Low temperature phase equilibria in the Fe–Ni and Fe–Ni–P systems: application to the thermal history of metallic phases in meteorites

A. D. ROMIG, JR
Sandia National Laboratories, Albuquerque, NM 87185, U.S.A.

and

J. I. GOLDSTEIN
Lehigh University, Bethlehem, PA 18015, U.S.A.

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Abstract—The solubility limits of the α (kamacite) and γ (taenite) phases in the Fe-Ni and Fe-Ni-P phase diagrams have been measured at low temperatures, 700–300 °C. The predicted α + γ retrograde solubility below 500 °C was demonstrated experimentally for the first time in the Fe-Ni system. The minimum solubility of Ni in γ at the γ + α + γ boundary increases with decreasing temperature to as much as 54 wt% at 300 °C. The addition of P increases the maximum solubility of Ni in γ by as much as 1.6 wt% and decreases the minimum solubility of Ni in γ by as much as 7 wt% at 300 °C.

The solubility limits of kamacite and taenite were also obtained from heat-treated samples of the Grant and Cape York iron meteorites. The data indicate that in iron meteorites minor and trace elements other than P do not significantly shift the Ni solubility limits of the Fe–Ni and Fe–Ni–P phase diagrams. The measured phase diagrams can be used to explain the Agrell effect and the differences in maximum Ni content of taenite among irons and chondrites. The formation of plessite and the influence of the measured solubility limits on the cooling rate simulation method are also considered.

INTRODUCTION

The metallic phases in meteorites typically contain Fe, 5–30 wt% Ni and various amounts of P, Co, C, and S. In iron meteorites, the structure contains a high Ni parent phase, taenite (γ-fcc), and a low Ni phase kamacite (α-bcc) which together form the Widmanstätten pattern. Tetraektaeite, an ordered form of γ-FeNi, has been observed in essentially all slowly cooled meteorites, including several iron meteorites (CLARKE and SCOTT, 1980). There are also several common types of non-metallic inclusions: schreibersite, (FeNi)3P, cohenite, (FeNi)3C, and troilite, FeS.

Electron microprobe (EMP) and more recently scanning transmission electron microscope (STEM) analyses of the metal phases and phosphide inclusions have shown that meteoritic metal phases are not in bulk equilibrium (GOLDSTEIN and OGILVIE, 1965; LIN et al., 1977). However, the Ni gradients in the α, γ and (FeNi)3P which are measured by these techniques are useful for determining the rate at which a meteorite cooled. With concentration gradient data it is possible to model the growth process for (FeNi)3P (RANDICH and GOLDSTEIN, 1975) and the Widmanstätten pattern (WOOD, 1964; GOLDSTEIN and OGILVIE, 1965; GOLDSTEIN and SHORT, 1967) in iron meteorites and kamacite growth in chondrites (WOOD, 1967) using numerical techniques. Once the cooling rates of the metallic phases are obtained by these modeling techniques, one can postulate the size, thermal history, and structure of parent bodies.

The earliest growth models (WOOD, 1964; GOLDSTEIN and OGILVIE, 1965; WOOD, 1967; GOLDSTEIN and SHORT, 1967) assumed that the meteorite behaved like a binary Fe–Ni alloy. Later models for Widmanstätten growth (WILLIS and WASSON, 1978; MOREN and GOLDSTEIN, 1978) used a pseudo-binary approximation which included the effect of P on the Fe–Ni phase diagram and diffusivities. The most sophisticated model (MOREN and GOLDSTEIN, 1979) used the ternary phase diagram and ternary diffusivities. The ternary models assume that other minor elements do not significantly alter the kinetics and thermodynamics of the phase transformations.

To accurately simulate the growth process of kamacite the α/α + γ and α + γ/γ phase boundaries in the Fe–Ni and Fe–Ni–P system must be known from 700 to 300 °C. Below 300 °C diffusion in γ is so sluggish that the growth of α is essentially zero and no measurable chemical changes will occur (GOLDSTEIN and SHORT, 1967). The compositions which existed at 300 °C will in effect be 'frozen in'. In addition, the Ni solubility in (FeNi)3P and the Fe-Ni interdiffusion coefficients must be known as a function of temperature.

The previously described cooling rate models all used versions of the Fe–Ni and Fe–Ni–P phase diagrams where the solubility limits were only measured above 500 °C. Below 500 °C, only extrapolated solubility limits were available. The Fe–Ni and Fe–Ni–P phase diagrams have recently been determined for the temperature range 700–300 °C (ROMIG and GOLDSTEIN, 1980). Specific observations pertaining to the metallography, chemical composition and cooling rates of the metal phases of meteorites can now be discussed with the aid of the new phase diagram. Some of these
observations are: (1) The Agett dip at the α/γ interfaces in iron and stony-iron meteorites; (2) The higher Ni content region near α/γ interfaces in P free chondrites. This region is preponderantly tetrataenite; and (3) The different types of morphology for plessite in iron meteorites. In addition the choice of phase diagram should affect the calculated cooling rates using the Wood method.

THE PHASE DIAGRAMS

The experimental design and procedure used to determine the Fe-Ni and Fe-Ni (P-saturated) phase diagrams have been discussed in detail by ROMIG and GOLDSTEIN (1980). Briefly, the procedure involved the induction melting of bulk alloys from the pure elements and a homogenization treatment in the taenite field at 1200°C followed by a water quench which transformed the taenite (γ) to martensic (α₂). The samples then received long-term (up to 14 months) isothermal heat treatments in the temperature range 300-700°C to produce the α + γ or α + γ + (FeNi)₃P assemblages. The compositions of the coexisting phases were measured using electron microprobe (EMP) and scanning transmission electron microscope (STEM) techniques. These techniques and their application to the determination of metallurgical phase diagrams have been discussed in the literature (GOLDSTEIN and OIGLIV, 1966; ROMIG and GOLDSTEIN, 1980). For alloys which were fully equilibrated, the compositions of the coexisting phases defined the endpoints of the two-phase tie-lines and three-phase tie-triangles. If the alloys were not fully equilibrated, the interface compositions define the tie-line endpoints, since local equilibrium is assumed to exist at the interface (JOST, 1952; GOLDSTEIN and OIGLIV, 1966). Substantial experimental evidence exists which verifies this assumption for Fe-Ni and Fe-Ni-P alloys (ROMIG and GOLDSTEIN, 1980).

Figure 1 shows the isothermal tie-line data for the Fe-Ni and Fe-Ni (P-saturated) phase diagrams. Figure 1a shows the α + γ phase fields for the Fe-Ni binary and Fe-Ni-P pseudobinary systems and Fig. 1b gives an expanded view of the α + γ + γ solvus line. The addition of P causes the α + γ field to contract considerably. The equations of the power series curve fit for the α + γ and γ + γ + γ solvus lines are:

\[
\text{Fe-Ni} \quad \text{Fe-Ni-P} \\
\text{GRANT} \quad \text{CAPE YORK}
\]

Fig. 1a. Comparison of Fe-Ni and Fe-Ni (P-saturated) phase diagrams. Ni solubility in the Grant and Cape York α and γ phases is also shown.

Fig. 1b. Expanded view of α + γ solvus line shown in Fig. 1a.
given in Table 1. The maximum solubility of Ni in α has shifted from 6.2 wt% Ni at ≈ 475°C to 7.7 wt% Ni at ≈ 450°C. In addition the minimum Ni solubility in γ at 300°C has shifted from 54.6 to 46.0 wt% Ni.

To determine if other elements present in iron meteorites (Co, C, Cu, etc.) influence the Ni solubilities in α and γ, samples from the low-Ni, low-P containing Cape York (III A) and high-Ni, high-P containing Grant (III B) iron meteorites were given the same heat treatment as the synthetic alloys. To minimize the loss of volatiles, the meteorite samples were homogenized for 1 month in a single-phase taenite field at 1200°C in an evacuated fused silica capsule. After quenching to form α₂-martensite, the samples were given long-term isothermal treatments to produce the multiphase α + γ or α + γ + (FeNi)₃P structures. Table 2 lists the heat treatments and the structures that were formed. The α₂-martensite decomposed and taenite plates were produced in the α₂ or kamacite matrix. When P saturation occurs (<700°C for Grant, ≤ 500°C for Cape York) irregular phosphides (Ph) are observed. The Cape York composition places the meteorite in the α + Ph phase field at ≤ 400°C so that α + γ solubility limits could not be measured. In the Grant meteorite the α₂ did not decompose to α + γ + Ph at 300°C as expected.

Figure 2 shows a series of photomicrographs (optical and scanning electron microscope) of typical α + γ and α + γ + Ph structures produced by heat treatment of the Cape York and Grant meteorites. The γ-taenite plates which are produced are readily observed. Figure 3 shows examples of the concentration profiles obtained from STEM X-ray microanalysis. The measured Ni concentrations in γ and α at γ interfaces are the equilibrium tie-line values which control α + γ growth. The error bars have been calculated from the X-ray counting statistics (Rommel and Goldstein, 1980). The tie-line values for the two meteorites are listed in Table 3.

The tie-line values for Grant and Cape York are plotted in Fig. 1, on the Fe-Ni and Fe-Ni (P-saturated) phase diagrams. Since Grant is P-saturated at and below 700°C, the α/α + γ and γ/α + γ solubility limits should agree with Fe Ni (P-saturated) solvus lines. The Ni solubilities of the α and γ phases in the Grant samples are statistically indistinguishable from the measured P-saturated solvus lines. The Ni solubilities of the α and γ phases in the Cape York samples also agree with the P-saturated curves at 500°C where Cape York is P-saturated. At 600 and 700°C, where Cape York is not P-saturated, the measured α/α + γ and γ/α + γ solubilities fall between the Fe-Ni and Fe-Ni (P-saturated) curves. The error bars for the meteoritic alloy data are of the same order of magnitude as the error bars shown for the synthetic alloy data. A comparison of meteoritic alloy and synthetic alloy data indicates that other minor and trace elements present in iron meteorites do not significantly shift the Ni solubility limits. Therefore the measured Fe-Ni and P-saturated Fe-Ni phase diagrams are directly applicable to the study of the metal phases in meteorites.

### DISCUSSION

#### The Agrell effect

Figure 4 shows a Ni concentration profile measured across the α/γ interface in the Grant iron meteorite.
Fig. 3a. Ni concentration profile measured on a Cape York meteorite sample, tempered at 600°C for 75 days. The data was taken with the STEM at a step size of 500 Å.

Fig. 3b. Ni concentration profile measured on a Grant meteorite sample, tempered at 400°C for 105 days. The microstructure is shown in Fig. 2c. The data was taken with the STEM at a step size of 500 Å.

The diffusion profile may be explained by the nucleation and diffusion controlled growth of α (Widmanstätten pattern). Since the growing kamacite (α) phase has a lower Ni content than the parent γ, the growth of the α depends on the movement of Ni from α into the residual γ. The rate of diffusion of Ni in γ controls the rate of growth of the α. In addition as the temperature decreases, the Ni content in γ at the α + γ interface increases. A steep concentration profile develops in the phase because of the slow diffusion rate of Ni away from the α/γ interface. The α phase has essentially uniform composition because diffusion in the α phase is still fast enough to maintain chemical homogeneity. At lower temperatures (≤ 500°C) the diffusion profile may be explained by the nucleation and diffusion controlled growth of α (Widmanstätten pattern).
Fig. 2a. Optical micrograph of a Cape York (Fe - 7.86 wt% Ni - 0.17 wt% P) sample heat treated at 700°C for 75 days. The microstructure contains taenite (G) plates in a kamacite (A) matrix. Scale bar = 20 μm.

Fig. 2b. SEM micrograph of a Cape York (Fe - 7.86 wt% Ni - 0.17 wt% P) sample heat treated at 500°C for 75 days. The microstructure contains taenite (G) plates in a kamacite (A) matrix. Spherical phosphides, (FeNi),P are also present (Ph). Scale bar = 0.25 μm.

Fig. 2c. SEM micrograph of a Grant (Fe - 9.41 wt% Ni - 0.78 wt% P) sample heat treated at 400°C for 105 days. The microstructure contains taenite (G) plates in a kamacite (A) matrix. Spherical phosphides, (FeNi),P are also present (Ph). Scale bar = 5 μm.
Fig. 5a. SEM micrograph of an Fe \( 30.7 \, \text{wt\%} \) Ni alloy quenched from 1200°C to produce \( \alpha_2 \). The alloy was tempered at 450°C for 120 days. The microstructure contains taenite plates in a kamacite matrix. Scale bar = 1 \( \mu \text{m} \).

Fig. 5b. SEM micrograph of an Fe \( 15.2 \, \text{wt\%} \) Ni alloy quenched from 1200°C to produce \( \alpha_2 \). The alloy was tempered at 500°C for 270 days. The microstructure contains taenite plates in a kamacite matrix. Scale bar = 5 \( \mu \text{m} \).

Fig. 5c. Plessite microstructure in the Hoba iron meteorite (IVB, 16.4 wt\% Ni). The structure is very similar to that produced in the experimental alloys (compare to Figs 5a and 5b). Scale bar = 5 \( \mu \text{m} \).
Thermal history of metallic phases in meteorites

Figure 4. Ni concentration gradient across a kamacite-taenite-kamacite area in the Grant meteorite (9.4 wt% Ni) taken with the EMP. The Ni depletion in \( \alpha \) at the \( \alpha/\gamma \) boundary (indicated by the arrow) is known as the Agrell effect.

fusion of Ni in \( \alpha \) is too slow to produce a chemically homogeneous phase. As a result, a concentration gradient develops in the \( \alpha \)-phase and this gradient is particularly significant close to the \( \alpha/\gamma \) interface. The large Ni depletion near the \( \alpha/\gamma \) interface is known as the Agrell effect (AGRELL et al., 1963), and has been the basis for the previously assumed retrograde solubility of Ni in \( \alpha \) at low temperatures.

The development of the Agrell effect can now be explained in detail using the \( \alpha/\alpha + \gamma \) solubility limits measured at and below \( \sim 475^\circ \mathrm{C} \) (Fig. 1). The retrograde solubility for the \( \alpha/\alpha + \gamma \) solvus line causes the Ni concentration in \( \alpha \) at the \( \alpha/\gamma \) boundary to decrease with decreasing temperature. The Ni gradient near the interface occurs because the slow diffusion of Ni below \( 500 ^\circ \mathrm{C} \) no longer allows Ni to move from the interior of the \( \alpha \) phase. If the \( \alpha/\alpha + \gamma \) solvus line did not bend back to lower Ni contents at low temperatures, there would be a Ni enrichment of the \( \alpha \) phase at the \( \alpha/\gamma \) interface. Early investigators (RINGWOOD and KAUFMAN, 1962) tried to rationalize the decrease in solubility at low temperatures by employing a pressure effect (up to 50,000 atm). The results of the phase diagram study indicate, as postulated by AGRELL et al. (1963), that the Ni depletion in \( \alpha \) near the \( \alpha/\gamma \) boundary can be explained solely by the retrograde solubility of the \( \alpha/\alpha + \gamma \) boundary in the Fe-Ni system at low pressure.

Implications to chondrites

Iron meteorites typically contain some phosphorus (\( > 0.02 \text{ wt}\% \)) and some IIIB irons contain up to 1.0 wt\% P (BUCHWALD, 1975). At low temperatures, below 500 °C, virtually all iron meteorites will be P saturated and hence will contain (FeNi)\textsubscript{3}P precipitates. Conversely, chondritic metal is essentially P-free except for Type II (C2) carbonaceous chondrites (Olsen et al., 1973; SMITH and GOLDSMITH, 1977). Concentration profiles measured on iron meteorites with the STEM and EMP have shown the \( \gamma \)-phase to contain up to 50 wt% Ni at the \( \alpha/\gamma \) interface (Lin et al., 1977, 1979). Similar measurements taken on ordinary chondrites show that the \( \gamma \) phase, now transformed to tetrataenite, can contain up to 57 wt% Ni (SCOTT and CLARKE, 1979) at the \( \alpha/\gamma \) interface. Since most iron meteorites and chondrites have similar cooling rates ([1–10 °C/Myr]), WOOD (1979)], it might be expected that the maximum Ni contents in \( \gamma \) would be the same for metal phases in irons and chondrites. The reason for the higher Ni contents in the \( \gamma \) phase of chondritic metal has not been resolved.

At low temperatures (\( \lesssim 500^\circ \mathrm{C} \)), iron meteorites are saturated with phosphorus. Hence, the measured \( \alpha/\gamma \) interface compositions are those given by the Fe-Ni (P-saturated) diagram (Fig. 1). The metal in the chondrites is not saturated with P, and in some cases the metal contains \( \lesssim 0.02 \text{ wt}\% \) P. The measured \( \alpha/\gamma \) interface compositions for these meteorites are those given by the binary Fe-Ni phase diagram. At 300 °C, the \( \gamma \) phase in the Fe-Ni binary system contains 54.6 ± 41 wt% Ni, but the \( \gamma \) phase in the Fe-Ni (P-saturated) system contains only 46.0 ± 3.2 wt% Ni. Therefore the differences in maximum Ni contents between iron meteorites and chondrites can be attributed to the presence or absence of P in the metal phase.

The metal particles in the mesosiderites (POWELL, 1971; AGOSTO et al., 1981) and enstatite achondrites (WASSON and WAI, 1970) contain measurable P in the metal phase as well as discrete phosphides. In addition some of the howardites (HEWINS, 1979) contain at least 0.01 wt% P. The Fe-Ni (P-saturated) diagram should control the Ni distribution between metal phases in these meteorites. The mesosiderites are a particularly interesting group of meteorites since the taenite phase has a high Ni content (48–56 wt% Ni) containing the ordered FeNi phase, tetrataenite (CLARKE and SCOTT, 1980; AGOSTO et al., 1981) and cloudy taenite (AGOSTO et al., 1981). If the mesosiderites cooled at the same rate as the irons and the majority of chondrites, Ni contents at 50 wt% or below would be expected. The fact that mesosiderites have a much slower cooling rate, \( \sim 0.1 \text{ °C/Myr} \) (POWELL, 1971) may provide an answer to this problem. The Ni solubility in \( \alpha \) and \( \gamma \) at the \( \alpha/\gamma \) boundary probably follows the phase diagram solubility limits to lower temperatures (\( < 300^\circ \mathrm{C} \)) than for the faster cooling meteorites, and the maximum Ni content in \( \gamma \) will be 'frozen in' at lower temperatures. This process should increase the Ni content in \( \gamma \) and decrease the Ni content in \( \alpha \) (see Fig. 1). Data on Ni solubilities of \( \alpha \) and \( \gamma \) in ALHA 77219, an Antarctic mesosiderite (AGOSTO et al., 1981) are consistent with these predicted composition trends.

Computer models which simulate the growth of kamacite in the metal particles of chondrites or in iron meteorites depend strongly on the form of the \( \alpha/\alpha + \gamma \) and \( \gamma/\alpha + \gamma \) phase boundaries. The fact that different phase boundaries must be considered for chondrites and irons and measured values are now
available between 300 and 500°C argues for a re-evaluation of the input parameters for the models. This topic will be discussed in a later section in reference to cooling rates for the IVA irons.

Implications for the formation of plessite and ordered FeNi

In addition to the Widmanstätten pattern, many iron meteorites also contain a mixture of $\alpha + \gamma$ known as plessite (Massalski et al., 1966; Lin et al., 1977, 1979; Buchwald, 1975). Some of the plessite forms by the $\alpha_2 \rightarrow \alpha + \gamma$ transformation sequence where martensite decomposes to $\alpha + \gamma$. This phase transformation is identical to that used to prepare the $\alpha + \gamma$ structures analyzed in this study. In meteorites the parent taenite-$\gamma$ metal cools and at some appropriate temperature the $\alpha$-phase nucleates and grows in the $\gamma$. As cooling continues, the taenite areas of the sample increase in Ni content. At low temperatures, the meteorite crosses the martensite start temperature and taenite transforms to $\alpha_2$. The martensite start temperature is a strong function of Ni content decreasing with increasing Ni (Kaufman and Cohen, 1956). Because of the variation of martensite start temperature with Ni content, areas of the matrix containing less than 15 wt% Ni will have transformed to $\alpha_2$ at a temperature above 350°C. Our studies have shown that in the temperature range 300–700°C the $\alpha_2$ will decompose into $\alpha + \gamma$. All areas of the taenite matrix containing from 15 to 25 wt% Ni eventually transform to $\alpha_2$. For the higher Ni $\alpha_2$ regions, the martensite start temperature is so low that there is insufficient driving force for the $\alpha_2$ to decompose to $\alpha + \gamma$.

The similarity in microstructure between meteoritic plessite and decomposed $\alpha_2$ from our alloy studies is illustrated in Fig. 5. The plessite structure in the Hoba meteorite (Fig. 5c) is very similar to that produced in the synthetic alloys in which $\gamma$ plates nucleated and grew in the $\alpha_2$ matrix.

Recently, the ordered Fe-Ni phase has been reported in several iron meteorites (Albertsen et al., 1978a,b; Petersen et al., 1977; Jago, 1979; Bowles et al., 1978; Clarke and Scott, 1980) and in chondrites, mesosiderites and pallasites (Scott and Clarke, 1979; Mehta et al., 1980). The ordered phase was detected using Mössbauer and X-ray diffraction techniques as well as optical and electron microscopy. Albertsen et al. (1978a,b) suggest that when the meteorite cooled below the ordering temperature for the superstructure ($T_c = 320°C$) the $\gamma$ phase of appropriate composition became ordered. Jago (1979) has suggested that ordered Fe-Ni formed by spinodal decomposition.

The ordered phase was not observed in any of the alloys prepared for this study. Although the electron diffraction work on the experimental alloys was limited, no evidence for superlattice formation was detected. However, since the current theories on the formation of ordered Fe-Ni indicate that it formed when $\gamma$-taenite was slowly cooled, there is no reason to expect the ordered phase to be present in the synthetic alloys. In addition the high Ni $\gamma$-phase was produced by the decomposition of $\alpha_2$ rather than during the formation of the Widmanstätten pattern.

Cooling rate analysis for the IVA iron meteorites

All the cooling rate analyses require the Fe-Ni phase diagram as input data. Prior to this study the lowest temperature for which data were available was 500°C for the Fe-Ni phase diagram and 600°C for the Fe-Ni-P phase diagram. Below these temperatures only extrapolated solvus lines were available. This study has defined the system to 300°C where kamacite growth is presumably 'frozen in'. Therefore more accurate cooling rate analysis should be possible. The new phase diagram data has been used to obtain more accurate cooling rates for the IVA irons.

Several cooling rate simulations have been conducted to determine the cooling rate for the IVA iron meteorites. The cooling rates of this chemical group were most recently determined by Willis and Wasson (1978) and Moren and Goldstein (1978–79). Both Willis and Wasson (1978) and Moren and Goldstein (1978–79) used the Wood method but each chose different phase diagram values and diffusivities. In this case the Moren and Goldstein (1978) model was used with the Bork and Lai (1963) diffusivities for Ni in $\alpha$ and the Moren and Goldstein (1978–79) extrapolation for the effect of P on Ni diffusivity. The $\alpha/\alpha + \gamma$ and $\gamma/\alpha + \gamma$ boundaries for binary Fe-Ni and P-saturated Fe-Ni systems from the experimental data of Romig and Goldstein (1980) were employed (Fig. 1). A linear interpolation between the binary Fe-Ni and the P-saturated Fe-Ni solvus lines was used to determine the tie-lines for IVA irons which contained P, but were not P-saturated at any temperature (Moren and Goldstein, 1978, 1979).

If the cooling rate analysis for a given meteorite is correct, the predicted Ni concentration profiles in kamacite should agree with the measured concentration profiles. Differences between measured and calculated profiles are primarily due to errors in phase solubilities and are only slightly sensitive to errors in cooling rate. If the agreement between the calculated and measured compositions is not adequate, then the kamacite $\alpha/\alpha + \gamma$ boundaries should be modified as suggested by Willis and Wasson (1978). Excellent agreement was obtained for high P IVA irons. However, for low P IVAs it was necessary to shift the $\alpha/\alpha + \gamma$ boundary to slightly higher Ni contents as shown in Fig. 6. The new solubility curve still passes through the error bars associated with the Romig and Goldstein (1980) experimental measurements. A numerical description of the solvus lines as a function of temperature is required for the cooling rate model. A statistical least-squares curve fit through the solubility data did not yield an acceptable curve, in that the curve did not pass through the
Fig. 6. Modified \( \alpha/\alpha + \gamma \) boundary to fit kamacite Ni profiles in low P IVA irons (solid line). The data of Romig and Goldstein and least squares fit (dashed line) are also plotted. The modified \( \alpha/\alpha + \gamma \) solvus line passes through the error bars associated with the experimental measurements.

Fig. 7. Ni composition profile across the kamacite phase in the Signal Mountain IVA iron meteorite. The \( \alpha/\gamma \) interface is on the left of the diagram where distance = 0 on the horizontal axis. The calculated curve for a cooling rate of 55 C/Myr adequately fits the experimental data of Moren and Goldstein (1978).

CONCLUSION

The new Fe-Ni and Fe-Ni-P phase diagrams of Romig and Goldstein (1980) can be used to investigate the thermal history of iron meteorites. The new phase diagrams can be used to explain the following observations for the metallic phases in meteorites.
Other than Fe, the various elements present in iron meteorites do not significantly shift the Ni solubility limits. The measured Fe-Ni and Fe-Ni-P phase diagrams are directly applicable to meteorite studies.

(2) The development of the Agrell effect can be described by the retrograde solubility of Ni in kamacite.

(3) The differences in the maximum Ni content of taenite between iron meteorites and P-free chondrite metal are explained by comparing the $\gamma/\alpha + \gamma$ boundaries for binary Fe-Ni and for P-saturated Fe-Ni.

(4) The plessite structure in many meteorites can be explained by the decomposition of martensite $\alpha$ into $\gamma$ rods in an $\alpha$ matrix during the slow cooling of the parent meteorite body.

(5) When the new $\alpha/\alpha + \gamma$ and $\gamma/\alpha + \gamma$ solubility limits of ROMIG and GOLDSTEIN (1980) are incorpo-
TABLE 4

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REFERENCES


