The Fe-Ni (Iron-Nickel) System

By L.J. Swartzendruber
National Institute of Standards and Technology
V.P. Itkin
University of Toronto
and
C.B. Alcock
University of Notre Dame

Equilibrium Diagram

The equilibrium phases of the Fe-Ni system are: (1) the liquid, L; (2) the bcc, high-temperature (δFe) solid solution; (3) the fcc (γFe,Ni) solid solution; (4) the bcc, low-temperature (αFe) solid solution; and (5) the $FeNi_3$ intermetallic compound, which forms by a first-order order-disorder transformation below 517 °C and has an extended range of homogeneity.

Early systematic efforts to construct a phase diagram for Fe-Ni were made by [1899Osm], [05Gue], [10Heg], and [10Rue]. Evaluated phase diagrams for the Fe-Ni system were given previously by [38Mar], [Hansen], [Shunk], and [82Kub]. The present assessed Fe-Ni equilibrium diagram is shown in Fig. 1.

Liquidus and Solidus

The liquidus and solidus for Fe-rich alloys up to about 12 at.% Ni were measured by [57Hel] using thermal analysis. [23Han] measured the liquidus and solidus over the entire range of composition. Measurements were also made by [05Gue], [25Kas], [31Ben], [37Jen], [25Vog], [27Vog] and [28Vog]. The data are summarized in Table 1. According to [23Han], the minimum in the liquidus curve is located at 1438 °C (temperatures quoted throughout were converted to IPTS-68) and about 67 at.% Ni. According to [37Jen], the minimum is between 1422 and 1427 °C. Based on a least-squares fit taking into account both the measured boundaries and available thermodynamic data (see Thermodynamics), we find the most probable location for the minimum to be 1440 °C and 66.0 at.% Ni, in good agreement with [23Han].

[64Hum] calculated the Fe-rich liquidus/solidus based on an ideal-solution model. This procedure gives too large a separation between the liquidus and solidus when extended to Ni-rich alloys. The liquidus and solidus separations of Fig. 1 are based primarily on those predicted by the measured thermodynamic parameters in the liquid and fcc phases, with the assessed boundary location giving greatest weight to the measurements of the liquidus. These boundaries are close to the predictions of [85Tom], which were based on thermodynamic parameters measured using mass spectrometry. They are shown on an expanded scale in Fig. 2.

Phase Boundaries

Measurements of the (αFe/δFe) phase boundaries were made by [20Han], [23Han], [25Kas], and [57Hel]. Comparisons with thermodynamic measurements (see below) and with liquidus and solidus measurements indicate a narrow two-phase (αFe) + (δFe) region and a narrow peritectic reaction—L + (δFe) ↔ (γFe,Ni) at 1514 ± 2 °C and 3.5, 4.9, and 4.2 ± 0.5 at.% Ni, respectively. Measured values are listed in Table 1 and compared with the equilibrium diagram in Fig. 3.

(αFe)/(γFe,Ni) Phase Boundaries

Due to the sluggishness of the (γFe,Ni) → (αFe) and (αFe) → (γFe,Ni) phase transformations below 800 °C, the (αFe)/(γFe,Ni) equilibrium boundaries are difficult to determine (see Metastable Phases). [36Jet], [39Owe], [41Owe], and [49Owe] used powder X-ray diffraction (XRD) techniques down to 300 °C. [65Gol] used electron microprobe techniques to measure concentration profiles on samples equilibrated at temperatures as low as 500 °C. [80Rom] used a scanning transmission electron microscope (STEM) on samples equilibrated between 670 and 300 °C. These results, along with those of [69Sta], demonstrated clearly the retrograde solubility of Ni in (αFe). The data of [49Owe], [49Jon], [65Gol], and [80Rom] agree fairly well at 500 °C and above. The boundaries shown in Fig. 1 were constructed using these data, giving greatest weight to the results of [80Rom]. Numerical values determined by the various investigators are given in Table 2. Figure 3 shows the assessed boundaries and compares them with the experimental data. Enthalpies of the (αFe) → (γFe,Ni) transformation were measured by [26Kaw], [36Sam], [37Koe], [40Zui], [59Sch], and [67Hil].

$FeNi_3$

Evidence for ordered $FeNi_3$ was obtained first by [32Dah], [33Dah], [36Dah], [39Kus], and [39Lee] using XRD. Because of the nearly equal X-ray scattering factors for Fe and Ni, the ordering is difficult to observe with X-rays (see [38Haw]). The results of [39Lee] were confirmed by [39Haw], also with X-rays. Variations in the magnetic properties, electrical resistance, and hardness with heat treatment of alloys showing $FeNi_3$ order were investigated by [32Dah], [33Dah], and [36Dah]. Based on X-ray and electron microscope observation of annealed thin films and on the results of [52Hun], [63Heu] concluded that the (γFe,Ni) phase decomposes eutectoidally to (αFe) and $FeNi_3$ at 345 °C and 52 at.% Ni, a conclusion that still appears valid. (The existence of a eutectoid near this same point based on the magnetic transition had been postulated earlier; see [21Mer].)

The critical behavior of the temperature derivative of the resistivity around the $FeNi_3$ composition was investigated by [82Ore]. No anomaly in the resistivity was found at the order-disorder temperature, but one was found at the Curie temperature. The phase diagram in the composition range 69 to 77 at.% Ni and in the temperature range around 510 °C was studied in considerable detail by [80Van] and [81Van] using Mössbauer spectroscopy. They explained a 15 °C hysteresis zone between ordus and disordus as a magnetic effect. [81Lef] investigated the local atomic arrangement in $FeNi_3$ using neutron diffuse scattering and a single crystal quenched from four different temperatures. [72Cal] found that the order-disorder transformation of $FeNi_3$ is not second order and observed a two-phase zone of 5 or 6 °C for alloys between 71 and 75 at.% Ni. On the basis of a calorimetric study, [52Iid] and [54Iid] concluded that short-range order forms in $FeNi_3$ before long-range order is observable by other methods.

The ordering behavior of $FeNi_3$ was also investigated by [37Kal], [39Haw], [39Kay], [40Nix], [48Kal], [50Jos], [53Rhi], [53Gei], [57Lya], [57Vit], [58Kus], [62Kac], [63Dav], [63Tre], [65Gon], [72Cal], [73Cal], [75Bil], [75Leb], [77Hut], [79Des], and

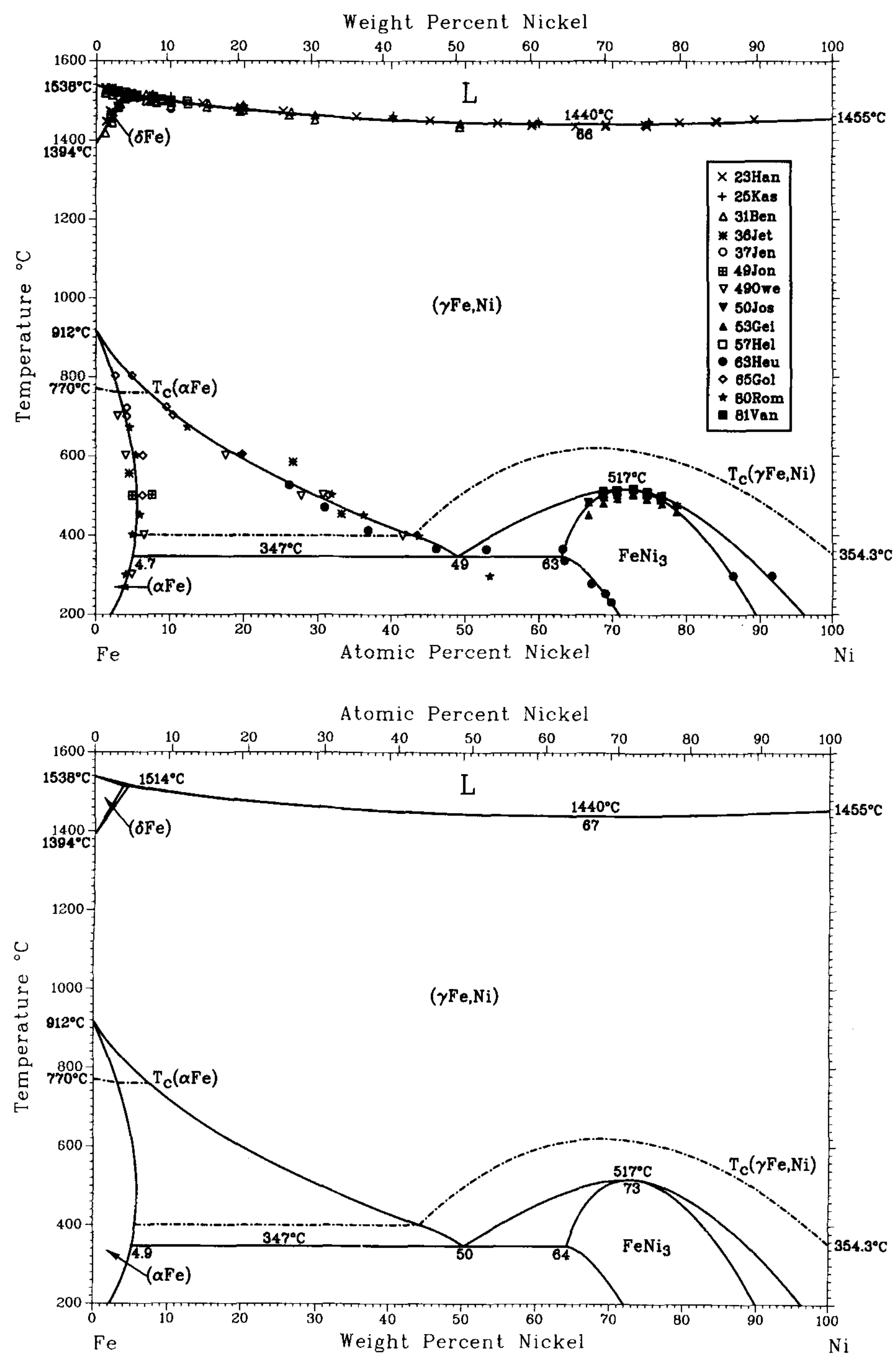

Fig. 1 Assessed Fe-Ni phase diagram with selected experimental data.

Table 1 High-Temperature Phase Boundary Data for Fe-Ni Alloys

Composition, at.% Ni	Liquidus	Solidus	Temperature, °C (δFe)/(δFe) + (γFe,Ni)	(δFe) + (γFe,Ni)/(γFe,Ni)
From [10Rue]				
0	1538	...	...	...
9.6	1515	...	...	...
19.2	1488	...	...	...
29.0	1472	...	...	...
38.8	1452	...	...	...
48.8	1448	...	...	...
58.8	1443	...	...	...
68.9	1441	...	...	...
79.2	1446	...	...	...
100	1455	...	...	...
From [23Han]				
1.1	1532	...	1447	...
2.0	1530	...	1471	...
2.9	1523	...	1497	...
3.7	1521	...	1504	...
5.1	1506	...	...	...
5.8	1506	...	...	...
8.0	1501	...	...	...
10.0	1496	...	...	...
14.6	1493	...	...	...
24.7	1474	...	...	...
34.8	1460	...	...	...
45.1	1449	...	...	...
54.6	1443	...	...	...
59.3	1442	1437	...	...
65.1	1439	1435	...	...
66.7	1439	...	...	...
69.3	1439	1434	...	...
74.5	1440	1436	...	...
79.2	1445	...	...	...
84.2	1447	...	...	...
89.1	1453	...	...	...
From [25Kas]				
1.3	1532	1526	1454	...
2.0	1530	1520	1470	...
5.0	1518	...	...	...
7.5	1516	1510	1512	...
10.0	1510	1504	...	...
20.0	1488	1488	1484	...
40.0	1463	1456	...	...
60.0	1447	1441	...	...
80.0	1448	1443	...	...
From [31Ben]				
1.1	1526	1519	1417	...
2.1	1526	1512	1443	...
3.0	1523	...	1490	...
3.9	1518	1507	...	...
6.6	1514	1499	...	...
7.1	1511	1497	...	...
7.8	1507	1497	...	...
8.0	1509	1493	...	...
10.0	1504	1485	...	...
14.9	1492	1483	...	...
19.5	1477	1472	...	...
19.9	1483	1475	...	...
25.7	1472	1462	...	...
29.3	1464	1451	...	...
49.2	1441	1432	...	...

(continued)

Note: All results corrected to IPTS-68 and to agree with 1538 °C as the melting temperature of pure Fe and 1455 °C as the melting temperature of pure Ni.

Table 1 High-Temperature Phase Boundary Data for Fe-Ni Alloys (continued)

Composition, at.% Ni	Liquidus	Solidus	Temperature, °C (δFe)/(δFe) + (γFe,Ni)	(δFe) + (γFe,Ni)/(γFe,Ni)
From [37Jen]				
10.0	...	1479	...	...
20.0	...	1458	...	...
30.0	...	1447	...	...
40.0	...	1441	...	...
50.0	...	1440	...	...
60.0	...	1439	...	...
70.0	...	1418	...	...
80.0	...	1423	...	...
90.0	...	1438	...	...
From [57Hel]				
1.84	1528	1526	1455	1462
2.79	1524	1520	1484	1483
3.76	1520	1514	1503	1506.5
4.62	1516	1511.5	1514	...
5.72	1513.5	1510	...	...
7.61	1508.5	1503.5	...	...
8.95	1502.5	1598.5	...	...
12.23	1497	1491	...	...

Note: All results corrected to IPTS-68 and to agree with 1538 °C as the melting temperature of pure Fe and 1455 °C as the melting temperature of pure Ni.

[84Lef]. Experimental values reported by various investigators are listed in Table 3 and compared in Fig. 4.

Metastable Phases

At low temperature (under about 800 °C), the (αFe) + (γFe,Ni) field is relatively broad, and attainment of equilibrium involves considerable diffusion. Diffusion rates at these lower temperatures are low; consequently, very long times are required to establish equilibrium, and normal conditions favor a diffusionless (or martensitic) transformation. This transformation exhibits considerable hysteresis. In early work, [20Han] used metallography to determine two sets of boundaries for the (αFe) + (γFe,Ni) two-phase region—one on heating, and one on cooling. The (γFe,Ni)/(αFe) + (γFe,Ni) boundary determined in this way agrees closely with that determined by thermal analysis (the (αFe)/(αFe) + (γFe,Ni) boundary is not detected by thermal analysis). [20Han] also concluded that the (αFe) → (γFe,Ni) transformation is accelerated by the presence of impurities.

From a practical standpoint, a diagram giving the details of this irreversible transformation is often of more importance than one giving the equilibrium boundaries in this region. Figure 5 exhibits experimental transformation measurements of [25Pes], [27Hon], [49Jon], and [56Kau] and compares them with the equilibrium boundaries. In this figure, the supersaturated bcc phase that results from the diffusionless transformation is denoted α_2. The solid lines are estimates of A_s, M_s, A_f, and M_f, where A_s and M_s are the so-called austenite and martensite start temperatures (10 vol.% of the alloy having transformed), and A_f and M_f are the so-called austenite and martensite finish temperatures (90 vol.% of the alloy having transformed). These lines are valid only over a range of cooling and heating temperatures between approximately 2 and 150 °C/min. The uncertainties in the estimated A_s, A_f, M_s, and M_f temperatures are large, but decrease as the Ni concentration decreases.

In the α_2 or (γFe,Ni) field, the alloy will be all (γFe,Ni) if it is being cooled from the (γFe,Ni) field or all α_2 if it is being heated from the α_2 field. Because the transformation from (γFe,Ni) to α_2 is diffusionless, it can occur at very low temperatures for alloys with greater than 30 at.% Ni. [56Kau] reported the M_s temperature of (−223 °C) (50 K) for a 33 at.% Ni alloy. In addition, the M_s temperatures of various steels are known [54Mey, 48Fis, 74Ume, 63Yeo, 82Bro1] to change with the temperature at which they are austenized. That this change is due to the effect of austenizing temperature on grain size was shown by [51Mac] and [74Ume]. For an Fe-31 at.% Ni alloy, [74Ume] found that the M_s temperature varied between 200 and 230 °C as the grain size varied between 5 and 70 μm. Impurities and internal stresses also have an important effect on the transformation temperatures [*e.g.* 82Rod].

The diffusionless character of the α_2 → (γFe,Ni) transformation was shown clearly by [32Sch]. [34Deh] reported that the transformed alloy is bcc, and is not tetragonal as is Fe-C martensite, with the microstructural similarity of the two martensites being due to the similar way in which they transform from the γ phase. [35Sch] found that for greater than 10 at.% Ni, the (γFe,Ni) → (αFe) transformation temperature could not be lowered by long annealing times (up to 100 h). Some early diagrams, such as that of [36Mer], were drawn showing the irreversibility of the diffusionless transformation directly.

[62Gil] reported that the diffusionless transformation is massive type for Ni contents less than about 15 at.%. For very rapid cooling and/or for higher Ni concentration, [66Hum] and [62Gil] reported that the transformation is martensitic type.

According to [49Jon], the diffusionless α_2 → (γFe,Ni) transformations are independent of the cooling or heating rate for rates between 2 and 150 °C/min. [76Ino] and [82Ray] showed that the

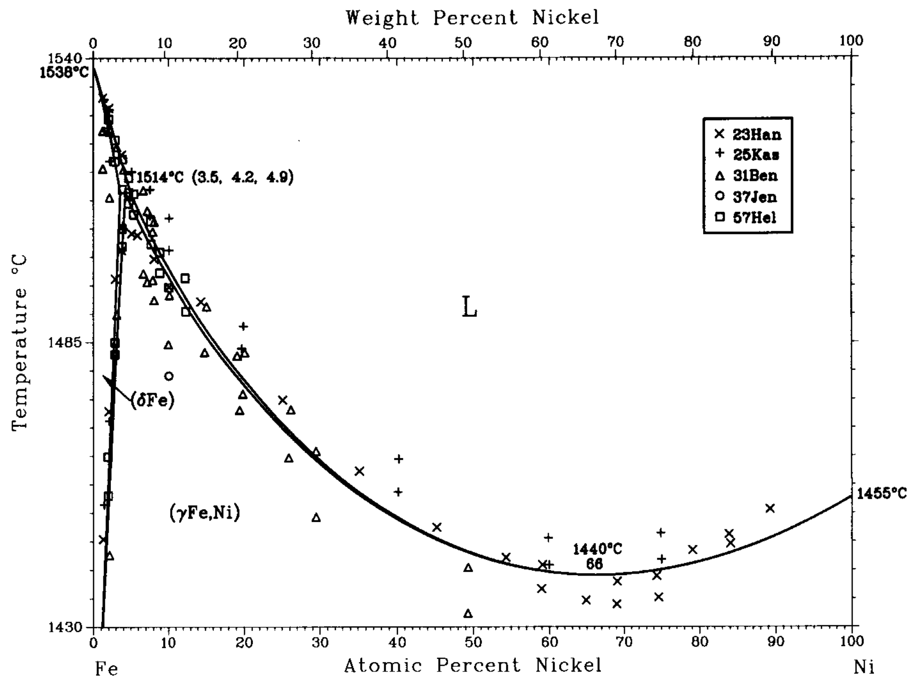

Fig. 2 High-temperature region of the Fe-Ni phase diagram.

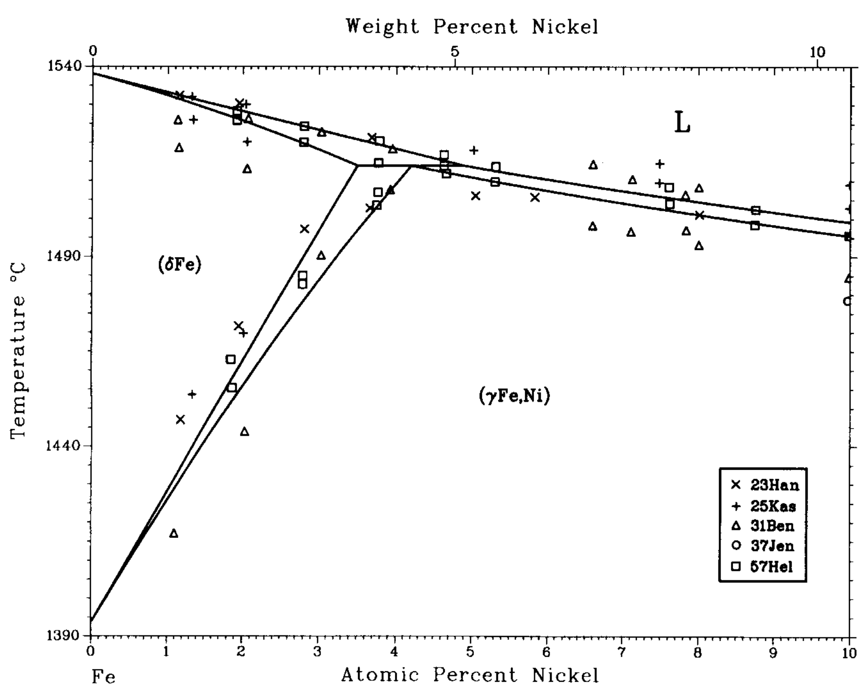

Fig. 3 (αFe)/(δFe) boundaries and the peritectic reaction in Fe-Ni.

Table 2 (αFe)/(γFe,Ni) Equilibrium Phase Boundary Measurements

Temperature, °C	Composition, at.% Ni (αFe)/(αFe) + (γFe,Ni)	Composition, at.% Ni (αFe) + (γFe,Ni) + (γFe,Ni)	Anneal time, days	Technique	Reference
817	1.0	...	...	X-ray	[30Rob]
806	...	3	...	Magnetic	[40Pic]
800	1.0	4.5	...	X-ray	[39Owe]
	1.9 ± 0.15	3.5 ± 0.3	31	(a)	[65Gol]
744	...	6	...	Magnetic	[40Pic]
721	...	7.6	...	Magnetic	[40Pic]
720	3.8 ± 0.3	8.5 ± 0.3	7	(b)	[65Gol]
717	2.6	...	...	X-ray	[30Rob]
705	...	9	...	Magnetic	[40Pic]
700	2.5	9	...	X-ray	[39Owe]
	3.9 ± 0.2	9.4 ± 0.2	56	(b)	[65Gol]
672	3.94	...	0.7	X-ray	[36Jet]
670	4.3 ± 0.2	12.1 ± 0.4	74	(b)	[80Rom]
668	...	12	...	Magnetic	[40Pic]
672	2.7	...	...	X-ray	[39Owe]
657	4.1	...	...	X-ray	[30Rob]
625	...	16	...	Magnetic	[40Pic]
600	3.5	14	...	X-ray	[39Owe]
	5.3 ± 0.3	19.3 ± 0.5	180	(a)	[65Gol]
	5.2 ± 0.5	19.4 ± 1.4	127	(b)	[80Rom]
585	...	26.20	457	X-ray	[36Jet]
	...	20	...	Magnetic	[40Pic]
572	...	23	...	Magnetic	[40Pic]
557	4.0	...	...	X-ray	[39Owe]
550	...	18.5	...	X-ray	[39Owe]
540	...	25	...	Magnetic	[40Pic]
526	...	25.9 ± 4	...	(c)	[63Heu]
523	11.2	...	...	X-ray	[30Rob]
557	4.22	...	1	X-ray	[36Jet]
518	12.6	...	...	X-ray	[30Rob]
500	5.0	26.5	...	X-ray	[39Owe]
	6.0 ± 1.0	31.5 ± 0.5	608	(a)	[65Gol]
	5.5 ± 0.4	31.7 ± 2.3	270	(b)	[80Rom]
496	5.0	...	...	X-ray	[39Owe]
	6.07	...	734	X-ray	[36Jet]
467	...	31.1 ± 4	...	(c)	[63Heu]
456	5.5	...	...	X-ray	[39Owe]
	5.91	33.36	3150	X-ray	[36Jet]
450	5.8 ± 0.5	36.4 ± 2.8	120	(b)	[80Rom]
412	...	37.0 ± 4	...	(c)	[63Heu]
400	6.5	41.5	...	X-ray	[39Owe]
	4.9 ± 0.5	43.8 ± 3.1	270	(b)	[80Rom]
370	...	46.3 ± 4	...	(c)	[63Heu]
365	...	34	...	Magnetic	[43Has]
350	5.8	49	28	X-ray	[39Owe]
	...	49	...	X-ray	[52Hun]
300	...	56.5	28	X-ray	[39Owe]
	4.0 ± 0.5	53.4 ± 4.1	430	(b)	[80Rom]

(a) Diffusion couple, analyze with electron probe. (b) Quench as α_2, anneal, analyze with electron probe. (c) Carbonyl vapor pressure.

martensitic transformation in Fe-24 wt.% Ni can be suppressed to below room temperature by splat cooling. For alloys with less than about 30 at.% Ni, the transformation is isothermal, and the transformation temperature is strongly dependent on impurity contents. Above 30 at.% Ni, the transformation is athermal and less dependent on impurities [83Kam]. Further investigations of the nature of the $\alpha_2 \rightarrow$ (γFe,Ni) transformation were made for example by [29Gos], [30Rob], [48Fis], [47Oel], [51Smo], [62Bre], [62Yeo], [63Gol], [67Rob], [71Geo], [77Roi], [79Mat], [81Bor], [82Duf], [84Bor], [84Izm], and [84Rin].

Considerable supercooling of liquid Fe-Ni alloys is possible. [78Con] observed supercooling of up to 150 K in an alumina crucible for alloys between 6 and 90 at.% Ni. [83Abb] studied supercooling in levitation melted 25 at.% Ni samples, obtaining supercooling up to 270 °C, somewhat less than the 300 °C reported by [66Kat] for alloys surrounded by glass coatings. Transformation of (γFe,Ni) to (αFe) in thin films was investigated by [78Gal].

Alloys containing approximately 20 to 50 at.% Ni—the so-called Invar alloys—exhibit anomalous thermomechanical and thermochemical behavior, including a region of very low coefficient

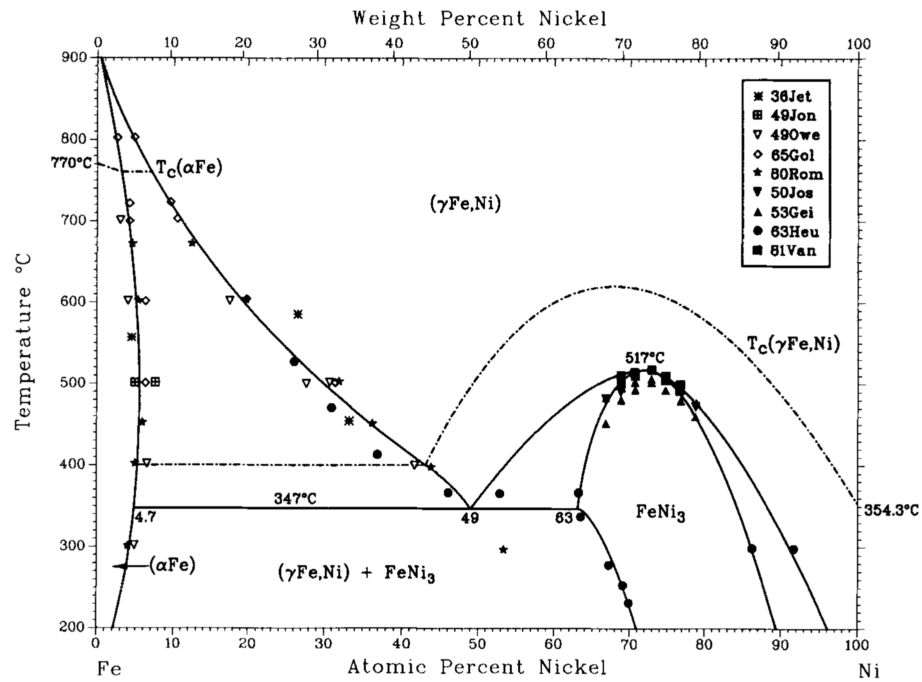

Fig. 4 Low-temperature region of the Fe-Ni phase diagram.

of thermal expansion. [79Cha] showed that these Invar anomalies tend to disappear in alloys that have been electron irradiated to enhance diffusion and thereby accelerate the approach to true equilibrium. Thus it is probable that the Invar anomalies are a characteristic of metastable alloys. Literature on the Invar state is extensive, and we refer here to [60Kon], [64Ban], [72Wei], [78Kat], [78Cha], and [79Shi], where many additional references may be found. Recently, [85Chu2] proposed that the presence and disappearance of the Invar anomalies are related to a spinodal gap due to a tricritical point arising from the magnetic transition in fcc alloys (see Fig. 6).

An orthorhombic phase in thin films with a composition in the (αFe) + (γFe,Ni) region of the equilibrium diagram was indicated by [58Pin]. This phase was not retained above 650 °C. [56Cec] postulated that small particles of 30 at.% Ni that were rapidly cooled from the liquid state could pass directly to the (αFe) phase. A surface phase, either orthorhombic or tetragonal, which formed on 50 at.% Ni magnetic tapes after 18 months at room temperature was reported by [59Ana]. A reversible transformation from one fcc structure to two fcc structures below about 150 °C in 30 to 45 at.% Ni alloys was reported by [61Ana]. Rapidly solidified Fe-Ni alloys were also studied by [73Miz], [79Bos], [84Gor], and [84Miu].

Metastable FeNi and Fe_3Ni

The existence of ordered structures based on Fe_3Ni and FeNi have been proposed by a number of investigators. For the equiatomic composition, an order-disorder reaction below 321 ± 2 °C was reported by [60Pau], [62Pau1], and [62Pau2] for alloys that were heavily irradiated by neutrons. [56Tin] gave X-ray data supporting the existence of an ordered structure near the Fe_3Ni composition. The existence of Fe_3Ni and FeNi ordered structures was investigated further by [43Hos], [58Kus], [60Pau], [61Ban], [63Heu], [63Mar], [64Nee], [70Gro], [71Hau], [79Sco], and [84Cen]. Ordering in FeNi after either electron or neutron irradiation was observed by [78Cha] and [79Cha]. FeNi superstructure was observed in meteorites by [77Pet] and investigated further by [79Sco], [80Meh], and [82Gol]. In a study of meteorites, [82Jag] found that compositions of 30 to 40 at.% Ni consisted of ordered (γFe,Ni) + ordered FeNi, whereas [79Lin], in a STEM study of Fe-Ni meteorites, found decomposition into (αFe) + (γFe,Ni) with ~5 and 47 at.% Ni, respectively.

[82Gol] proposed a metastable phase diagram, with FeNi having AuCu superlattice structure to account for the "cloudy zone" structure found in meteorites [78Alb1, 78Alb2]. [84Ros1] and [84Ros2] recently proposed that ordered FeNi be included as an equilibrium phase in the Fe-Ni diagram. Figure 6 compares the cluster variation calculations of [84Yam] for the ordering reactions with the assessed diagram of Fig. 1. Also shown in Fig. 10 are the calculations by [85Chu2], [85Chu3], and [86Chu] of a possible tricritical point and spinodal arising from the magnetic interaction. [71Hau] identified Fe_3Ni order in Invar alloys using electron diffraction and pointed out its similarity to Fe_3Ni. Computer modeling of the order-disorder transformation in $FeNi_3$ was performed by [74Gol]. Recent work on Fe-Ni meteorites by [89Reu] also pointed to the existence of FeNi and Fe_3Ni in the equilibrium diagram.

The FeNi and Fe_3Ni ordered structures are not shown on the diagram of Fig. 1. Although still an open question, it is probable that these ordered phases are metastable or unstable structures

Table 3 FeNi3 Equilibrium Boundary Measurements

Reference	Technique	Equilibrium	Temperature, °C	Composition, at.% Ni
[50Jos]	Dilatometry	$(\gamma Fe,Ni)/FeNi_3$	479	67
			491	69
			500	71
			504	73
			501	75
			492	77
			474	79
[53Gei]	Dilatometry	$(\gamma Fe,Ni)/(\gamma Fe,Ni) + FeNi_3$	482	67
			495	69
			504	71
			509	73
			503	75
			494	77
			477	79
	Dilatometry	$(\gamma Fe,Ni) + FeNi_3/(\gamma Fe,Ni)$	452	67
			481	69
			494	71
			503	73
			492	75
			480	77
			461	79
[63Heu]	Carbonyl vapor pressure	$(\gamma Fe,Ni)/(\gamma FeNi) + FeNi_3$	365	53 ± 4
		$(\gamma FeNi) + FeNi_3$	365	62 ± 4
		$FeNi_3/FeNi_3 + (\gamma Fe,Ni)$	300	87 ± 4
		$FeNi_3 + (\gamma Fe,Ni)/(\gamma Fe,Ni)$	300	92 ± 4
		$(\alpha Fe) + FeNi_3/FeNi_3$	333	63.3
			319	64.5
			277	67.4
			253	69.2
			232	70.2
[81Van]	Mössbauer spectroscopy	$(\gamma Fe,Ni)/(\gamma Fe,Ni) + FeNi_3$	510	69
			516	71
			516	73
			511	75
			501	77
		$(\gamma Fe,Ni) + FeNi_3/(\gamma Fe,Ni)$	505	69
			512	71
			515	73
			508	75
			494	77

reached in alloys in which the sluggish $(\gamma Fe,Ni) \rightarrow (\alpha Fe) + FeNi_3$ eutectoid reaction has been suppressed.

Crystal Structures and Lattice Parameters

A summary of the crystal structures found in Fe-Ni alloys is given in Table 4, and lattice parameters are listed in Table 5. Measured values of the lattice parameters for the (αFe) and (γFe,Ni) phases vs composition are shown in Fig. 7 and 8. The solid lines in Fig. 7 and 8 represent a weighted least-squares fit to these values.

[37Owe1] found that the (γFe,Ni) phase lattice parameter at room temperature (20 °C) as a function of composition reaches a maximum value of 0.3597 nm at 39 at.% Ni and then diminishes at almost the same rate at which it increases. [37Bra] made lattice spacing measurements on alloys containing 27 to 100 at.% Ni that were quenched from 700, 800 and 900 °C. This quenching gave larger lattice spacings than annealed, ordered alloys. Values shown in Fig. 8 are for their annealed alloys, which are more representative of equilibrium. [26Osa1] and [26Osa2] measured the lattice parameters and the densities for alloys annealed at 1150 °C and then slow cooled. [63Dav] investigated the variation in lattice parameter in $FeNi_3$ on annealing at 480 °C for up to 1000 h.

Lattice parameters were also measured by [21And], [22Kir], [23Bai], [23Mck], [27Jun], [31Phr], [37Owe1], [37Owe2], [37Owe3], [37Owe4], [37Owe5], [41Owe], [49Hah], [53Wak], [54Lih], [55Roy], [55Sut], [66Abr], [69Ree], [69Asa], and [83Sen]. The most extensive work is that of [41Owe]. Over most of the region of the Fe-Ni diagram, lattice parameters measured at room temperature will depend on the exact heat treatment given the alloy.

Thermodynamics

[Hultgren,B] assessed the thermodynamic work on Fe-Ni through about 1972. [73Kau] and [70Pre1] reviewed thermodynamic properties of the system for use in calculations of the phase diagram. Since then, phase diagram calculations were

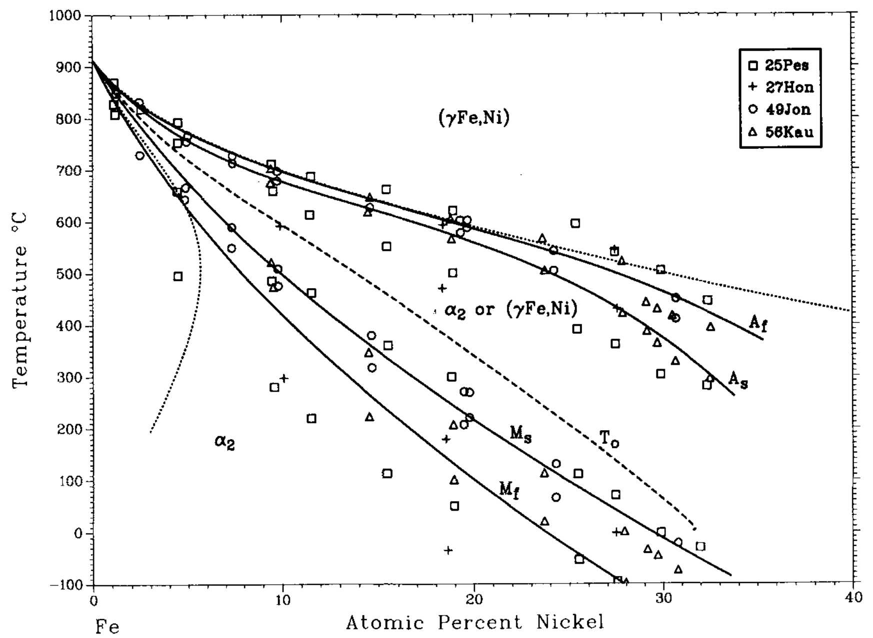

Fig. 5 Transformation diagram for Fe-Ni alloys.

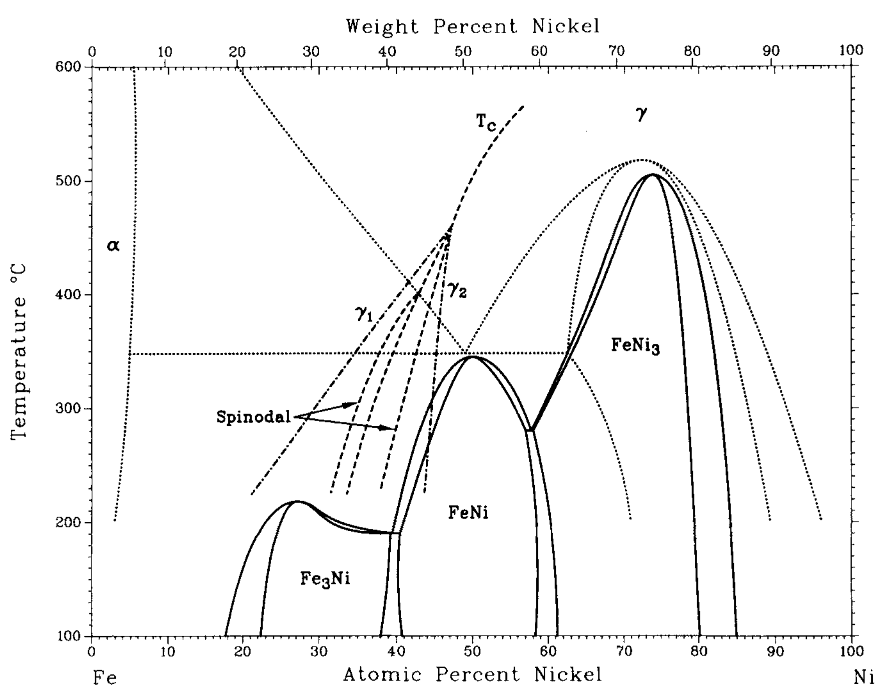

Fig. 6 Comparison of cluster variation calculation and spinodal calculation with the equilibrium boundaries.

Table 4 Fe-Ni Crystal Structure Data

Phase	Composition, at.% Ni	Pearson symbol	Space group	Strukturbericht designation	Prototype
(δFe)(a)	0 to 3.5	*cI2*	*Im*$\bar{3}$*m*	*A2*	W
(γFe,Ni)(b)	0 to 100	*cF4*	*Fm*$\bar{3}$*m*	*A1*	Cu
(αFe)(c)	0 to 5.5	*cI2*	*Im*$\bar{3}$*m*	*A2*	W
$FeNi_3$	63 to 85	*cP4*	*Pm*$\bar{3}$*m*	$L1_2$	$AuCu_3$
Metastable phases					
FeNi	...	*tP2*	*P4/mmm*	$L1_0$	AuCu
Fe_3Ni	...	*cP4*	*Pm*$\bar{3}$*m*	$L1_2$	$AuCu_3$

(a) From 1538 to 1394 °C at 0 at.% Ni. (b) From <1394 to 912 °C at 0 at.% Ni; at all temperatures at 100 at.% Ni. (c) Below <912 °C at 0 at.% Ni.

Table 5 Fe-Ni Lattice Parameter Data

Phase	Composition, at.% Ni	Lattice parameter, nm	Comment	Reference
(δFe)	0 to 3.5	0.29322	At 1394 °C, 0 at.% Ni	[65Pea]
(γFe,Ni)	0 to 100	0.36468	At 916 °C, 0 at.% Ni	[65Pea]
		0.35240	At 25 °C, 100 at.% Ni	[Massalski2]
(αFe)	0 to 5.5	0.28664	At 20 °C, 0 at.% Ni	[65Pea]
$FeNi_3$	63 to 85	0.35523	At 20 °C, 75 at.% Ni	[65Pea]
Metastable phases				
FeNi	...	...	...	...
Fe_3Ni	...	...	...	...

made by [74Bas], [74Rao], [77Has], [77Lar], [79Lar], [80Lar], [81Imr], [81Nis], [82Cha], [82Vel], [85Chu2], [86Chu1], and [86Chu2].

[74Rao] analyzed phase diagram data, together with thermochemical information, to deduce analytical equations for the thermodynamic functions in solutions. [77Kub] assessed partial and integral enthalpies and entropies of mixing for (γFe,Ni) alloys. [82Vel] derived analytical polynomial expressions for the integral enthalpies of mixing, excess entropies, and the Gibbs energies for the liquid and (γFe,Ni) alloys and used those expressions for the evaluation of the phase diagram.

Enthalpies of mixing of liquid alloys were measured in calorimeters by dropping one pure solid component into a bath with the other component molten. This method was used by [71Toz], [81Igu], [74Bat], and [66Elt]. [70Pre1] used differential thermal analysis for determination of the heat of mixing. The study of [66Elk] contradicts the other investigations, has considerable scatter of experimental values, and was dropped from further consideration. The study of [71Toz] gave unreasonably low values of heats of mixing; they were replaced with new values by the same authors in [81Igu]. The experimental results of [81Igu], [74Bat], and [70Pre1] agree satisfactorily (see Fig. 9).

Enthalpies of mixing for solid alloys were obtained by calorimetric measurement of the heat of reaction between powdered components at 1400 to 1600 K. This method was used by [63Den], [67Kub], and [71Spe]. [61Ste] dissolved solid components and alloys in liquid tin inside the calorimeter at 1123 K. The results of [63Den], [67Kub], [71Spe], and [61Ste] agree satisfactorily and they are also shown in Fig. 9. When all the experimental results are plotted in one graph (see Fig. 9), it is obvious that the data for solid and liquid alloys are partially overlapping, *i.e.*, the enthalpies of mixing for solid and liquid alloys are the same, within the experimental error.

The problem of differentiating the data for liquid and solid alloys was discussed by [77Kub] and [70Pre1]. [70Pre1] measured heats of melting of ten alloys. Their results deviate from the additive value by 400 to 700 J/mol, which can be compared with the errors in determination of the heat of melting of components given by [70Pre2]: ±750 J/mol. If the experimental data for both the solid and liquid heats of mixing are least-squares fitted to a four-term Redlich-Kister expression, the following equation is obtained for the excess enthalpy:

$$H^{ex} = X_{Fe}X_{Ni}[-16\,226 - 14\,982(X_{Fe} - X_{Ni}) + 200(X_{Fe} - X_{Ni})^2 + 11\,382(X_{Fe} - X_{Ni})^3]$$

This curve is plotted as a solid line in Fig. 9. The uncertainty in the integral values of heat of mixing is on the order of ±600 J/mol. In Fig. 9, the dotted line represents the liquid excess enthalpies calculated from the thermodynamic model below, and the dashed line represents the solid excess enthalpies calculated from the same model.

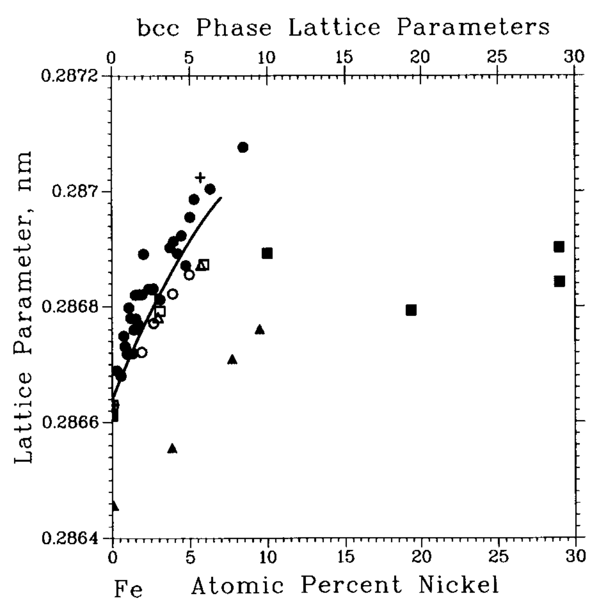

Fig. 7 Lattice parameters of (αFe) at 20 °C.

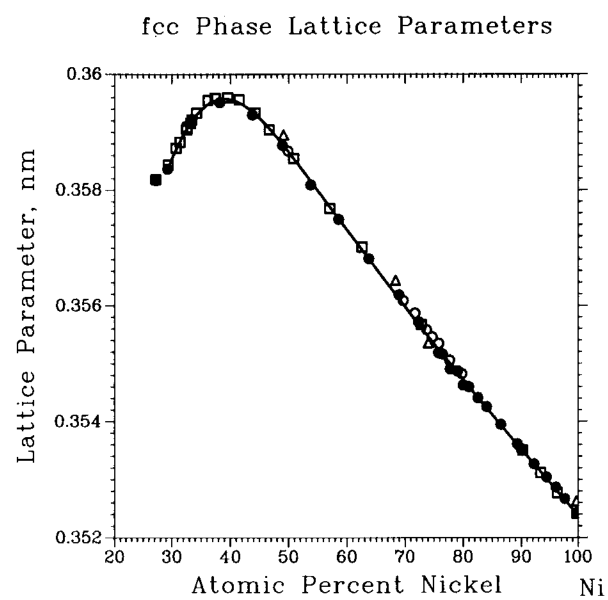

Fig. 8 Lattice parameters of (γFe,Ni) at 20 °C.

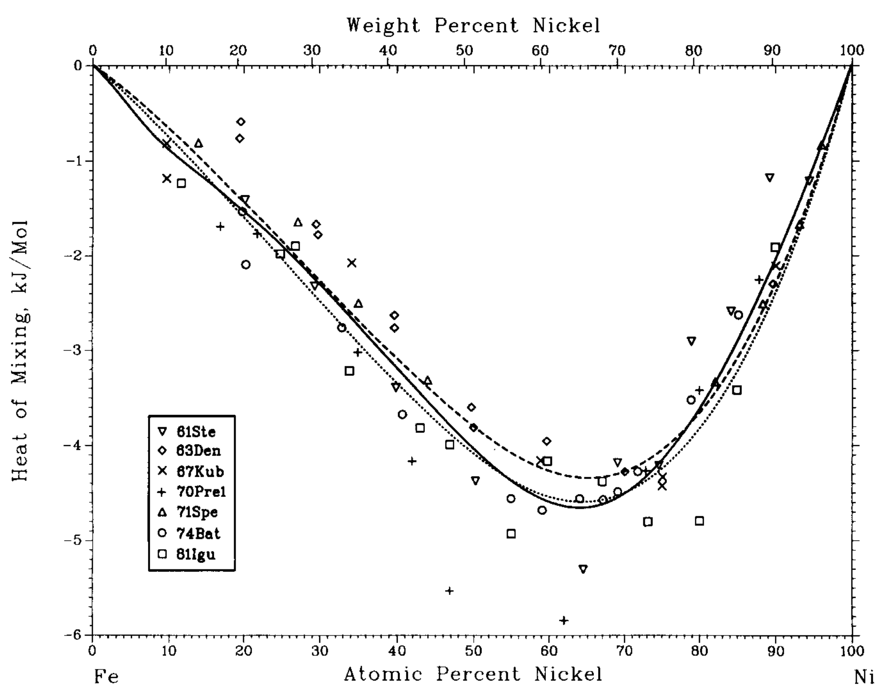

Fig. 9 Heats of mixing for solid and liquid Fe-Ni alloys.

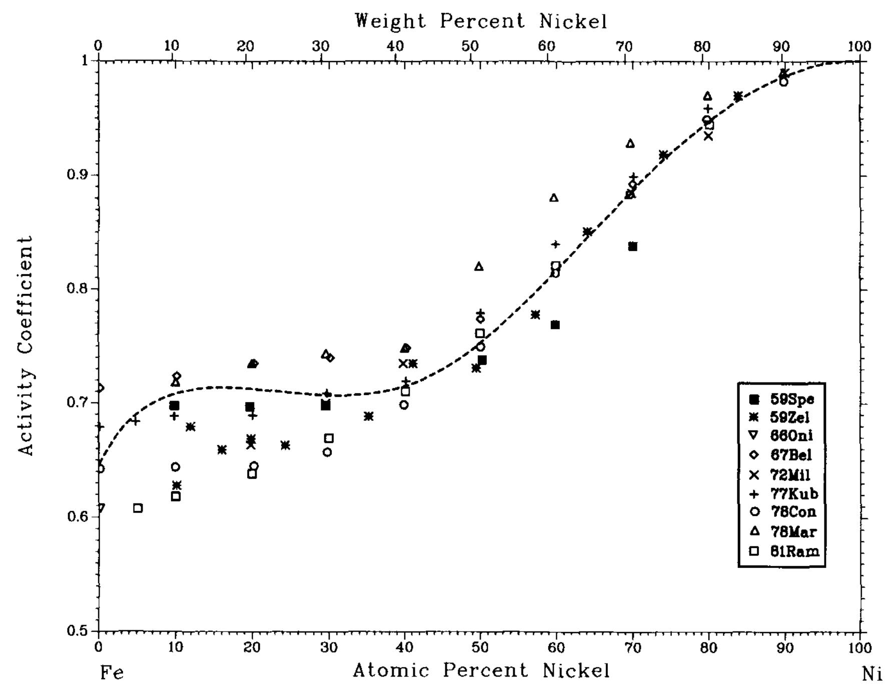

Fig. 10 Ni activity coefficients for liquid Fe-Ni alloys at 1873 K.

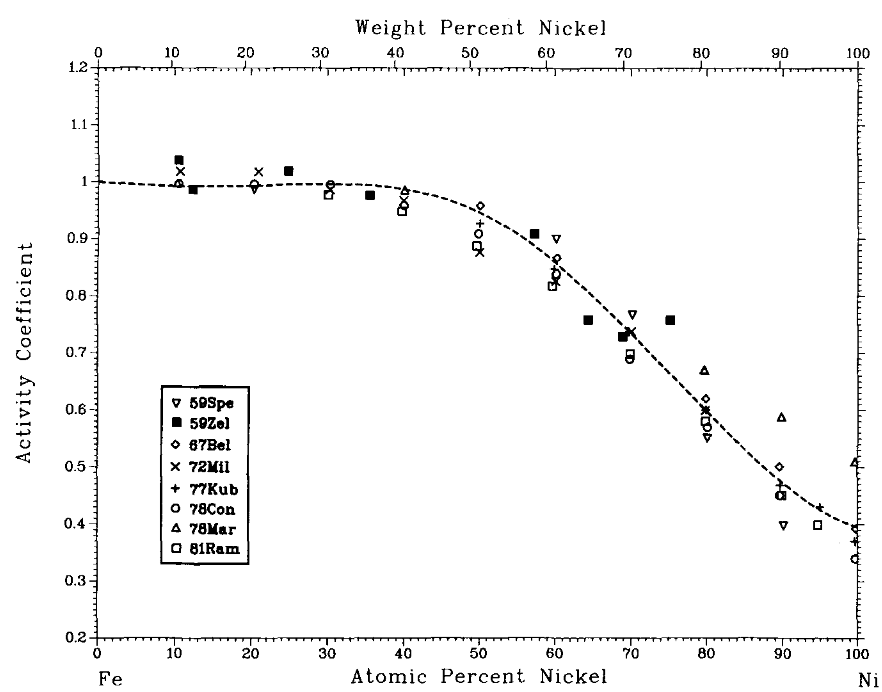

Fig. 11 Fe activity coefficients for liquid Fe-Ni alloys at 1873 K.

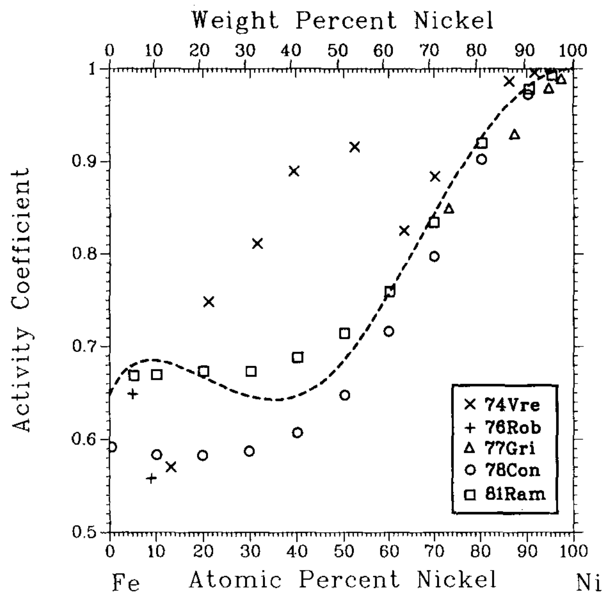

Fig. 12 Ni activity coefficients for (γFe,Ni) at 1473 K.

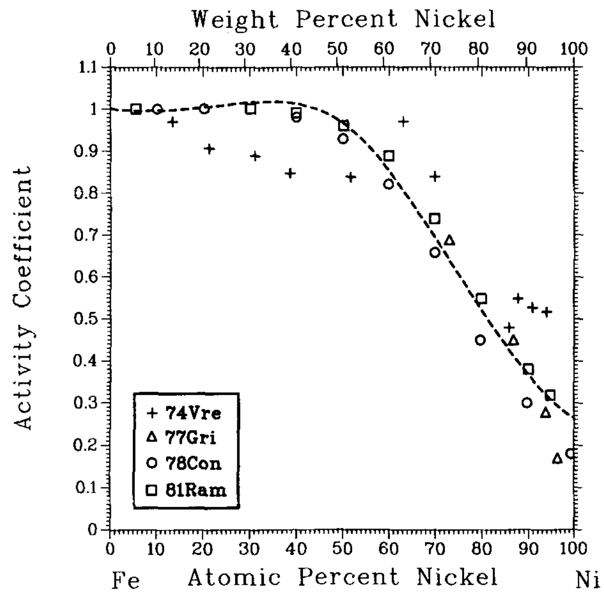

Fig. 13 Fe activity coefficients for (γFe,Ni) at 1473 K.

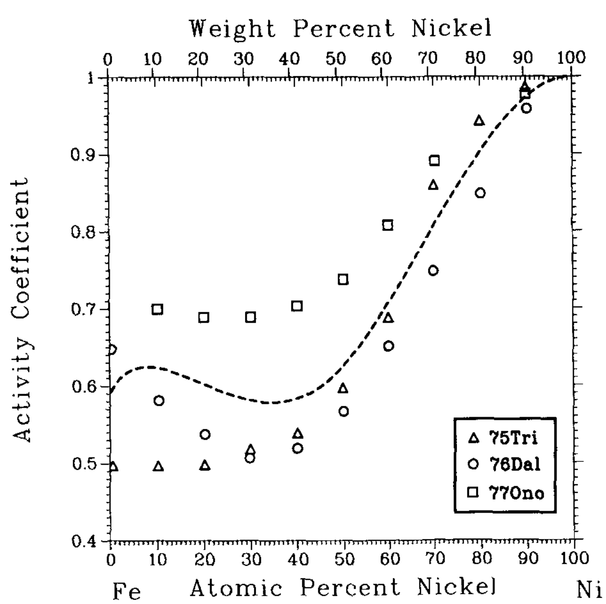

Fig. 14 Ni activity coefficients for (γFe,Ni) at 1273 K.

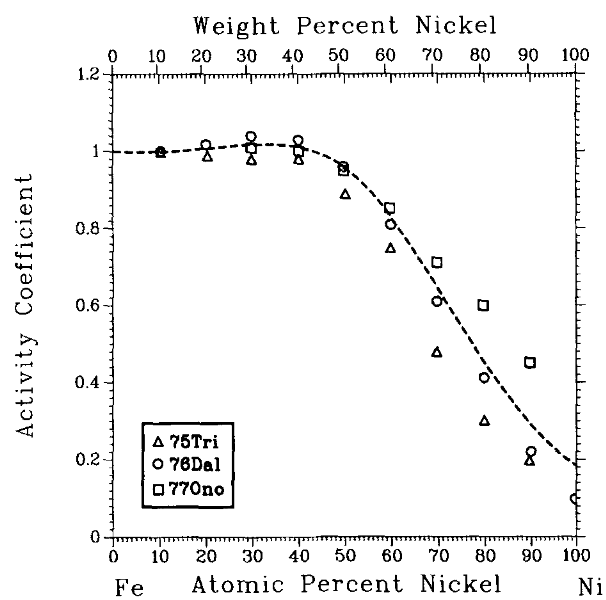

Fig. 15 Fe activity coefficients for (γFe,Ni) at 1273 K.

Table 6 Thermodynamic Parameters Used to Model the Fe-Ni Phase Diagram

Liquid phase

$G(\text{Fe,L}) = 0$

$G(\text{Ni,L}) = 0$

$G^{ex}(\text{L}) = X_{Fe}X_{Ni}[-16\,391 + 3.17\,T + (12\,075 - 2.6\,T)(X_{Fe} - X_{Ni}) + (-2000 + T)(X_{Fe} - X_{Ni})^2 + (-1500 - T)(X_{Fe} - X_{Ni})^3]$

bcc phase

$G(\text{Fe,bcc}) = 12\,736.4 - 17.216\,T + 23.18\,T\ln T - 0.0048155\,T^2$

$G(\text{Ni,bcc}) = -12\,500 + 9\,T$

$G^{ex}(\text{bcc}, T > 1667\text{ K}) = X_{Fe}X_{Ni}[1950 - 3.05\,T + (-2000 + T)(X_{Fe} - X_{Ni})^2 + (-1500 - T)(X_{Fe} - X_{Ni})^3]$

$G^{ex}(\text{bcc}, T < 1185\text{ K}) = X_{Fe}X_{Ni}[13\,274 - 13\,T + (-2000 + T)(X_{Fe} - X_{Ni})^2 + (-1500 - T)(X_{Fe} - X_{Ni})^3]$

$G^{ex}(\text{bcc}, 500 < T < 1850\text{ K}) = X_{Fe}X_{Ni}(9381 - 8.775\,T)$

$G(\text{bcc,mag}) = RT_C(\text{bcc})\ln[\beta(\text{bcc}) + 1]f(t)$

$t = T/T_C(\text{bcc})$

$f(t < 1) = -0.9053 + t - 0.153\,t^4 - 0.068\,t^{10} - 0.00153\,t^{16}$

$f(t > 1) = -0.06417\,t^{-4} - 0.002037\,t^{-14} - 0.0004278\,t^{-24}$

$T_C(\text{bcc}) = 1043X_{Fe} + X_{Fe}X_{Ni}[-757.6 + 1946(X_{Fe} - X_{Ni}) + 2153(X_{Fe} - X_{Ni})^2 - 2779(X_{Fe} - X_{Ni})^3]$

$\beta(\text{bcc}) = 2.22X_{Fe} + X_{Fe}X_{Ni}[1.176 + 1.445(X_{Fe} - X_{Ni}) + 2.275(X_{Fe} - X_{Ni})^2 - 2.042(X_{Fe} - X_{Ni})^3]$

fcc phase

$G(\text{Fe,fcc}) = 11\,274 - 16.3878\,T + 22.03\,T\ln T - 0.0041755\,T^2$

$G(\text{Ni,fcc}) = 3667.6 - 14.4177\,T + 20.113\,T\ln T - 0.004561\,T^2$

$G^{ex}(\text{fcc}) = X_{Fe}X_{Ni}[-15\,291 + 3.47\,T + (12\,061 - 2.5\,T)(X_{Fe} - X_{Ni}) + (-2000 + T)(X_{Fe} - X_{Ni})^2 + (-1500 - T)(X_{Fe} - X_{Ni})]$

$G(\text{fcc,mag}) = RT_C(\text{fcc})\ln[\beta(\text{fcc}) + 1]f(t)$

$t = T/T_C(\text{fcc})$

$f(t < 1) = -0.5597 - 0.6315\,t - 0.09178\,t^4 + 0.001872\,t^{10} - 0.007715\,t^{16}$

$f(t > 1) = -0.03184\,t^{-4} + 0.002468\,t^{-14} - 0.0019904\,t^{-24}$

$T_C(\text{fcc}) = -80X_{Fe} + 627.4X_{Ni} + X_{Fe}X_{Ni}[2040.5 - 1250(X_{Fe} - X_{Ni}) - 2627(X_{Fe} - X_{Ni})^2 - 1784(X_{Fe} - X_{Ni})^3]$

$\beta(\text{fcc}) = -1.59X_{Fe} + 0.62X_{Ni} + X_{Fe}X_{Ni}[8.644 + 7.691(X_{Fe} - X_{Ni}) + 4.435(X_{Fe} - X_{Ni})^2 + 0.585(X_{Fe} - X_{Ni})^3]$

$FeNi_3$ phase

$G(\text{Fe in FeNi}_3) = 1127.4 - 16.388\,T + 22.03\,T\ln T + 0.0041755\,T^2$

$G(\text{Ni in FeNi}_3) = 3667.6 - 14.418\,T + 20.11\,T\ln T - 0.0045610\,T^2$

$G^{ex}(\text{FeNi}_3) = X_{Fe}X_{Ni}[-24\,185 + 1.9\,T + 21\,475(X_{Fe} - X_{Ni}) + (-1700 + T)(X_{Fe} - X_{Ni})^2 + (-1500 - T)(X_{Fe} - X_{Ni})^3]$

$G(\text{FeNi}_3\text{,mag}) = RT_C(\text{FeNi}_3)\ln[\beta(\text{FeNi}_3) + 1]f(t)$

$t = T/T_C(\text{FeNi}_3)$

$f(t < 1) = -0.5597 - 0.6315\,t - 0.09718\,t^4 + 0.001872\,t^{10} - 0.007715\,t^{16}$

$f(t > 1) = -0.03184\,t^{-4} + 0.002468\,t^{-14} - 0.0019904\,t^{-24}$

$T_C(\text{FeNi}_3) = -80X_{Fe} + 627.4X_{Ni} + X_{Fe}X_{Ni}[2040.5 - 1250(X_{Fe} - X_{Ni}) - 2627(X_{Fe} - X_{Ni})^2 - 1784(X_{Fe} - X_{Ni})^3]$

$\beta(\text{FeNi}_3) = -1.59X_{Fe} + 0.62X_{Ni} + X_{Fe}X_{Ni}[8.644 + 7.691(X_{Fe} - X_{Ni}) + 4.435(X_{Fe} - X_{Ni})^2 + 0.585(X_{Fe} - X_{Ni})^3]$

Note: X_{Fe} and X_{Ni} are atomic fractions; Gibbs energy values are in J/mol; and T is in K.

Measurements of the activities in liquid alloys using the transportation method with a stream of inert gas were made by [59Zel] at 1830 to 1891 K, by [78Mar] at 1873 K, and by [66Oni] in dilute alloys at 1825 to 1930 K. The transpiration method based on analysis of condensate evaporated in vacuum was used by [59Spe] at 1783 to 1873 K, by [72Mil] at 2178 to 2558 K, and by [71Tse] at 1873 K. The Knudsen cell with a mass spectrometer was used by [77Kub] at 1773 to 1923 K, by [78Con] at 1500 to 1900 K, by [67Bel] at 1863 K, and by [81Ram] at 1373 to 1923 K. The results obtained by [71Tse] deviate considerably from other studies and were discarded. All other investigations appear to be in reasonable agreement, at least over most of the concentration range. Most of the results are plotted in Fig. 10 and 11. (In these figures, the dotted lines represent the values calculated from the thermodynamic model given below.) From the analysis of information given in the original papers, it is difficult to reject a study completely or to give preference to any particular group of investigations.

[72Dav], [78Con], and [81Ram] also made measurements of activities in the solid alloys. Solid alloy activity measurements using CO/CO_2 equilibrium over the Fe-Ni-O system were made by [77Gri] at 1573 K for alloys between 0 and 27 at.% Ni. [76Rob] reported on Ni activities in two alloys with 4.8 and 9.4 at.% Ni at 1400 to 1550 K measured by Knudsen cell with a mass spectrometer. These results agree satisfactorily and are plotted in Fig. 12 and 13. (In these figures, the dotted lines represent the values calculated from the thermodynamic model given below.) Early investigations of solid activities were made by [58Lyu], who measured vapor pressures of alloys using a mass spectrometer at 1463 to 1583 K and by [74Vre] using the transpiration method at 1509 K for alloys between 13 and 94 at.% Ni. The results of [58Lyu] are close to ideal values for both components—in considerable contradiction with the other results—and were dropped from further consideration. The results of [74Vre], plotted in Fig. 12 and 13, were given low weight because of their scatter and contradiction with the later investigations.

Table 7 Average Magnetic Moments Measured for Ferromagnetic Fe-Ni Alloys

Phase	Composition, at.% Ni	μ, Bohr magnetons	Reference
(αFe)	0	2.22	[63Cra]
	1.4	2.21	[25Pes]
	1.5	2.24	[63Cra]
	3.0	2.26	[63Cra]
	3.5	2.22	[25Pes]
	4.3	2.27	[63Cra]
	5.1	2.23	[25Pes]
	6.2	2.29	[63Cra]
	6.9	2.24	[25Pes]
	9.3	2.28	[63Cra]
	11.3	2.23	[25Pes]
	11.5	2.29	[63Cra]
	15.9	2.22	[25Pes]
	18.9	2.23	[63Cra]
	19.0	2.21	[25Pes]
	23.3	2.17	[63Cra]
	25.2	2.13	[25Pes]
	25.5	2.12	[25Pes]
	29.7	2.00	[25Pes]
	30.4	2.00	[63Cra]
	0	2.20	[25Pes]
(γFe,Ni)	32.5	1.93	[63Cra]
	30.8	1.25	[63Cra]
	32.1	1.61	[63Cra]
	34.3	1.77	[63Cra]
	35.3	1.82	[63Cra]
	40.8	1.80	[25Pes]
		1.84	[63Cra]
	42.0	1.79	[25Pes]
	43.5	1.77	[25Pes]
	49.6	1.67	[25Pes]
	49.8	1.69	[63Cra]
	51.0	1.65	[25Pes]
	57.7	1.52	[25Pes]
	60.0	1.50	[63Cra]
	67.0	1.36	[25Pes]
	79.7	1.07	[63Cra]
	80.2	1.06	[25Pes]
	87.7	0.88	[25Pes]
	100	0.61	[25Pes, 63Cra]

With decreasing temperature, the vapor pressure and the reliability of activity measurements drop rapidly. The difference in values of the Ni activity coefficients at 1473 K (Fig. 12) between two similar investigations [78Con, 67Bel] looks natural, considering the probable uncertainty of the methods used. For both solid and liquid alloys, the uncertainty in determination of the activity coefficient of either of the components is on the order of ±0.03 for a component in an alloy near the pure component, ±0.08 in alloys around the equiatomic composition, and ±0.15 for a component in alloy near infinite dilution.

Other reports of activities in solid alloys were provided by [49Kub], [53Ori], [69Kus], [64Roe], [70Gat], [72Dav], [75Tri], [76Dal], [77Ono], and [79Tan]. Most of these contradict each other, and it is worthwhile to plot only some of the latest studies. [75Tri] measured CO/CO_2 equilibrium over the Fe-Ni-O system at 1273 K. [76Dal] used the same technique at 1065 to 1380 K. [77Ono] measured the Fe activities by the emf method at 1023 to 1423 K. Figures 14 and 15 show that at 1273 K, the results of three of these studies agree satisfactorily. (The dotted lines in the figures represent the values calculated from the thermodynamic model given below.)

Specific heat measurements in the Fe-Ni system at low temperatures were reported by [40Kee], [64Gup], [65Ehr], and [66Shi] and at higher temperatures by [39Lee], [73Kol], and [82Bro2].

An attempt was made to construct a thermodynamic model that represents the Fe-Ni diagram over the widest possible temperature range and agrees, within the above stated experimental errors, with the thermodynamic measurements. This model was used as an aid in the evaluation of the measured phase diagram boundaries, and greater weight was given to these boundaries than to the thermodynamic measurements. In the model, the Gibbs energy for a phase p is represented by:

$$G(p) = X_{Fe}G(p,\text{Fe}) + X_{Ni}G(p,\text{Ni}) + G(p,\text{mag}) + RT(X_{Fe}\ln X_{Fe} + X_{Ni}\ln X_{Ni}) + G(p)^{ex}$$

where $G(p,\text{Fe})$ is the Gibbs energy of pure Fe, and $G(p)^{ex}$ is the nonmagnetic excess free energy. Following [74Ind], the magnetic contribution to the Gibbs energy is of the form:

$$G(p,\text{mag}) = RT_C(p)\ln(\beta(p) + 1)f(t)$$

where t is the reduced temperature T/T_C, T_C is the Curie temperature, and β is magnetic moment in Bohr magnetons. Both T_C and β are functions of composition. In the Fe-Ni system, all three phases in the equilibrium diagram are ferromagnetic, and the magnetic contribution is significant, especially at temperatures below 912 °C. Early estimates of the magnetic contributions to phase equilibrium in the Fe-Ni system were given by [73Sch].

The functions for T_C and β for the bcc and fcc phases were obtained by least-squares fitting the literature data. For the $FeNi_3$ phase, T_C and β values were taken to be approximately equal to those in the fcc phase. For the bcc phase, the function $f(t)$, as expanded in a power series by [78Hil], was used (the resultant contribution to the Gibbs energy agrees well with the alternate form used by [85Chu1]). For the fcc phase, the same power series for $f(t)$ was used, with the coefficients being obtained by least-squares fitting the evaluated specific heat data of [84Des] for Ni. For pure Fe, the thermodynamic functions given by [79Agr] were used. For pure Ni, the enthalpies of melting and specific heat values given in the evaluation of [84Des] were used to construct the nonmagnetic part of the thermodynamic functions. For bcc Ni, the lattice stability estimates of [73Kau] were used. In assessing the diagram, the thermodynamic modeling and optimization procedure of [81Sun] were used. For the liquidus and solidus, greatest weight was given to the liquidus measurements, especially those of [57Hel].

The parameters found by a combination of optimization and trial and error to best fit the diagram are given in Table 6, and the calculated Fe-Ni diagram is shown in Fig. 16. Above about 500 °C, the calculated and assessed diagrams are nearly identical (± 1 °C in temperature and ±0.5 at.% in composition). At lower temperatures, the assessed and calculated boundaries differ somewhat. Especially noticeable is the tricritical point predicted by the model and arising from the influence of the magnetic contribution

Table 8 Measured Curie Temperatures vs Composition for Fe-Ni Alloys

Phase	Composition, at.% Ni	Curie, Temperature, °C	Reference
(αFe)	0	771	[25Pes]
		770	[29Gos]
	1.4	766	[25Pes]
	2.8	763	[29Gos]
	3.5	758	[25Pes]
	4.8	755	[29Gos]
	5.1	752	[25Pes]
	6.9	748	[25Pes]
	15.9	740	[25Pes]
	19.0	715	[25Pes]
	23.0	565	[43Hos]
	29.7	597	[25Pes]
	31.3	535	[25Pes]
	33.3	460	[25Pes]
	33.8	435	[25Pes]
(γFe,Ni)	29.7	120	[25Pes]
	30.8	100	[63Cra]
	31.3	160	[25Pes]
	31.8	174	[25Pes]
	32.1	156	[63Cra]
	33.3	228	[25Pes]
	33.8	245	[25Pes]
	35.3	261	[25Pes]
		228	[63Cra]
	36.1	250	[63Cra]
	37.0	285	[25Pes]
	38.5	300	[29Gos]
	39.0	317	[25Pes]
	40.8	321	[25Pes]
		354	[63Cra]
	42.0	346	[25Pes]
	43.5	403	[25Pes]
	45.0	468	[53Wak]
	47.1	415	[29Gos]
	49.3	506	[25Pes]
	49.8	513	[63Cra]
	50.0	520	[53Wak]
	51.0	522	[25Pes]
(γFe,Ni)(cont.)	55.0	558	[53Wak]
	57.7	590	[25Pes]
	60.0	592	[53Wak]
		591	[63Cra]
	65.0	613	[53Wak]
	67.0	612	[25Pes]
	68.0	616	[53Wak]
	70.0	614	[53Wak]
	72.0	608	[53Wak]
	74.0	600	[53Wak]
	75.0	598	[53Wak]
	76.0	589	[53Wak]
	78.0	585	[53Wak]
	79.7	570	[63Cra]
	80.0	577	[53Wak]
	80.2	576	[25Pes]
	81.0	571	[53Wak]
	85.0	543	[53Wak]
	87.7	511	[25Pes]
	100.0	360	[25Pes]
		361 ± 1	[63Cra]
		354.3	[68Kou]
$FeNi_3$	45.0	494 ± 5	[53Wak]
	50.0	543	[53Wak]
	55.0	580	[53Wak]
	60.0	616	[53Wak]
	65.0	636	[53Wak]
	68.0	668	[53Wak]
	70.0	680	[53Wak]
	72.0	696	[53Wak]
	74.0	691	[53Wak]
	75.0	681	[53Wak]
	76.0	654	[53Wak]
	78.0	624	[53Wak]
	80.0	599	[53Wak]
	81.0	584	[53Wak]
	85.0	543	[53Wak]

to the Gibbs energy. (The tricritical point was also calculated by [77Hut].) [85Chu2] gave convincing arguments for the existence of this tricritical point, but further experimental confirmation appears necessary. In fitting the (αFe)/(δFe) and (αFe)/(γFe,Ni) experimental boundaries, better fits are obtained if the expression for the excess energy of the bcc phase is divided into two temperature regions—one for the (αFe) and one for the (δFe) region. An expression for the bcc excess energy that covers the entire temperature range, which gives a good approximation to the observed boundaries and which is more sensible from a thermodynamic point of view, is also included in Table 6.

In Fig. 9, the heats of mixing obtained from the parameters of Table 6 are compared with the measured values (the dotted line is for the liquid, the dashed line for the solid). In Fig. 10 through 15, the theoretical values of the activities calculated from the model parameters (dotted lines) are compared with measured values. In all instances, agreement is within experimental error. However, the fits are in some respects unsatisfying, especially for the Ni-rich heats of mixing and Fe-rich Ni activities. The slight oscillation in the Ni activity coefficients on the Fe-rich side (Fig. 12 and 14) evidently is unjustified by the data. This may be in part due to the poor accuracy of the measured values of the solidus and liquidus of the Ni rich alloys.

Pressure

The equilibrium diagram for 50, 100, and 150 kbar was calculated by [61Kau1]. [61Kau2] showed that pressure lowers the (γFe,Ni) → (αFe) transformation temperatures. [66Mcq] investigated the effect of pressure on the density of Fe-Ni alloys by the shock technique up to 2000 kbar. Using XRD, [68Tak] measured the effect of pressure on the crystal structure and molar volume.

Magnetism

The saturation magnetization, average magnetic moments, and Curie temperatures for single-phase fcc alloys from 30 to 100 at.% Ni were measured by [63Cra]. They also measured the average magnetic moment for single-phase bcc alloys in the range 0 to 30 at.% Ni. Magnetic moments on individual Fe and Ni atoms were measured by [62Col], [73Cab], [74Nis], and [55Shu] between 40 and 100 at.% Ni. The use of magnetic measurements for

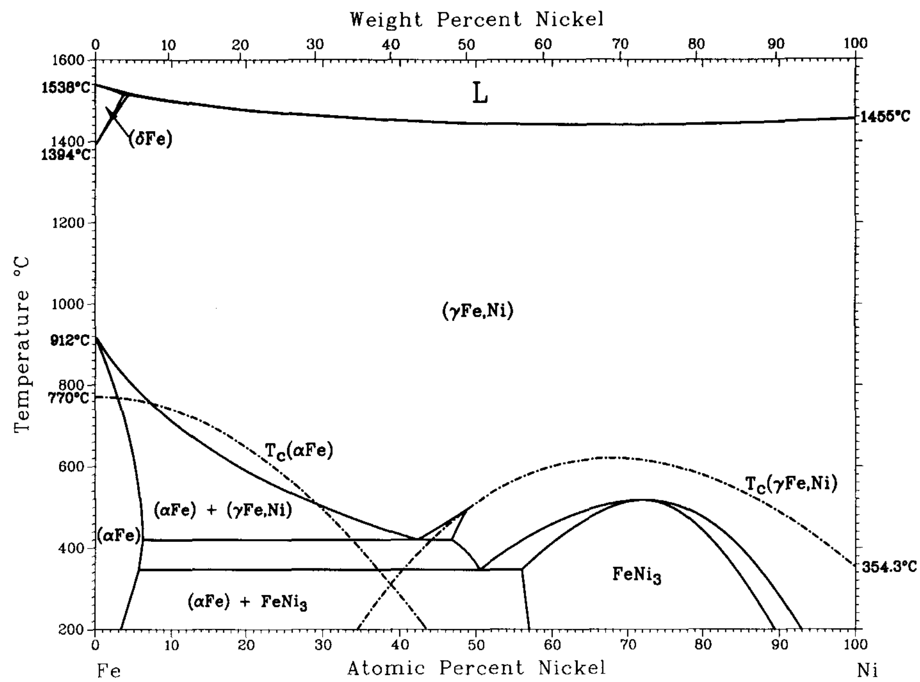

Fig. 16 Calculated Fe-Ni phase diagram.

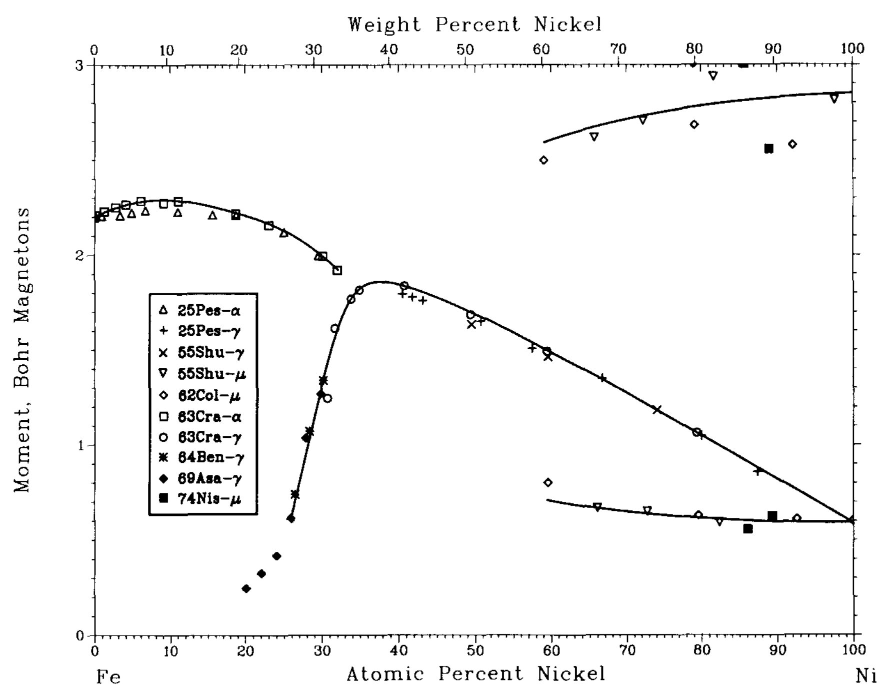

Fig. 17 Magnetic moments of Fe-Ni alloys.

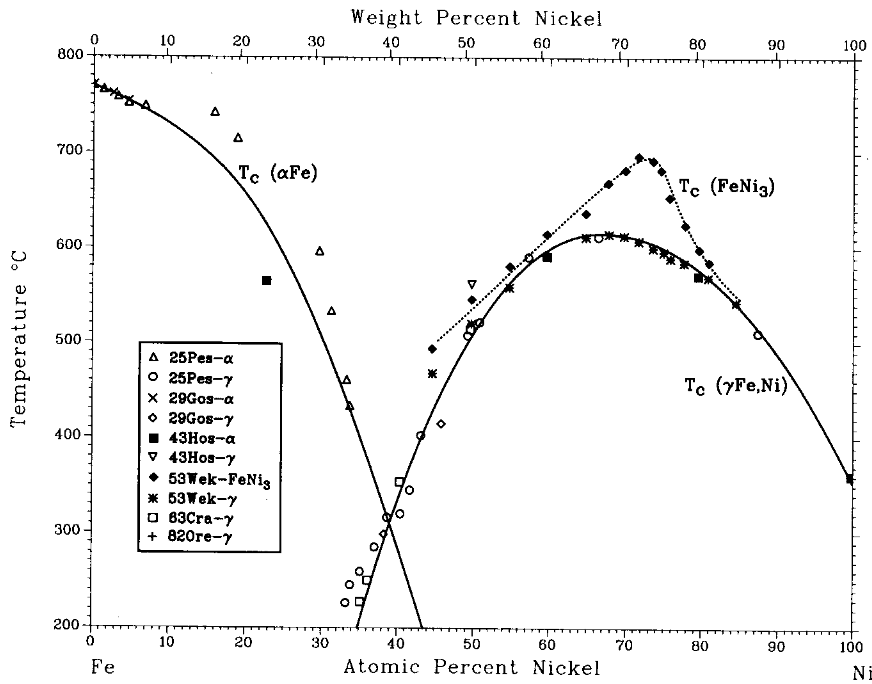

Fig. 18 Curie temperatures of Fe-Ni alloys.

studying two-phase Fe-Ni alloys was described by [39Suc] and [40Pic]. The effect of heat treatment on the magnetic properties of $FeNi_3$, including the maximum permeability, coercive force, remanent, and saturation magnetization was investigated by [53Wak]. By extrapolating the magnetization vs temperature curves, they estimated the Curie temperatures for ordered $FeNi_3$ and found a higher Curie temperature for the ordered alloys than for the disordered. A slightly higher saturation magnetization is also found for the ordered alloys ([40Gra], see Table 7). Figure 17 and Table 7 compare the various measured magnetic moments, and Fig. 18 and Table 8 compare the various measured Curie temperatures. The Curie temperature of pure Ni is taken as 627.4 K, in accordance with [68Kou] and [82Rhy].

Alloys of high maximum permeability, the so-called permalloys, can be formed by rapidly cooling alloys near the $FeNi_3$ composition [32Dah, 38Kay, 53Boz1, 53Boz2, 64Sch]. The magnetic properties of an equiatomic single crystal of FeNi that had been ordered metastably in the AuCu structure by neutron irradiation below 320 °C were studied by [64Nee]. Further anomalies in magnetic properties and phase separation have been observed by [51Suc], [59Dek] and [61Gor]. [75Ind] showed how the Curie temperature variation in (γFe,Ni) may be closely fitted to a Redlich-Kister form with a single interaction term. [77Mio] showed how this interaction parameter is related to the two-moment model for γFe of [63Wei]. [73Miz] measured Curie temperatures and magnetic moments in rapidly quenched amorphous quasibinary alloys with 0 to 90 at.% Ni and boron and phosphorus additions.

Cited References

1899Osm: F. Osmond, "On the Alloys of Iron and Nickel," *Compt. Rend.*, *128*, 304-307 (1899) in French. (Equi Diagram; Experimental; #)

05Gue: W. Guertler and G. Tammann, "On the Alloys of Nickel and Cobalt with Iron," *Z. Anorg. Chem.*, *45*, 205-216 (1905) in German. (Equi Diagram; Experimental; #)

10Heg: F. Hegg, "Thermomagnetic Study of Ferro-nickels," *Arch. Sci. Phys. Nat. Geneve*, *30*, 15-45 (1910) in French. (Equi Diagram; Experimental; #)

10Rue: R. Ruer and E. Schuz, "The Iron-Nickel System," *Metallurgie*, *7*, 415-470 (1910) in German. (Equi Diagram; Experimental; #)

20Han: D. Hanson and H.E. Hanson, "The Constitution of the Nickel-Iron Alloys," *J. Iron Steel Inst.*, *102*, 39-64 (1920). (Equi Diagram, Meta Phases; Experimental)

21And: M.R. Andrews, "X-ray Analysis of Three Series of Alloys," *Phys. Rev.*, *18*, 245-254 (1921). (Crys Structure; Experimental)

21Mer: P.D. Merica, "Iron-Nickel Alloys," *Chem. Met. Eng.*, *24*, 375-378 (1921). (Equi Diagram; Theory; #)

22Kir: F. Kirchner, "Structure Determination with X-rays," *Ann. Phys.*, *69*, 59-81 (1922) in German. (Crys Structure; Experimental)

23Bai: E.C. Bain, "The Crystal Structures of Solid Solutions," *Trans. AIME*, *68*, 625-641 (1923). (Crys Structure; Experimental)

***23Han:** D. Hanson and J.R. Freeman, "The Constitution of the Alloys of Iron and Nickel," *J. Iron Steel Inst.*, *107*, 301-321 (1923). (Equi Diagram; Experimental)

23Mck: L.W. McKeehan, "The Crystal Structure of Iron-Nickel Alloys," *Phys. Rev.*, *21*, 402-407 (1923). (Crys Structure; Experimental)

25Kas: T. Kase, "On the Equilibrium Diagram of the Iron-Carbon-Nickel System," *Sci. Rep. Tohoku Imp. Univ.*, *14*, 173-217 (1925). (Equi Diagram; Experimental)

***25Pes:** M. Peschard, "Contribution to the Study of Ferro-nickels," *Rev. Métall.*, *22*, 430-676 (1925) in French. (Meta Phases, Magnetism; Experimental)

25Vog: R. Vogel, "On the Structure of Iron-Nickel Meteorites," *Z. Anorg. Chem.*, *142*, 193-228 (1925) in German. (Equi Diagram; Experimental; #)

26Kaw: M. Kawakami, "On the Specific Heat of Iron-Nickel Alloys," *Sci. Rep. Tohoku Imp. Univ.*, *15*, 251-262 (1926). (Equi Diagram; Experimental)

26Osa1: A. Osawa, "The Relation Between Space-Lattice Constant and Density of Iron-Nickel Alloys," *Sci. Rep. Tohoku Imp. Univ.*, *15*, 387-398 (1926). (Crys Structure; Experimental)

26Osa2: A. Osawa, "On the Relation Between the Lattice Constant and the Density of Iron-Nickel Alloys," *J. Iron Steel Inst.*, *113*, 447-456 (1926). (Crys Structure; Experimental)

27Hon: K. Honda and S. Miura, "On the Determination of the Heterogeneous Field in the System Fe-Ni," *Sci. Rep. Tohuku Imp. Univ.*, *16*, 745-753 (1927). (Meta Phases; Experimental)

27Jun: A.O. Jung, "The Structure and Lattice Constants of Artificial and Natural Iron Alloys," *Z. Krist.*, *65*, 309-334 (1927) in German. (Crys Structure; Experimental)

27Vog: R. Vogel, "On the Structure of Iron Meteorites," *Arch. Eisenhüttenwes.*, *1*, 605-611 (1927) in German. (Equi Diagram; Experimental)

28Vog: R. Vogel, "On the Structure of Iron-Nickel Meteorites," *Z. Anorg. Chem.*, *142*, 193-228 (1928) in German. (Equi Diagram; Experimental; #)

29Gos: G. Gossels, "Investigation of the Hysteresis Stability of Iron-Nickel Alloys," *Z. Anorg. Chem.*, *182*, 19-27 (1929) in German. (Meta Phases, Magnetism; Experimental)

30Rob: O.L. Roberts and W.P. Davey, "An X-ray Study of the A_3 Point of Iron and Some Iron-Nickel Alloys," *Met. Alloys*, *1*, 648-654 (1930). (Equi Diagram, Meta Phases; Experimental)

***31Ben:** H. Bennedek and P. Schafmeister, "The Area of the Delta-Gamma Transformation in the Iron-Nickel System," *Arch. Eisenhüttenwes.*, *5*, 123-125 (1931) in German. (Equi Diagram; Experimental)

31Phr: G. Phragmen, "X-ray Investigation of Certain Nickel Steels of Low Thermal Expansion," *J. Iron Steel Inst.*, *123*, 465-477 (1931). (Crys Structure; Experimental)

32Dah: O. Dahl, "On the Question of Supercooled Transformations of State in Iron-Nickel Alloys (The High Permeability of Air Cooled Permalloy)," *Z. Metallkd.*, *24*, 107-111 (1932) in German. (Equi Diagram, Magnetism; Experimental)

32Sch: E. Scheil, "On the Origin of the Transformation of Austenite into Martensite in the Vicinity of Room Temperature," *Z. Elektrochem.*, *38*, 554-557 (1932) in German. (Meta Phases; Experimental)

33Dah: O. Dahl and J. Pfaffenberger, "A Contribution on Iron-Nickel Alloys," *Z. Metallkd.*, *25*, 241-245 (1933) in German. (Equi Diagram; Experimental)

34Deh: V. Dehlinger, "Kinetics and Phase Diagram of the Irreversible Transformation in the Iron-Nickel System," *Z. Metallkd.*, *5*, 112-116 (1934) in German. (Meta Phases; Experimental)

35Sch: E. Scheil, "The Irreversibility of Iron-Nickel Alloys and their Equilibrium Diagram," *Arch. Eisenhüttenwes.*, *9*, 163-166 (1935). (Meta Phases; Experimental)

36Dah: O. Dahl, "Cold Working and Relaxation in Alloys with Ordered Atomic Distributions," *Z. Metallkd.*, *28*, 133-138 (1936) in German. (Equi Diagram; Experimental)

***36Jet:** E. Jette and F. Foote, "X-ray Study of Iron-Nickel Alloys," *Trans. AIME*, *120*, 259-276 (1936). (Equi Diagram; Experimental)

36Sam: H.O. von Samonson-Himnelstjerna, "The Heat Content and Heat of Formation of Melted Alloys," *Z. Metallkd.*, *28*, 197-202 (1936) in German. (Equi Diagram; Experimental)

36Mer: P.D. Merica, "Constitution of Iron-Nickel Alloys," *Metals Handbook*, American Society for Metals, Cleveland, OH, 271-273 (1936). (Meta Phases; Review; #)

37Bra: A.J. Bradley, A.H. Jay, and A. Taylor, "The Lattice Spacing of Iron-Nickel Alloys," *Philos. Mag.*, *23*, 545-547 (1937). (Crys Structure; Experimental)

37Jen: C.H.M. Jenkins, E.H. Bucknall, C.R. Austin, and G.A. Mellor, "Some Alloys for Use at High Temperatures," *J. Iron Steel Inst.*, *136*, 187-222 (1937). (Equi Diagram; Experimental; #)

37Kal: O. Kallback, "Determination of the Order-Disorder Point in $FeNi_3$," *Ark. Mat. Astron. Fys.*, *34B*, 17-21 (1947). (Equi Diagram; Experimental)

37Koe: F. Koerber, W. Oelsen, and H. Lichtenberg, "On the Thermochemistry of Alloys II. Direct Determination of the Heats of Formation of the Ternary Alloys Fe-Ni-Al, Fe-Co-Al, Cu-Ni-Al, Fe-Al-Si, and a Portion of the Cu-Mn-Al System," *Mitt. Kaiser Wilhelm Inst. Eisenforsch.*, *19*, 131-159 (1937) in German. (Equi Diagram; Experimental)

37Owe1: E.A. Owen and E.L. Yates, "X-ray Investigation of Pure Iron-Nickel Alloys. Part I: Thermal Expansion of Alloys Rich in Nickel," *Proc. Phys. Soc. (London)*, *49*, 17-28 (1937). (Crys Structure; Experimental)

37Owe2: E.A. Owen and E.L. Yates, "X-ray Investigation of Pure Iron-Nickel Alloys. Part 2: Thermal Expansion of Some Further Alloys," *Proc. Phys. Soc. (London)*, *49*, 178-188 (1937). (Crys Structure; Experimental)

37Owe3: E.A. Owen and E.L. Yates, "An X-ray Investigation of Pure Iron-Nickel Alloys. Part 3: The Thermal Expansion of Alloys Rich in Iron," *Proc. Phys. Soc. (London)*, *49*, 307-314 (1937). (Crys Structure; Experimental)

37Owe4: E.A. Owen, E.L. Yates, and A.H. Sully, "An X-ray Investigation of Pure Iron-Nickel Alloys. Part 4: The Variation of Lattice Parameter with Composition," *Proc. Phys. Soc. (London)*, *49*, 315-322 (1937). (Crys Structure; Experimental)

37Owe5: E.A. Owen, E.L. Yates, and A.H. Sully, "An X-ray Investigation of Pure Iron-Nickel Alloys. Part 5: The Variation of Thermal Expansion with Composition," *Proc. Phys. Soc. (London)*, *49*, 323-325 (1937). (Crys Structure; Experimental)

38Haw: F.E. Haworth, "An X-ray Test of Superstructure in $FeNi_3$," *Phys. Rev.*, *54*, 693-698 (1938). (Equi Diagram; Experimental)

38Kay: S. Kaya, "The Superlattice in Iron-Nickel Alloys and the Permalloy Problem," *J. Fac. Sci. Hokkaido Imp. Univ.*, *2*, 29-53 (1938). (Magnetism; Experimental)

38Mar: J.S. March, *The Alloys of Iron and Nickel*, McGraw Hill, New York, 24-55 (1938). (Equi Diagram; Review; #)

39Haw: F.E. Haworth, "Superstructure in $FeNi_3$," *Phys. Rev.*, *56*, 289-231 (1939). (Equi Diagram; Experimental)

39Kay: S. Kaya and M. Nakayama, "The Superstructure in Iron-Nickel-Cobalt Alloys and the Perminvar Problem," *Z. Phys.*, *112*, 420-429 (1939) in German. (Equi Diagram; Experimental)

39Kus: A. Kussmann, "Evidence for a Superstructure Phase in the Iron-Nickel System," *Z. Metallkd.*, *31*, 212-214 (1939) in German. (Equi Diagram; Experimental)

39Lee: P. Leech and C. Sykes, "The Evidence for A Superlattice in the Nickel-Iron Alloy Ni_3Fe," *Philos. Mag.*, *27*, 742-753 (1939). (Equi Diagram, Thermo; Experimental)

39Owe: E.A. Owen and A.H. Sully, "The Equilibrium Diagram of Iron-Nickel Alloys," *Philos. Mag.*, *27*, 614-636 (1939). (Equi Diagram; Experimental; #)

39Suc: W. Sucksmith, "The Measurement of Magnetic Saturation Intensities at Different Temperatures," *Proc. R. Soc. (London)*, *170*, 551-557 (1939). (Magnetism; Experimental)

40Gra: E.M. Grabbe, "Ferromagnetic Anisotropy, Magnetization at Saturation, and Superstructure in Ni_3Fe and Nearby Compositions," *Phys. Rev.*, *57*, 728-734 (1940). (Magnetism; Experimental)

40Kee: W.H. Keesom and B. Kurrelmeyer, "Specific Heats of Alloys of Nickel with Copper and with Iron from 1.2° to 20°K," *Physica*, *7*, 1003-1024 (1940). (Thermo; Experimental)

40Nix: F.C. Nix, H.G. Beyer, and R. Dunning, "Neutron Studies of Order in Fe-Ni Alloys," *Phys. Rev.*, *58*, 1031-1034 (1940). (Equi Diagram; Experimental)

40Pic: A.T. Pickles and W. Sucksmith, "A Magnetic Study of the Two-Phase Iron-Nickel Alloys," *Proc. R. Soc. (London) A*, *175*, 331-334 (1940). (Equi Diagram, Magnetism; Experimental)

40Zui: A.J. Zuithoff, "The Exact Measurement of the Specific Heats of Solid Substances at High Temperature XII. The Specific Heats of Iron-Nickel Alloys of Various Compositions Between 100° and 1400 °C," *Rec. Trav. Chim.*, *59*, 131-160 (1940). (Equi Diagram; Experimental; #)

41Owe: E.A. Owen and A.H. Sully, "On the Migration of Atoms in Iron-Nickel Alloys," *Philos. Mag.*, *31*, 314-338 (1941). (Equi Diagram, Crys Structure; Experimental)

43Hos: K. Hoselitz and W. Sucksmith, "A Magnetic Study of the Two-Phase Iron-Nickel Alloys, II," *Proc. R. Soc. (London)*, *1*, 30 (1943). (Equi Diagram, Meta Phases, Magnetism; Experimental)

47Oel: W. Oelsen and F. Wever, "On the Influence of Elements on the Polymorphism of Iron," *Arch. Eisenhüttenwes.*, *19*, 97-104 (1947) in German. (Meta Phases; Theory)

48Fis: J.C. Fisher, J.H. Hollomon, and D. Turnbull, "Nucleation," *J. Appl. Phys.*, *19*, 775-784 (1948). (Meta Phases; Theory)

48Kal: O. Kallback, "Determination of the Order-Disorder Point in $FeNi_3$," *Ark. Mat. Astron. Fys.*, *34B*(17), 1-6 (1948). (Equi Diagram; Experimental)

49Hah: H. Hahn and H. Muhlberg, "The System Iron/Nickel/Nitrogen," *Z. Anorg. Chem.*, *259*, 121-134 (1949) in German. (Crys Structure; Experimental)

***49Jon:** F.N. Jones and W.I. Pumphrey, "Free Energy and Metastable States in the Iron-Nickel and Iron-Manganese Systems," *J. Iron Steel Inst.*, *163*, 121-131 (1949). (Equi Diagram, Meta Phases; Experimental)

49Kub: O. Kubaschewski and O. von Goldbeck, "The Thermodynamics of the Iron-Nickel Alloys," *Trans. Faraday Soc.*, *45*, 948-960 (1949). (Thermo; Experimental)

***49Owe:** E.A. Owen and Y.H. Liu, "Further X-Ray Study of the Equilibrium Diagram of the Iron-Nickel System," *J. Iron Steel Inst.*, *123*, 132-136 (1949). (Equi Diagram; Experimental; #)

***50Jos:** E. Josso, "Equilibrium Diagram for the Order to Disorder Transformation of Iron-Nickels near Ni_3Fe," *Compt. Rend.*, *230*, 1467-1469 (1950). (Equi Diagram; Experimental)

51Mac: E.S. Machlin and M. Cohen, "Burst Phenomenon in the Martensitic Transformation," *Trans. AIME*, *191*, 746-754 (1951). (Meta Phases; Experimental)

51Smo: R. Smoluchowski, "Statistical Properties of Solid Solutions," *Phys. Rev.*, *84*, 511-518 (1951). (Meta Phases; Theory)

51Suc: W. Sucksmith, "Magnetic Saturation Intensity and Some Related Measurements," *J. Phys. Radium*, *12*, 430-436 (1951). (Magnetism; Experimental)

52Hun: F. Hund, "Characterization of Nickel-Iron Alloy Powders at Low Temperature and Investigations of Lattice Changes," *Z. Elektrochem.*, *56*, 609-612 (1952) in German. (Equi Diagram; Experimental)

52Iid: S. Iida, "Formation Energy of Superlattice for Ni_3Fe, (I) Cooperative Formation of Superlattice at the Critical Temperatures," *J. Phys. Soc. Jpn.*, *7*, 373-379 (1952). (Equi Diagram; Experimental)

53Boz1: R.M. Bozorth and J.G. Walker, "Magnetic Crystal Anisotropy and Magnetostriction of Iron-Nickel Alloys," *Phys. Rev.*, *89*, 624-628 (1953). (Magnetism; Experimental)

53Boz2: R.M. Bozorth, "The Permalloy Problem," *Rev. Mod. Phys.*, *25*, 42-48 (1953). (Magnetism; Experimental)

***53Gei:** A.H. Geisler, "Written Discussion of [53Rhi]," *Trans. ASM*, *45*, 1051-1054 (1953). (Equi Diagram; Experimental)

53Ori: R.A. Oriani, "Thermodynamic Activities in Iron-Nickel Alloys," *Acta Metall.*, *1*, 448-454 (1953). (Thermo; Experimental)

***53Rhi:** F.N. Rhines and J.B. Newkirk, "The Order-Disorder Transformation Viewed as a Classical Phase Change," *Trans. ASM*, *45*, 1029-1046 (1953). (Equi Diagram; Theory)

53Wak: R.J. Wakelin and E.L. Yates, "A Study of the Order-Disorder Transformation in Iron-Nickel Alloys in the Region $FeNi_3$," *Proc. Phys. Soc. (London) B*, *66*, 221-240 (1953). (Crys Structure, Magnetism; Experimental)

54Iid: S. Iida, "Formation Energy of Superlattice in Ni_3Fe (II) Kinetics of the Superlattice in the Stage of Local Ordering," *J. Phys. Soc. Jpn.*, *9*, 346-354 (1954). (Equi Diagram; Experimental)

54Lih: F. Lihl, "Phase Boundaries in the Iron-Nickel System at Temperatures Below 300 °C," *Arch. Eisenhüttenwes.*, *25*, 475-478 (1954) in German. (Crys Structure; Experimental)

54Mey: M.R. Meyerson and S.J. Rosenberg, "The Influence of Heat Treating Variables on the Martensite Transformation in SAE 1050 Steel," *Trans. ASM*, *46*, 1225-1253 (1954). (Meta Phases; Experimental)

55Roy: P. Royen and H. Reinhart, "The Influence of Alloying Iron with Gold, Silver, Copper, of Nickel on Iron Oxidation Equilibrium," *Z. Anorg. Chem.*, *281*, 18-36 (1955) in German. (Crys Structure; Experimental)

55Shu: C.G. Shull and M.K. Wilkinson, "Neutron Diffraction Studies of the Magnetic Structure of Alloys of Transition Elements," *Phys. Rev.*, *97*, 304-310 (1955). (Magnetism; Experimental)

55Sut: A.L. Sutton and W. Hume-Rothery, "The Lattice Spacings of Solid Solutions of Titanium, Vanadium, Chromium, Manganese, Cobalt and Nickel in Alpha-Iron," *Philos. Mag.*, *46*, 1295-1309 (1955). (Crys Structure; Experimental)

56Cec: R.E. Cech, "Evidence for Solidification of a Metastable Phase in Fe-Ni Alloys," *Trans. AIME*, *206*, 585-589 (1956). (Meta Phases; Experimental)

56Kau: L. Kaufman and M. Cohen, "The Martensitic Transformation in the Iron-Nickel System," *Trans. AIME*, *206*, 1393-1401 (1956). (Meta Phases; Experimental)

56Tin: Y. Tino, "Possible Existence of Fe_3Ni," *Sci. Rep. Tohoku Imp. Univ.*, *40*, 17-23 (1956). (Meta Phases; Experimental)

***57Hel:** A. Hellawell and W. Hume-Rothery, "The Constitution of Alloys of Iron and Manganese with Transition Elements of the First Long Period," *Philos. Trans. R. Soc. (London) A*, *249*, 417-459 (1957). (Equi Diagram, Thermo; Experimental)

57Lya: B.G. Lyashchenko, D.F. Litvin, I.M. Puzei, and Yu.G. Abov, "Neutron Diffraction of Iron-Nickel Alloys of the Permalloy Class," *Kristallografiya*, 2, 64-73 (1957) in Russian; TR: *Sov. Phys. Crystallogr.*, *2*, 59-67 (1957). (Equi Diagram; Experimental)

57Vit: L.M. Viting, "Investigation of the Iron-Nickel-Cobalt System in the Region of the Metallic Compounds Ni_3Fe and FeCo," *Zh. Neorg. Khim.*, *2*, 367-374 (1957) in Russian; TR: *J. Inorg. Chem.*, *2*(2), 217-228 (1957). (Equi Diagram; Experimental)

58Kus: A. Kussmann and K. Jessen, "Investigation of Atomic Ordering in Iron-Nickel-(Platinum) Alloys with Low Thermal Expansion," *Arch. Eisenhüttenwes.*, *29*, 585-594 (1958) in German. (Equi Diagram, Meta Phases; Experimental)

58Lyu: A.P. Lyubimov, V.Ya. Zobens, and V.P. Rakhovskii, "A Mass Spectrometric Determination of the Thermodynamic Characteristics of Binary Metallic Systems," *Zh. Fiz. Khim.*, *32*, 1804-1808 (1958) in Russian. (Thermo; Experimental)

58Pin: B.Ya. Pines and I.P. Grebennils, "A New Crystalline Phase in Thin Films of Fe-Ni Alloys," *Kristallografiya*, *3*[1], 461-466 (1958) in Russian; TR: *Sov. Phys. Crystallogr.*, *3*, 460-464 (1958). (Meta Phases; Experimental)

59Ana: N.I. Ananthanarayanan and R.J. Peavler, "Room Temperature Decomposition of Austenite in Fifty Percent Nickel-Fifty Percent Iron Magnetic Alloy Tapes," *J. Appl. Phys.*, *30*, 202S-203S (1959). (Meta Phases; Experimental)

59Dek: M.V. Dekhtyar and N.M. Kazantseva, "Structure Changes and Anomalous Temperature Dependence of the Magnetic Properties of Ni-Fe Alloys (50 Percent Ni)," *Fiz. Met. Metalloved.*, *8*, 412-416 (1959) in Russian; TR: *Phys. Met. Metallogr.*, *8*, 84-87 (1959). (Magnetism; Experimental)

59Sch: F. Scheil and W. Normann, "Investigation of the Thermodynamics of the $\alpha \leftrightarrow \gamma$ Transformation in Iron-Nickel Alloys," *Arch. Eisenhüttenwes.*, *30*, 751-754 (1959) in German. (Equi Diagram; Experimental)

59Spe: R. Speiser, A.J. Jacobs, and J.W. Spertnak, "Activities of Iron and Nickel in Liquid Iron-Nickel Solutions," *Trans Metall. Soc. AIME*, *215*, 185-192 (1959). (Thermo; Experimental)

59Zel: G.R. Zellars, S.L. Payne, J.P. Morris, and R.L. Kipp, "The Activities of Iron and Nickel in Liquid Fe-Ni Alloys," *Trans. Metall. Soc. AIME*, *215*, 181-185 (1959). (Thermo; Experimental)

60Kon: E.J. Kondorski and V. Sedov, "Antiferromagnetism of Iron in Face-Centered Crystalline Lattice and the Causes of Anomalies in Invar Physical Properties," *J. Appl. Phys.*, *31*, 331S-335S (1960). (Meta Phases; Experimental)

60Pau: J. Paulene and D. Dautreppe, "Neutron Orientation Superstructure Created during Irradiation in a Magnetic Field of an Fe-Ni(50-50 Percent) Alloy," *Compt. Rend.*, *250*, 3804-3806 (1960) in French. (Meta Phases; Experimental)

61Ana: N.I. Anathanarayanan and P.J. Peuler, "A New Reversible Solid State Transformation in Iron-Nickel Alloys in the Invar Range of Composition," *Nature*, *192*, 962-963 (1961). (Meta Phases; Experimental)

61Ban: Y. Bando, "The Formation of Superstructure in Fe_3Ni Fine Particles," *J. Phys. Soc. Jpn.*, *16*, 2342-2343 (1961). (Meta Phases; Experimental)

61Gor: V.I. Gorbunov, "Investigation of the Structure of Irreversible Alloys of the Iron-Nickel System," *Fiz. Met. Metalloved.*, *12*, 78-83 (1961) in Russian; TR: *Phys. Met. Metallogr.*, *12*(1), 68-72 (1961). (Magnetism; Experimental)

61Kau1: L. Kaufman and A.E. Ringwood, "High Pressure Equilibria in the Iron-Nickel System and the Structure of Metallic Meterorite," *Acta Metall.*, *9*, 941-944 (1961). (Pressure; Theory)

61Kau2: L. Kaufman, A. Leyenaar, and J.S. Harvey, "The Effect of Hydrostatic Pressure on the F.C.C.-B.C.C. Reactions in Iron-Base Alloys," *Progress in Very High Pressure Research*, F. Bundy *et al.*, Eds., J. Wiley and Sons, New York, 90-108 (1961). (Pressure; Experimental)

61Ste: W. Steiner and O. Krisement, "Heat of Formation of γ Iron-Nickel Alloys at 850 °C," *Arch. Eisenhüttenwes.*, *32*, 701-707 (1961) in German. (Thermo; Experimental)

62Bre: J.F. Breedis and C.M. Wayman, "The Martensitic Transformation in Fe-31 wt. Pct Ni," *Trans. Metall. Soc. AIME*, *224*, 1128-1133 (1962). (Meta Phases; Experimental)

62Col: M.F. Collins, R.V. Jones, and R.D. Lawde, "On the Magnetic Moments and the Degree of Order in Iron-Nickel Alloys," *J. Phys. Soc. Jpn.*, *17*, Supplement B-III, Proc. Int. Conf. on Magn. and Crys., Kyoto, Sep 25-30, 19-26 (1962). (Magnetism; Experimental)

***62Gil:** A. Gilbert and W.S. Owen, "Diffusionless Transformation in Iron-Nickel, Iron-Chromium and Iron-Silicon Alloys," *Acta Metall.*, *10*, 45-54 (1962). (Meta Phases; Experimental)

62Kac: S. Kachi, Y. Bando, and S. Higuchi, "The Phase Transformations of Iron-Rich Iron-Nickel Alloy in Fine Particles," *Jpn. J. Appl. Phys.*, *1*, 307-313 (1962). (Equi Diagram; Experimental)

62Pau1: J. Pauleve, D. Dautreppe, J. Laugier, and L. Neel, "A New Order-Disorder Transition in Fe-Ni (50-50)," *J. Phys. Radium*, *23*, 841-843 (1962) in French. (Meta Phases; Experimental)

62Pau2: J. Pauleve, D. Dautreppe, J. Laugier, and L. Neel, "Establishment of an Ordered Structure in FeNi by Irradiation with Neutrons," *Compt. Rend.*, *254*, 965-968 (1962) in French. (Meta Phases; Experimental)

62Yeo: R.B.C. Yeo, "Isothermal Martensite Transformation in Iron Base Alloys of Low Carbon Content," *Trans. Metall. Soc. AIME*, *224*, 1222-1227 (1962). (Meta Phases; Experimental)

63Cra: J. Crangle and G.C. Hallam, "The Magnetization of Face-Centered-Cubic and Body-Centered-Cubic Iron and Nickel Alloys," *Proc. R. Soc. (London) A*, *272*, 119-132 (1963). (Magnetism; Experimental)

63Dav: R.G. Davies and N.S. Stoloff, "Order and domain Hardening in Cu_3Au Type Superlattice Alloys," *Acta Metall.*, *11*, 1347-1353 (1963). (Equi Diagram, Crys Structure; Experimental)

63Den: W.A. Dench, "Adiabatic High-Temperature Calorimeter for the Measurements of Heats of Alloys," *Trans. Faraday Soc.*, *59*, 1279-1292 (1963). (Thermo; Experimental)

63Gol: A.J. Goldman and C.N.J. Wagner, "Faulting in Deformed Austenite and Martensite," *Acta Metall.*, *11*, 405-413 (1963). (Meta Phases; Experimental)

***63Heu:** T. Heumann and G. Karsten, "Carbonyl Vapor Method for Determination of Phase Equilibria in the Low Mobility Temperature Range Applied to Iron-Nickel Alloys," *Arch. Eisenhüttenwes.*, *34*, 781-785 (1963). (Equi Diagram, Meta Phases; Experimental; #)

63Mar: A. Marchand, J. Pauleve, and D. Dautreppe, "Resistivity of and FeNi (50-50 Percent) Alloy Ordered by Irradiation with Neutrons," *Compt. Rend.*, *257*, 2987-2989 (1963) in French. (Meta Phases; Experimental)

63Tre: R.G. Treuting and B.W. Batterman, "A Diffractometer Study of Long-Range Ordering in Ni_3Fe and Associated Permalloys," *J. Appl. Phys.*, *34*, 2005-2006 (1963). (Equi Diagram; Experimental)

63Wei: R.J. Weiss, "The Origin of the Invar Effect," *Proc. Phys. Soc. (London)*, *82*, 281-288 (1963). (Magnetism; Theory)

63Yeo: R.B.G. Yeo, "The Effect of Alloying Elements on the Transformation of Fe-22.5 Pct Ni Alloys," *Trans Metall. Soc. AIME*, *227*, 884-890 (1963). (Meta Phases; Experimental)

64Ban: Y. Bando, "The Magnetization of Face Centered Cubic Iron-Nickel Alloys in the Vicinity of Invar Region," *J. Phys. Soc. Jpn.*, *19*, 237 (1964). (Meta Phases, Magnetism; Experimental)

64Gup: K.P. Gupta, C.H. Cheng, and P.A. Beck, "Low Temperature Specific Heat of F.C.C. Alloys of the 3d-Transition Elements," *J. Phys. Chem. Solids*, *25*, 73-83 (1964). (Thermo; Experimental)

64Hum: W. Hume-Rothery and R.A. Buckley, "Liquidus $\leftrightarrow$ Solidus Relations in Iron Alloys: Ideal Solutions," *J. Iron Steel Inst.*, *202*, 531-533 (1964). (Equi Diagram; Theory)

64Nee: L. Neel, J. Paulene, R. Pauthenet, J. Laugier, and D. Dautreppe, "Magnetic Properties of an Iron-Nickel Single Crystal Ordered by Neutron Bombardment," *J. Appl. Phys.*, *35*, 873-876 (1964). (Meta Phases, Magnetism; Experimental)

64Roe: G.A. Roeder and W.W. Smeltzer, "The Dissociation Pressures of Iron-Nickel Alloys," *J. Electrochem. Soc.*, *111*, 1074-1078 (1964). (Thermo; Experimental)

64Sch: A.D. Schindler and C.M. Williams, "Investigations of the Effects of Neutron and He(3) Irradiation on the Magnetic Properties of Permalloy Thin Films," *J. Appl. Phys.*, *35*, 877-879 (1964). (Magnetism; Experimental)

65Ehr: R. Ehrat and D. Rivier, "Low Temperature Specific Heats of Dilute Nickel Alloys," *Helv. Phys. Acta*, *38*, 643-645 (1965) in French. (Thermo; Experimental)

***65Gol:** J.I. Goldstein and R.E. Ogilvie, "A Re-Evaluation of the Iron-Rich Portion of the Fe-Ni System," *Trans. Metall. Soc. AIME*, *223*, 2083-2087 (1965). (Equi Diagram; Experimental)

65Gon: V.I. Gonamkov, I.M. Puzei, and A.A. Loshmanov, "A Study of Superlattice Structure in Ni_3Fe," *Kristallografiya*, *10*, 416-418 (1965) in Russian; TR: *Sov. Phys. Crystallogr.*, *10*, 338-340 (1965). (Equi Diagram; Experimental)

65Pea: W.B. Pearson, "Handbook of Lattice Spacings and Structures of Metals-2," International Series of Monographs in Metal Physics and Physical Metallurgy, Volume 8, G.V. Raynov Ed., National Research Council, Ottawa, 1965.

66Abr: E.P. Abrahamson II and S.L. Lopata, "The Lattice Parameters and Solubility Limits of Alpha Iron as Affected by Some Binary Transition-Element Additions," *Trans. Metall. Soc. AIME*, *236*, 76-87 (1966). (Crys Structure; Experimental)

66Elk: A. El-Khasan, K. Abdel-Aziz, A.A. Vertman, and A.M. Samarin, "Thermochemistry of Molten Nickel or Iron Alloys," *Izv. Akad. Nauk SSSR, Met.*, (3), 19-31 (1966) in Russian; TR: *Russ. Metall.*, (3), 10-16 (1966). (Thermo; Experimental)

66Hum: W. Hume-Rothery, *The Structures of Alloys of Iron*, Pergamon Press, New York, NY, 121 (1966). (Meta Phases; Review)

66Kat: T.Z. Kattamis and M.C. Flemings, "Dendrite Structure and Grain Size of Undercooled Melts," *Trans. Metall. Soc. AIME*, *236*, 1523-1532 (1966). (Meta Phases; Experimental)

66Mcq: R.G. McQueen and S.P. Marsh, "Shock Wave Compression of Iron-Nickel Alloys and the Earth's Core," *J. Geophys. Res.*, *71*, 1751-1756 (1966). (Pressure; Experimental)

66Oni: M. Onillon and M. Olette, "Determination of the Thermodynamic Functions for Dilute Solutions of Nickel in Liquid Iron," *C. R. Acad. Sci. (Paris) C*, *263*, 1122-1125 (1966) in French. (Thermo; Experimental)

66Shi: S.S. Shinozaki and A. Arrott, "Electronic Specific Heat of Dilute Alloys: Fe(Ti), Fe(V), Fe(Cr), Fe(Mn), Fe(Co), Fe(Ni), Fe(Al), Fe(Si), Fe(Mo), Fe(W), and Ag(Au)," *Phys. Rev.*, *152*, 611-622 (1966). (Thermo; Experimental)

67Bel: G.R. Belton and R.J. Frueham, "The Determination of Activities by Mass Spectroscopy. I. The Liquid Metallic Systems Iron-Nickel and Iron Cobalt," *J. Phys. Chem.*, *71*, 1403-1409 (1967). (Thermo; Experimental)

67Hil: M. Hillert, T. Wade, and H. Wada, "The Alpha-Gamma Equilibrium in Fe-Mn, Fe-Mo, Fe-Ni, Fe-Sb, Fe-Sn and Fe-W Systems," *J. Iron Steel Inst.*, 539-546 (1967). (Equi Diagram; Theory)

67Kub: O. Kubaschewski and L.E.H. Stuart, "Heats of Formation and Heat Capacities in the System Iron-Nickel-Chromium," *J. Chem. Eng. Data*, *12*, 418-420 (1967). (Thermo; Experimental)

67Rob: M.J. Roberts and W.S. Owen, "The Strength of Martensitic Iron-Nickel Alloys," *Trans. ASM*, *60*, 687-692 (1967). (Meta Phases; Experimental)

68Kou: J.S. Kouvel and J.B. Comly, "Magnetic Equation of State for Nickel Near its Curie Point," *Phys. Rev. Lett.*, *20*, 1237-1239 (1968). (Magnetism; Experimental)

68Tak: T. Takahashi, W.A. Bassett, and H.K. Mao, "Isothermal Compression of the Alloys of Iron up to 300 Kilobars at Room Temperature: Iron-Nickel Alloys," *J. Geophys. Res.*, *73*, 4717-4725 (1968). (Pressure; Experimental)

69Asa: H. Asano, "Magnetism of Gamma Fe-Ni Invar Alloys with Low Nickel Concentration," *J. Phys. Soc. Jpn.*, *27*(3), 542-533 (1969). (Crys Structure, Magnetism; Experimental)

69Kus: M.T. Kusho, V.F. Balakirev, R.Yu. Dobrovinskii, G.M. Popov, A.N. Men, and G.I. Chufarov, "The Activities of the Components of Solid Solutions in the System Nickel-Iron-Oxygen," *Zh. Fiz. Khim.*, *43*, 3095-3098 (1969) in Russian; TR: *Russ. J. Phys. Chem.*, *43*, 1739-1740 (1969). (Thermo; Experimental)

69Ree: R.P. Reed and R.E. Schramm, "Lattice Parameters of Martensite and Austenite in Fe-Ni Alloys," *J. Appl. Phys.*, *40*, 3453-3458 (1969). (Crys Structure; Experimental)

69Sta: R.E. Staub and J.L. McCall, "Metallographic Studies of an Iron-Nickel Meteorite Following Long-Time Heat Treatments," Proc. of the 2nd Annual Technical Meeting, Sept. 8-10, 1969 San Francisco International Metallographic Society, 337-344 (1969). (Equi Diagram; Experimental)

70Gat: C. Gatellier, D. Henriet, and M. Olette, "Determination of the Thermodynamic Activities of the Constituents of Solid Fe-Ni Alloys by the Electrochemical Method," *Compt. Rend.*, *271*, 453-460 (1970) in French. (Thermo; Experimental)

70Gro: Y. Grosand and J.J. Pauleve, "Mössbauer Effect Study of Order in a 50-50 Fe-Ni Alloy Irradiated by Neutrons or Electrons," *J. Phys.*, *31*, 459-470 (1970) in French. (Meta Phases; Experimental)

70Pre1: B. Predel and R. Mohs, "Thermodynamic Investigations of the Fe-Ni and Fe-Co Systems," *Arch. Eisenhüttenwes.*, *41*, 143-149 (1970) in German. (Thermo; Experimental)

70Pre2: B. Predel and R. Mohs, "A New High Temperature Calorimeter and its Application to the Determination of the Mixing Enthalpy of Liquid Cobalt-Nickel Alloys," *Arch. Eisenhüttenwes.*, *41*, 61-66 (1970) in German. (Thermo; Experimental)

71Geo: I.Y. Georgiyeva and O.P. Maksimora, "On the Interrelation Between Kinetics and Structure During Martensitic Transformations," *Fiz. Met. Metalloved.*, *32*, 364-376 (1971) in Russian; TR: *Phys. Met. Metallogr.*, *32*(2), 135-146 (1971). (Meta Phases; Experimental)

71Hau: G. Hausch and H. Warlimont, "Structural Inhomogeneity in Fe-Ni Invar Alloys Studied by Electron Diffraction," *Phys. Lett. A*, *36*, 415-416 (1971). (Meta Phases; Experimental)

71Spe: P.J. Spencer, F.H. Hayes, and L. Elford, "Relationships Between Binary and Ternary Properties: A Calorimetric Investigation of the Fe-Co-Ni System," in Chemical Metallurgy of Iron and Steel, Proc. Int. Symp., London, 1971, The Iron and Steel Institute, 322-326 (1973). (Thermo; Experimental)

71Toz: Y. Tozaki, Y.I. Iguchi, S. Ban-ya, and T. Fuwa, "Heat of Mixing of Iron Alloys," in Chemical Metallurgy of Iron and Steel, Proc. Int. Symp., London, 1971, The Iron and Steel Institute, 130-132 (1973). (Thermo; Experimental)

71Tse: L.Sh. Tsemekhman, S.E. Vaisburd, and Z.F. Shirokova, "Activities in Iron-Nickel, Iron-Cobalt, and Nickel-Cobalt Binary Melts," *Zh. Fiz. Khim.*, *45*, 2074-2077 (1971) in Russian; TR: *Russ. J. Phys. Chem.*, *45*, 1176-1177 (1971). (Thermo; Experimental)

72Cal: Y. Calvayrac and M. Fayard, "Behavior of Iron-Nickel Alloys Around the Composition 75-25 in the Neighborhood of the Order-Disorder Transformation Temperature," *Mater. Res. Bull.*, *7*, 891-901 (1972) in French. (Equi Diagram; Experimental)

72Dav: H. Davies and W.W. Smeltzer, "Oxygen and Metal Activities of the Iron-Nickel-Oxygen System at 1000 °C," *J. Electrochem. Soc.*, *19*, 1362-1368 (1972). (Thermo; Experimental)

72Mil: K.C. Mills, K. Kinoshita, and P. Grieveson, "A Thermodynamic Study of Liquid Iron and Nickel Alloys Using Electromagnetic Levitation," *J. Chem. Thermodyn.*, *4*, 581-590 (1972). (Thermo; Experimental)

72Wei: R.J. Weiss, "The Invar Effect," *Philos. Mag.*, *26*(1), 261-263 (1972). (Meta Phases; Theory)

73Cab: J.W. Cable and E.O. Wollan, "Magnetic Moment Distribution in NiFe and AuFe Alloys," *Phys. Rev. B*, *7*, 2005-2016 (1973). (Magnetism; Experimental)

73Cal: Y. Calvayrac and M. Fayard, "Structural State and Mechanical Properties of Polycrystalline Ni_3Fe Alloys," *Phys. Status Solidi (a)*, *17*, 407-421 (1973). (Equi Diagram; Experimental)

73Kau: L. Kaufman and H. Nesor, "Calculation of the Binary Phase Diagrams of Iron, Chromium, Nickel and Cobalt," *Z. Metallkd.*, *64*, 249-257 (1973). (Thermo; Experimental)

73Kol: T.G. Kollie and C.R. Brooks, "The Heat Capacity of Ni_3Fe," *Phys. Status Solidi (a)*, *19*, 545 (1973). (Thermo; Experimental)

73Miz: T. Mizoguchi, K. Yamauchi, and H. Miyajima, "Ferromagnetism of Amorphous Iron Alloys," in *Amorphous Magnetism*, H.O. Hooper and A.M. deGraaf, Ed., Plenum Press, 325-330 (1973). (Meta Phases, Magnetism; Experimental)

73Sch: W.F. Schlosser, "Thermodynamics of an Invar Alloy," *Int. J. Magn.*, *4*, 49-55 (1973). (Thermo; Theory)

74Bas: M.I. Baskes, "Phase Stability of Iron Alloys," *Mater. Sci. Eng.*, *15*, 195-202 (1974). (Thermo; Theory; #)

74Bat: G.I. Batalin, N.N. Mineko, and V.S. Sundavtsova, "Enthalpy of Mixing and Thermodynamic Properties of Liquid Alloys of Iron with Manganese, Cobalt, and Nickel," *Izv. Akad. Nauk SSSR, Met.*, (5), 99-104 (1974) in Russian; TR: *Russ. Metall.*, (5), 82-86 (1974). (Thermo; Experimental)

74Gol: N.S. Golosov and B.V. Dudka, "Computer Modeling of the Order-Disorder Transformation in Cu_3Au and Ni_3Fe," *Phys. Status Solidi (b)*, *66*, 439-448 (1974). (Meta Phases; Theory)

74Ind: G. Inden, "Ordering and Segregation Reactions in B.C.C. Binary Alloys," *Acta Metall.*, *22*, 945-951 (1974). (Thermo; Theory)

74Nis: M. Nishi, Y. Nakai, and N. Kunitomi, "Magnetic Moments in Fe-Ni Alloys," *J. Phys. Soc. Jpn.*, *37*, 570 (1974). (Magnetism; Experimental)

74Rao: M.V. Rao and W.A. Tiller, "The Systems Fe-Cr and Fe-Ni: Thermochemistry and Phase Equilibria," *Mater. Sci. Eng.*, *14*, 47-54 (1974). (Thermo; Theory; #)

74Ume: M. Umemoto and W.S. Owen, "Effects of Austenitizing Temperature and Austenite Grain Size on the Formation of Athermal Martensite in an Iron-Nickel-Carbon Alloy," *Metall. Trans.*, *5*, 2041-2046 (1974). (Meta Phases; Experimental)

74Vre: J. Vrestal, A. Pokorna, and K. Stransky, "Determination of Thermodynamic Activities of Components in the Iron-Nickel System at T = 1509 K," *Kovové Mater.*, *1*, 3-9 (Thermo; Experimental)

75Bil: L. Billard and A. Chamberod, " On the Dissymmetry of Mössbauer Spectra in Iron-Nickel Alloys," *Solid State Commun.*, *17*, 113-118 (1975). (Equi Diagram; Experimental)

75Ind: G. Inden, "Determination of Chemical and Magnetic Interchange Energies in BCC Alloys," *Z. Metallkd.*, *66*, 577-582 (1975). (Magnetism; Theory)

75Leb: M. Lebienvenue and B. Dubois, "Study of the Order-Disorder Transformation in Ni_3Fe by Measurement of Internal Friction," *C.R. Acad. Sci. (Paris) C*, *280*, 1251-1253 (1975) in French. (Equi Diagram; Experimental)

75Tri: C.C. Trinel-Dufour and M.P. Perrot, "Activities of the Constituents of Fe-Ni Alloys Determined by Equilibrium Measurements in the Presence of an Oxide Phase," *C.R. Acad. Sci. (Paris) C*, *281*, 589-592 (1975) in French. (Thermo; Experimental)

76Dal: A.D. Dalvi and R. Sridhar, "Thermodynamics of the Fe-Ni-O and Fe-Ni Systems at 1065 K to 1380 K," *Can Metall. Q.*, *15*(4), 349-357 (1976). (Thermo; Experimental)

76Rob: D. Robinson and B.B. Argent, "Thermodynamics of Dilute Solutions of the First-Period Transition Elements in Iron," *Met. Sci.*, *10*, 219-221 (1976). (Thermo; Experimental)

76Ino: Y. Inokuti and B. Cantor, "Splat-Quenched Fe-Ni Alloys," *Scr. Metall.*, *10*, 655-659 (1976). (Meta Phases; Experimental)

77Gri: E.J. Grimsey and A.K. Biswas, "The Activity of Iron in Low-Iron Liquid (Ni+Au+Fe) and Solid (Ni+Fe) Alloys at 1573 K," *J. Chem. Thermodyn.*, *9*, 415-422 (1977). (Thermo; Experimental)

77Has: M. Hasebe and T. Nishizawa, "Analysis and Synthesis of Phase Diagrams of the Fe-Cr-Ni, Fe-Cu-Mn and Fe-Cu-Ni Systems," *Applications of Phase Diagrams in Metallurgy and Ceramics*, Nat. Bur. Stds. SP-496, U.S. Govt. Printing Office, Washington, DC, 1977. (Thermo; Experimental)

77Hut: H. Huthmann, "Factors Influencing Chemical and Magnetic Ordering Transformations in F.C.C. Iron-Nickel Alloys," thesis, Tech. Univ., Aachen (1977) in German. (Equi Diagram, Thermo; Experimental)

***77Kub:** O. Kubaschewski, K.H. Geiger, and K. Hack, "The Thermochemical Properties of Iron-Nickel Alloys," *Z. Metallkd.*, *68*, 337-341 (1977) in German. (Thermo; Experimental)

77Lar: L.N. Larikov and Y.V. Vsov, "Thermal Properties of Fe-Ni Alloys," *Akad. Nauk Ukr. SSR, Metallofiz.*, *68*, 3-14 (1977) in Russian. (Thermo; Theory; #)

77Mio: A.P. Miodownik, "The Calculation of Magnetic Contributions to Phase Stability," *Calphad*, *1*, 133-158 (1977). (Magnetism; Theory)

77Ono: K. Ono, Y. Veda, Y. Yamaguchi, and J. Moriyama, "Thermodynamic Study of Fe-Ni Solid Solution," *Trans. Jpn. Inst. Met.*, *18*, 610-616 (1977). (Thermo; Experimental)

77Pet: J.F. Petersen, A. Aydin, and J.M. Knudsen, "Mössbauer Spectroscopy of an Ordered Phase (Superstructure) of FeNi in an Iron Meteorite," *Phys. Lett. A*, *62*, 192-194 (1977). (Meta Phases; Experimental)

77Roi: A.L. Roitburd, "Predominant Effect of the Internal Stress Relaxation on Microstructural and Kinetic Features of Martensitic Transformation," *Phys. Status Solidi (a)*, *40*, 333-342 (1977). (Meta Phases; Experimental)

78Alb1: J.F. Albertsen, G.B. Jensen, and J.M. Knudsen, "Structure of Taenite in Two Meteorites," *Nature*, *273*, 453-454 (1978). (Meta Phases; Experimental)

78Alb2: J.F. Albertsen, M. Aydin, and J.M. Knudsen, "Mössbauer Effect Studies of Taenite Lamelle of Iron Meteorite Cape York (III.A)," *Phys. Scr.*, *17*, 467-472 (1978). (Meta Phases; Experimental)

78Cha: A. Chamberod, M. Roth, and L. Billard, "Small Angle Scattering in Invar Alloys," *J. Magn. Magn. Mater.*, *7*, 101-103 (1978). (Meta Phases; Experimental)

78Con: B.R. Conrad, T.S. McAneney, and R. Sridhan, "Thermodynamics of Iron-Nickel Alloys by Mass Spectroscopy," *Metall. Trans. B*, *9*, 463-468 (1978). (Meta Phases, Thermo; Experimental)

78Gal: G. Galeczki and A.A. Hirsch, "Gamma Phase Dispersions in Fe-Ni Alloys Below the Critical Concentration," *J. Magn. Magn. Mater.*, *7* 110-112 (1978). (Meta Phases; Experimental)

78Hil: M. Hillert, "Prediction of Iron-Base Diagram," in *Hardenability Concepts with Applications to Steel*, TMS-AIME, Warrendale, Pa, 5-27 (1978). (Thermo; Theory)

78Kat: A. Katsuki, "Physics and Applications of Invar Alloys," Honda Memorial Series on Materials Science No. 3 (1978). (Meta Phases, Thermo, Magnetism; Review)

78Mar: N. Maruyama and S. Ban-ya, "Measurements of Activities in Liquid Fe-Ni, Fe-Co, and Ni-Co Alloys by a Transportation Method," *J. Inst. Met. Jpn., 42*, 992-999 (1978) in Japanese. (Thermo; Experimental)

79Agr: J. Agren, "A Thermodynamic Analysis of the Fe-C and Fe-Ni Phase Diagram," *Metall. Trans. A, 10*, 1847-1852 (1979). (Thermo; Theory)

79Bos: O. Bostanjoglo, U. Heinecke, and R. Liedtke, "Possible Stabilization of Amorphous FeNi Films by Conduction Electrons," *Phys. Status Solidi (a), 56*, 569-572 (1979). (Meta Phases; Experimental)

79Cha: A. Chamberod, J. Laugier, and J.M. Penisson, "Electron Irradiation Effects on Iron-Nickel Invar Alloys," *J. Magn. Magn. Mater., 10*, 139-144 (1979). (Meta Phases; Experimental; #)

79Des: M.C. Desjonqueres and M. Lavanga, "Effects of Order on the Electronic Structure of Ferromagnetic Transition Metal Alloys: Application to FeCo and Ni_3Fe," *J. Phys. F, Met. Phys., 9*, 1733-1743 (1979). (Equi Diagram; Experimental)

79Lar: J.M. Larrain and H.H. Kellogg, "Use of Chemical Species for Correlation of Solution Properties," in *Calculation of Phase Diagrams and Thermochemistry of Alloy Phases*, TMS-AIME, Warrendale, PA, 130-144 (1979). (Thermo; Theory; #)

79Lin: L.S. Lin, J.I. Goldstein, and D.B. Williams, "Analytical Electron Microscopy Study of the Plessite Structure in Four III CD Iron Meteorites," *Geochim. Cosmochim. Acta, 43*, 725-737 (1979). (Meta Phases; Experimental)

79Mat: M. Matsui and K. Adachi, "Low Temperature Structure of Fe-Ni Alloys," *J. Magn. Magn. Mater., 10*, 152-154 (1979). (Meta Phases; Experimental)

79Sco: E.R.D. Scott and R.S. Clarke, "Identification of Clear Taenite in Meteorites as Ordered FeNi," *Nature, 281*, 360-362 (1979). (Meta Phases; Experimental)

79Shi: M. Shimizu, "Origin of the Anomalies and Thermodynamic Aspects of Iron-Nickel Invar Alloys," *J. Magn. Magn. Mater., 10*, 231-235 (1979). (Meta Phases; Theory)

79Tan: Y. Tanji, Y. Nakagawa, Y. Saito, K. Nishimura, and K. Nakatzuka, "Anomalous Thermodynamic Properties of Iron-Nickel (F.C.C.) Alloys," *Phys. Status Solidi (a), 56*, 513-519 (1979). (Thermo; Experimental)

80Lar: J.M. Larrain, "High Temperature Thermodynamic Properties of Iron-Nickel Alloys," *Calphad, 4*, 155-171 (1980). (Thermo; Theory; #)

80Meh: S. Mehta, P.M. Novotny, D.B. Williams, and J.I. Goldstein, "Electron-Optical Observations of Ordered Fe-Ni in the Estherville Meteorite," *Nature, 284*, 151-153 (1980). (Meta Phases; Experimental)

80Rom: A.D. Romig and J.I. Goldstein, "Determination of the Fe-Ni and Fe-Ni-P Phase Diagrams at Low Temperatures (700 to 300 °C)," *Metall. Trans. A, 11*, 1151-1159 (1980). (Equi Diagram; Experimental)

80Van: J.K. Van Deen and F. Van der Woude, "Phase Diagram of the Order-Disorder Transition in Ni_3Fe," *J. Phys., 41*, C1-367-C1-368 (1980). (Equi Diagram; Experimental)

81Bor: G. Bordin, G.C. Cecchi, and G.B. Fratucello, "Remarks on the Martensitic Transformation in Some Iron-Nickel Alloys," *Nuovo Cimento B, 61*, 338-346 (1981). (Meta Phases; Experimental)

81Igu: Y. Iguchi, Y. Tozaki, M. Kakizaki, T. Fuwa, and S. Ban-ya, "A Calorimetric Study of Heat of Mixing of Liquid Iron Alloys," *J. Iron Steel Inst. Jpn., 67*, 925-932 (1981) in Japanese. (Thermo; Experimental)

81Imr: G. Imrich-Swartz and H. Gamsjager, "Computer-Supported Evaluation of the Gibbs-Duhem Equation," *Ber. Hüttenmänn. Monatsh., 126*, 275-277 (1981) in German. (Thermo; Theory)

81Lef: S. Lefebvre, F. Bleu, M. Fayard, and M. Roth, "Neutron Diffuse Scattering Investigation of Different States of Local Order in $^{62}Ni_{0.765}Fe_{0.235}$," *Acta Metall., 29*, 749-761 (1981). (Equi Diagram; Experimental)

81Nis: T. Nishizawa and M. Hasebe, "Computer Calculation of Phase Diagrams of Iron Alloys," *J. Iron Steel Inst. Jpn., 67*, 2086-2097 (1981) in Japanese. (Thermo; Theory; #)

81Ram: W. Rammensee and D.G. Fraser, "Activities in Solid and Liquid Fe-Ni and Fe-Co Alloys Determined by Knudsen Cell Mass Spectrometry," *Ber. Bunsenges. Phys. Chem., 85*, 558-592 (1981). (Thermo; Experimental)

81Sun: B. Sundman, "A Computer Program for Optimizing Parameters in Thermodynamic Model," R. Inst. Stockholm, Sweden, Rep. D28 (1981). (Thermo; Theory)

***81Van:** J.K. Van Deen and F. Van der Woude, "Phase Diagram of the Order-Disorder Transition in Ni_3Fe," *Acta Metall., 29*, 1255-1262 (1981). (Equi Diagram; Experimental)

82Bro1: P.J. Brofman and G.S. Asell, "On The Morphology of Martensite in Fe-27 Ni Alloys," Proc. Int. Conf. on Solid-Solid Phase Transformations, TMS-AIME, Warrendale, PA, 1373-1377 (1982). (Meta Phases; Experimental)

82Bro2: C.R. Brooks, P.J. Meschter, and T.G. Kollie, "The Magnetic Heat Capacity of the Configurationally Disordered Ni-25 at% Fe Alloy," *Phys. Status Solidi (a), 73*, 189-198 (1982). (Thermo; Experimental)

***82Cha:** T.G. Chart, D.D. Gohil, and Z.S. Xing, "Calculated Phase Equilibria for the Cu-Ni-Fe System," NPL Rep. DMA(A) 54, National Physical Laboratory, Middlesex, UK, Aug (1982). (Thermo; Theory; #)

82Duf: F. Duflos and B. Cantor, "The Microstructure and Kinetics of Martensite Transformation in Splat-Quenched Fe and Fe-Ni Alloys-I. Pure Fe," *Acta Metall., 30*, 323-342 (1982). (Meta Phases; Experimental)

82Gol: J.I. Goldstein and D.B. Williams, "Low Temperature Phase Transformations in the Metallic Phases of Meteorites," Proc. Int. Conf. on Solid-Solid Phase Transformations, TMS-AIME, Warrendale, PA, 715-719 (1982). (Meta Phases; Experimental)

82Jag: R.A. Jago, P.E. Clark, and P.L. Rossiter, "The Santa Catharina Meteorite and the Equilibrium State of Fe-Ni Alloys," *Phys. Status Solidi (a), 74*, 247-254 (1982). (Meta Phases; Experimental)

82Kub: O. Kubaschewski, *Iron Binary Phase Diagrams*, Springer-Verlag, New York, NY, 73-78 (1982). (Equi Diagram; Review)

82Ore: J. Orehotsky, J.B. Sousa, and M.F. Pinheiro, "Critical Behavior in Ni_3Fe and Ni_3Mn," *J. Appl. Phys., 53*, 7939-7941 (1982). (Equi Diagram, Magnetism; Experimental)

82Ray: J.J. Rayment, O. Ashira, and B. Cantor, "The As-Quenched Microstructure of Rapidly Solidified Fe-25 wt.% Ni," Proc. Int. Conf. Solid-Solid Phase Transformations, TMS-AIME, Warrendale, PA, 1385-1389 (1982). (Meta Phases; Experimental)

82Rhy: J.J. Rhyne, "Magnetic Transition Temperatures of the Elements," *Bull. Alloy Phase Diagrams, 3*, 402 (1982). (Magnetism; Review)

82Rod: A. Rodrigues, C. Prioul, J. Plusquellec, and P.Y. Azou, "The Effects of Carbon and Time-Related Parameters on the Reheat Martensite Transformations in Fe-Ni-C Alloys at Subzero Temperatures," Proc. Int. Conf. Solid-Solid Phase Transformations, TMS-AIME, Warrendale, PA 1391-1395 (1982). (Meta Phases; Experimental)

82Vel: J. Velisek, "Correlation of Selected Thermodynamic and Phase Data in the Fe-Ni System," *Kovové Mater., 20*, 257-265 (1982). (Thermo; Theory; #)

83Abb: G.J. Abbaschian and M.C. Flemings, "Supercooling and Structure of Levitation Melted Fe-Ni Alloys," *Metall. Trans. A*, *14*, 1147-1157 (1983). (Meta Phases; Experimental)

83Kam: D.S. Kamenetskaya, O.P. Maksimora, and V.I. Shiryayev, "Features of the Martensite Transformation in High Purity Iron-Nickel Alloys," *Fiz. Met. Metalloved.*, *55*(5), 967-972 (1983) in Russian; TR: *Phys. Met. Metallogr.*, *55* (5), 121-127 (1983). (Meta Phases; Experimental)

83Sen: A. Sen Gupta and B.K. Banarjee, "High Temperature X-ray Study of Some Iron-Nickel Alloys," *Indian J. Phys. A*, *57*, 196-199 (1983). (Crys Structure; Experimental)

84Bor: G. Bordin, G.C. Cecchi, and I. Montanari, "Some Transport Properties in Martensitic Iron—Nickel Alloys," *Nuovo Cimento D*, *3*(2), 436-446 (1984). (Meta Phases; Experimental)

84Cen: P. Cenedese, F. Bley, and S. Lefebvre, "Atomic Short Range Order in a Fe-Ni Invar Alloy," *Phase Transformations in Solids*, Mater. Res. Symp. Proc., T. Tsakalakos, Ed., North-Holland, New York, 351-353 (1984). (Meta Phases; Experimental)

84Des: P.D. Desai and M.S. Desphande, "Thermodynamic Properties of Nickel," CINDAS Rep. 80, Purdue University, Layfayette, IN, Aug (1984). (Thermo; Review)

84Gor: A.M. Gorovol, A.I. Ushakov, V.G. Kazakov, Yu.L. Raodionov, and V.N. Goloborod'ko, "The Approach to the Equilibrium State in Films of Iron—Nickel Alloys," *Fiz. Met. Metalloved.*, *58*(1), 113-118 (1984) in Russian. (Meta Phases; Experimental)

84Izm: E.A. Izmailov, "The Transformation of Martensite into Austenite in Iron-Nickel Alloys," *Fiz. Met. Metalloved.*, *58*(1), 39-97 (1984). (Meta Phases; Experimental)

84Lef: S. Lefebvre, F. Bley, and P. Cenedese, "Determination of Short Range Order Parameters in $^{62}Ni_{0.765}Fe_{0.235}$ at 600 °C Effect of a Quench," *Phase Transformations in Solids*, Mater. Res. Symp. Proc., T. Tsakalakos, Ed., North-Holland, New York, 351-353 (1984). (Equi Diagram; Experimental)

84Miu: H. Miura, S. Isa, K. Omuro, "Production of Amorphous Iron—Nickel Based Alloys by Flame-Spray Quenching and Coatings on Metal Substrates," *Trans. Jpn. Inst. Met.*, *25*(4), 284-291 (1984). (Meta Phases; Experimental)

84Rin: O.S. Rinkevich and V. Zel'dovich, "An Analysis of the Growth Kinetics of New Austenite Grains During the Alpha-Gamma Transformation in an Iron-Nickel Alloy," *Fiz. Met. Metalloved.*, *58*(1), 142-148 (1984). (Meta Phases; Experimental)

84Ros1: P.L. Rossiter and R.A. Jago, "Towards a True Fe-Ni Phase Diagram," *Phase Transformation in Solids*, Mater. Res. Symp. Proc., T. Tsakalakos, Ed., 409-411, North Holland, New York (1984). (Meta Phases; Experimental; #)

84Ros2: P.L. Rossiter and P.J. Lawrence, "Phase Transformations in Fe-Ni Invar Alloys," *Philos. Mag. A*, *49*(4), 535-546 (1984). (Meta Phases; Experimental)

84Yam: H. Yamauchi and S. Radelaar, "Cu-Ni-Fe Coherent Phase Diagram," TMS-AIME, Warrendale, PA (1984). (Meta Phases; Theory)

85Chu1: Y.Y. Chuang, R. Schmid, and Y.A. Chang, "Magnetic Contributions to the Thermodynamic Functions of Pure Ni, Co, and Fe," *Metall. Trans. A*, *16*, 153-165 (1985). (Thermo; Theory)

85Chu2: Y.Y. Chuang, Y.A. Chang, and R. Schmid, "Magnetic Contribution to the Thermodynamic Functions of Alloys and the Phase Diagram of Fe-Ni System Below 1200 K," *Metall. Trans. A*, *16*, 153-165 (1985). (Meta Phases, Thermo; Theory)

85Tom: J. Tomiska and A. Neckel, "Thermodynamic Investigation of Fe-Ni Alloys: Mass Spectrometric Determination of Thermodynamic Mixing Effects and Calculation of the Melting Diagram," *Ber. Bunsenges. Phys. Chem.*, *89*, 1104-1109 (1985). (Equi Diagram; Thermo; Experimental)

86Chu1: Y.Y. Chuang, K.C. Hsieh, and Y.A. Chang, "A Thermodynamic Analysis of the Phase Equilibrium of the Fe-Ni System Above 1200 K," *Metall. Trans. A*, *17*, 1373-1379 (1986). (Meta Phases; Theory)

86Chu2: Y.Y. Chuang, Y.A. Chang, R. Schmid, and J.C. Lin, "Magnetic Contributions to the Thermodynamic Functions of Alloys and the Phase Equilibria of Fe-Ni System below 1200 K," *Metall. Trans. A*, *17*, 1361-1371 (1986). (Meta Phases; Equi Diagram; Theory)

89Reu: K.B. Reuter, D.B. Williams, and J.I. Goldstein, "Determination of the Fe-Ni Phase Diagram Below 400 °C," *Metall. Trans. A*, *20*, 719-724 (1989). (Equi Diagram, Meta Phases; Experimental)

Fe-Ni evaluation contributed by **L.J. Swartzendruber**, Metallurgical Structures Group, National Institute of Standards and Technology, Gaithersburg, MD 20899; **V.P. Itkin**, Department of Metallurgy and Materials Science, University of Toronto, Ontario M5S 1A4, Canada; and **C.B. Alcock**, Center for Sensor Materials, University of Notre Dame, 114 Cushing Hall, Notre Dame, IN 46556. This work was supported by ASM International. Literature searched through 1989. Dr. Swartzendruber is the former Alloy Phase Diagram Category Editor for binary iron alloys.