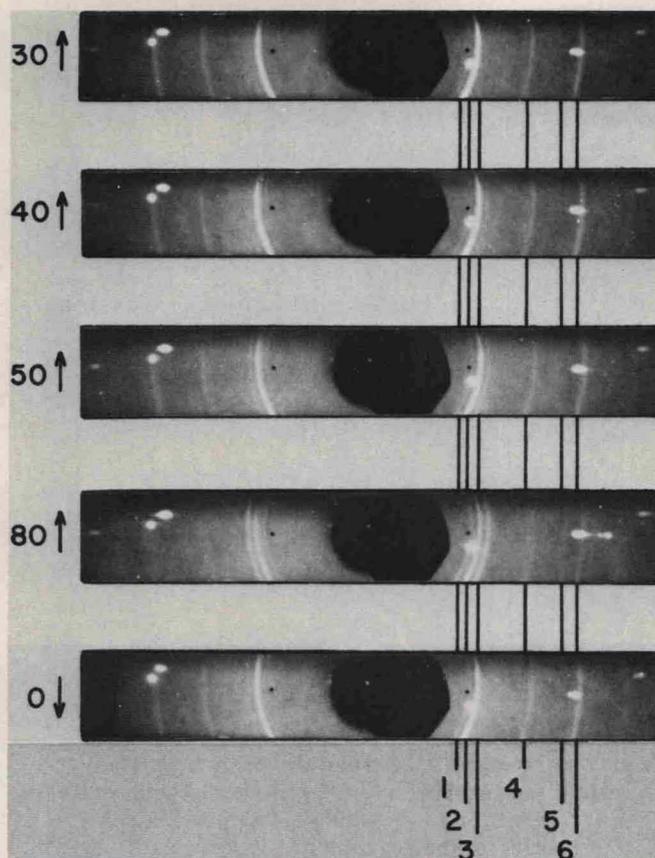$\Delta V^{a \rightarrow \epsilon}$ = −0.38 cu cm per g-atom

Substituting in Eq. [2]:

$$\Delta F^{a \rightarrow \epsilon}[300, P_0, x] = 0 = (1-x)1010 + x(1080)$$
$$+ x(1-x)(-6990) - 9.082 P_0 \qquad [3]$$

or,

$$P_0 \approx 111.2 - 763x + 769x^2 \qquad [4]$$
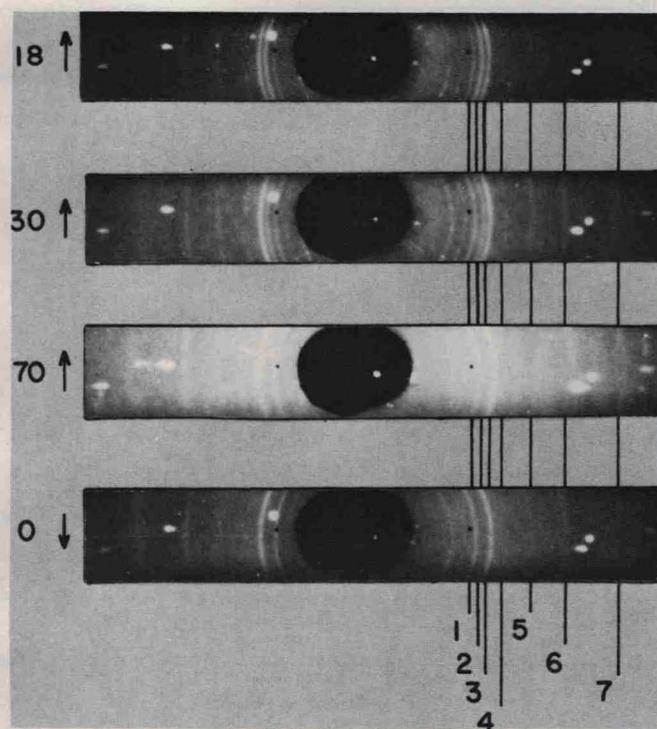
It can be seen that there is substantial agreement be-

Line	Interplanar Spacing, Å		Phase and Indices	
1	2.17		ϵ(100)	
2	2.04	α(110)	ϵ(002)	γ(111)
3	1.92		ϵ(101)	
4	1.43	α(200)		
5	1.25		ϵ(110)	γ(220)
6	1.17	α(211)		

Fig. 3—High-pressure X-ray diffraction patterns with diffraction lines identified. Sample was iron-4.9 pct manganese. Nominal pressures are given to the left of each diffraction pattern. Arrows pointing up show increasing pressure and arrows pointing down show decreasing pressures.

Line	Interplanar Spacing, Å		Phase and Indices	
1	2.17		ϵ(100)	
2	2.04	α(110)	ϵ(002)	γ(111)
3	1.92		ϵ(101)	
4	1.79			γ(200)
5	1.48		ϵ(102)	
6	1.25		ϵ(110)	γ(220)
7	1.08		ϵ(112)	γ(311)

Fig. 4—High-pressure X-ray diffraction patterns with diffraction lines identified. Sample was iron-17.7 pct manganese. Nominal pressures are given to the left of each diffraction pattern. Arrows pointing up show increasing pressure and arrows pointing down show decreasing pressure.

tween the calculated and the experimentally determined P_0. Furthermore, the driving force for the bcc → hcp martensite transformation, calculated by multiplying the difference in pressure between $P_{M_s}^{\alpha \to \epsilon}$ and P_0 by $23.9 \Delta V$, ranges from 227 cal per g-atom at 0 pct Mn[10] to 150 cal per g-atom at 13.9 pct Mn. This is in good agreement with determined values of 150 to 300 cal per g-atom calculated for the martensite transformation in iron alloys.[24]

Iron-Nickel-Chromium

The compositions of the Fe-Ni-Cr alloys studied (Table I, series 2A to 2D) were chosen to correspond closely to the composition of alloys which Minshall, Zukas, and Fowler[11,30] found to have low transformation pressures. Their transformation pressures were determined by means of dynamic pressurization and could not determine the structure of the phase formed at high pressure or the pressure at which it began to return to the ambient-pressure phase during pressure release. Also, the alloy compositions selected are close to those of some grades of stainless steels. The transformations in these materials are of considerable commercial importance, and several papers are available that deal with the transformations in such alloys under conditions of varying thermomechanical processes.[21-23,25-27]

Table III shows the percentage of phases present for these alloys at 0, 25, and 155 kbar as pressure was increased and at ambient pressure after all pressure was released. It can be seen that γ as well as α and ϵ phases are present in these alloys and that the transformations begin at much lower pressures than were observed in the Fe-Mn alloys. It is also evident that the 11.6 pct Ni-17.4 pct Cr alloy and the 12.3 pct Ni-13.5 pct Cr alloy retain their high pressure structure after pressure is released. This demonstrates that combined nickel and chromium additions promote the formation and stability of the hcp phase.

In Fig. 5, the combined alloying effects of Ni + Cr on the $\alpha \to \epsilon$ martensitic transformation of iron are plotted using the results of this investigation as well as the data of Fowler et al.[11,30] and Gust and Royce.[15] A smooth curve has been drawn through the data from