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WATERTOWN ARSENAL LABORATORY

EXPERIMENTAL REPORT

NO. WAL. 310/37-1 (14)

(6) PRINCIPLES OF PHASE TRANSFORMATIONS.

Second Partial ~~Report~~ no. 2 (9)

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BY

(10) W. West
Physicist

DATE (11) 13 January 1945

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2. Copies of this report have also been sent to the Frankford Arsenal, Springfield Armory, Watervliet Arsenal, Rock Island Arsenal, Ordnance Research and Development Center and to Carnegie Illinois Steel Corporation.

3. This report contains all the information deducible from the literature regarding the free energies of transfer of alloying elements between the ferrite, austenite and cementite phases of steel.

For the Commanding Officer:

N. A. MATTHEWS
Major, Ordnance Dept.,
Assistant.

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Watertown Arsenal Laboratory
Report Number WAL 310/37-1
Problem Number J-4.2

13 January 1945

PRINCIPLES OF PHASE TRANSFORMATIONS

Second Partial Report

OBJECT

. To test the methods developed in the First Partial Report of this series against experimental data available in the literature on medium ternary iron alloys, and to determine the constants of the appropriate equations for as many alloying elements as possible.

SUMMARY

Major factors in the heat treatment of a specimen of steel are, the transformations which the material undergoes on heating and cooling, the temperatures at which these transformations take place, and the speed at which they take place. The equations developed by Zener (Report Number WAL 310/37) are intended to permit calculation of the effects of one or more alloying elements on the first two of the above factors. If the validity of these equations can be established, and if the characteristic constants can be determined for the various alloying elements, it should be possible to predict the heat-treating properties of steel of a given composition, or to make up a steel of composition such that it would have specified heat-treating properties, at least so far as the first two factors mentioned above are concerned. It is obvious that this would be an important aid to practical steel-making.

In order to test Zener's equations the literature has been searched for pertinent experimental data on iron alloys containing carbon. Only actual results have been used, and not values from smoothed curves, except in the case of molybdenum, where only curves were available. A number of cases have been found in which the data confirm the theory within the limits of experimental error, and in which reliable constants for the equations can be determined. In other cases the data available are few, or discordant, and no conclusion can be reached either way. Only two cases have been found of clear-cut disagreement of experiment with theory. However, in view of experimental difficulties in work of this sort, the amount of agreement obtained gives confidence in the rather general applicability of the theory.

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I GENERAL DISCUSSION

A. Scope and Significance of This Report

One who attempts to collect and classify equilibrium data from various iron alloy systems is soon struck with the absence of any quantitative theory which can serve as a general background against which to compare and contrast results from different systems, at different temperatures, and with different concentrations. It is not necessary to wait for a perfect theory; investigation of divergences of theory from observation may prove of great value in acquiring understanding of the subject. For example, one has only to think of Raoult's Law as applied to aqueous solutions.

The equations developed by Zener represent an effort to provide such a quantitative theoretical background, and it is therefore desirable to subject this theory to such tests as can be applied. The present report is intended to be an application of available tests, and may thus be considered as a supplement to Zener's paper.

The equations make it possible to calculate the effect on the equilibrium concentration of one alloying element due to the presence of one or more other elements. In particular, they are intended to give, for alloy steels, the carbon concentrations in alpha and gamma phases in equilibrium with each other, and in gamma in equilibrium with cementite. They may, however be modified for use for non-carbon alloys. A summary is given later of the equations used in analysing the data in this paper, and the symbols are there defined.

About 125 papers have been examined for experimental data suitable for this investigation. An effort was made to look up all available reports of ternary systems including iron and carbon, as well as similar systems of higher order. Supplementary material was also obtained from a number of binary systems. A few non-carbon ternary systems were also found to which these methods could be applied.

A comparatively small proportion of the papers read provided usable material. In many systems the number of quantitative observations made in the iron-rich region is extremely small, and the smoothed curves to be found in most published phase diagrams are entirely useless for quantitative treatment. This opinion is confirmed by the authors of the "Alloys of Iron Research" series, whose remarks show clearly that they have no illusions as to the accuracy of many diagrams which they present. A further difficulty is due to the fact that these equations apply only to rather low percentages of alloying elements. The result is that at the lowest concentrations, where the best agreement might be hoped for, the errors of observation become relatively very large. The experimental difficulties in measurements of this kind of equilibrium are, of course, an old story.

In view of the above, it is gratifying to find a fairly substantial agreement of theory with experiment. As previously stated, only two cases have come to light of clear-cut disagreement. Referring to Table II, the $\alpha \rightarrow \gamma$ column, it may be said that for three metals, Mo, W, V, ΔG seems reliably established. For P the given value is from the Fe-P system, and no check has been possible with Fe-P-C. As described later, the value for Si is so small that its relative uncertainty is rather great. For the important alloying elements Mn and Ni considerable uncertainty exists, no doubt largely because of the difficulty of attaining equilibrium at the lowered temperatures. Cu suffers from the same thing, and in addition has only a few points from but a single observer. Cr is discussed in detail later.

In the cementite-γ column Cr and Mn seem fairly reliable, and Cu very doubtful, due to insufficient and inconsistent data. Among the complex carbides the case of V is rather promising, but existing data are few and very inconsistent.

Of special interest are the cases which clearly disagree with the theory, Fe-Cr-C and Fe-Ni-P. It might be worthwhile to investigate other cases of the latter type, with and without carbon, since experimental and theoretical study of these may well be illuminating to the whole theory.

As is shown later, it is possible to get at Ni indirectly through the system Fe-Ni-W. Study of this combination with carbon, and of Fe-Ni-V with or without carbon, might throw light on the important but hitherto inscrutable question of Ni. The same method might succeed for Mn.

B. Summary of Equations and Symbols

The following equations are taken from the First Partial Report, the numbers used there being retained.

Note that in the equations temperatures refer to the absolute scale, and compositions to atomic concentrations. All numerical data in this report employ Centigrade temperatures and weights per cent. Superscripts refer to phases, and subscripts to components.

R = molecular gas constant = 1.99 cal.

T = absolute temperature

C_j = atomic concentration of element j

G = free energy

Σ = a summation covering all elements present except iron and carbon.

1. Alpha-Gamma Equilibrium.

It is now pointed out by Zener that in both body-centered alpha-phase and face-centered gamma phase interstitial positions exist at the edges of the cubes, as well as at the center of the cube for the face-centered form and at the centers of the faces for the body-centered form. There are therefore three times as many interstitial positions per lattice atom in the alpha-phase as in the gamma, and the corresponding ΔG_c becomes -8100.

$$C_c^\gamma = (C_c^\gamma)_0 + \Sigma \left\{ \frac{e^{\Delta G_j/RT}-1}{1-3e^{\Delta G_c/RT}} \right\} C_j^\gamma \qquad (31)$$

$$(C_c^\gamma)_0 = \frac{\Delta G_{Fe}/RT}{1-3e^{\Delta G_c/RT}} \qquad (23)$$

(carbon concentration in absence of other alloying elements)

Δ here refers to a transfer of 1 gram atom of the indicated element from the alpha to the gamma phase. $\Delta G_c = -8,100$. For ΔG_{Fe} see Table I.

2. Cementite → Gamma Equilibrium.

$$C_c^\gamma = (C_c^\gamma)_1 \Big/ \left[1 + \Sigma C_j^\gamma \left\{ e^{(\Delta G_j - \Delta G_{Fe})/3RT} - 1 \right\} \right]^3 \qquad (35)$$

$$(C_c^\gamma)_1 = 1/4\ e^{-\Delta G_{Fe}/RT} \qquad (38)$$

(carbon concentration in absence of other alloying elements).

Δ here refers to a transfer of 1 mol of carbide, $(\text{metal})_3C$, from the cementite to the gamma phase. $\Delta G_{Fe} = 5300$.

3. Constants For Use In Above Equations.

TABLE I

Temp. (^{o}C)	$\Delta G_{Fe}/RT$ ($\alpha \rightarrow \gamma$) cal %	$(C_c^{\gamma})_o$ ($\gamma \rightleftarrows \alpha$) wt %	$(C_c^{\gamma})_1$ ($\gamma \rightleftarrows$ cementite) wt %
700	0.050	1.11	0.83
800	0.0135	0.31	1.00
910	0	0	1.24
1000	-0.0054	-0.13	1.45
1100	-0.0077	-0.20	1.71
1200	-0.0071	-0.20	
1300	-0.0044	-0.13	
1400	0	0	
1500	0.0069	0.25	

II EXAMINATION OF INDIVIDUAL ALLOYING ELEMENTS

In the following pages analyses are made of the experimental data on the carbon content of the gamma-phase in equilibrium with, respectively, alpha-phase and cementite. Constants have been chosen to give calculated curyes agreeing as closely as possible with the experimental results, and the degree of correlation is observed over the available temperature and concentration ranges. Two non-carbon systems have also been included.

RESULTS

In Table II are given the constants as determined. ΔG for $\alpha \rightarrow \gamma$ represents the free energy of transfer of one gram-atom of the alloying element from the alpha to the gamma phase; ΔG for cementite $\rightarrow \gamma$ represents the free energy of transfer of one gram-mol of A_3C from the carbide to the gamma phase, A being the alloying element.

TABLE II

Alloying Element	ΔG $\alpha \rightarrow \gamma$	Cementite
Cr	(?)	13,000*
Cu	- 500 (?)	20,000 (?)
Mn	-1000 (?)	11,000
Mo	+1500	**
Ni	-1050 (?)	No data
P	+3100	No data
Si	+ 450	***
W	+1250	**
V	+2000	**

* for Cr < 2.5% only.
** complex carbides other than cementite.
***relation of graphite and carbide uncertain.

A. Chromium

1. Alpha-Gamma Equilibrium.

The iron-chromium system was discussed in the First Partial Report, and it was shown that the simplified equations had to be extended to include an interaction term before results of theory could be brought into agreement with experiment. Examination of experimental results for the iron-chromium-carbon system also shows divergence from theory.

In Figure 1 are plotted a large number of observations of Ac_3 and Ar_3 obtained dilatometrically by Wever and Jellinghaus[1] and also some points based on observations of microstructures by Tofaute, Sponheuer and Bennek.[2] A few cooling-curve results by the former, and dilatometric points by the latter authors, have not been plotted, but show no divergence from the results given. The dotted curves represent C_o^{α} for the iron-carbon system. It is seen that near the axis the transformation curve is lowered slightly (as must necessarily be the case for small percentages of chromium), and that as carbon is increased the Ar_3 points maintain this slight lowering, while the Ac_3 points rise markedly above the iron-carbon curve. The possibility exists that this rise is only apparent, and is due to slow rate of dissolving of carbide present before heating began. This hypothesis is supported by the increasing carbon. On the other hand, Ac points are generally considered more reliable than Ar. Further, there has been acceptance of an A_3 curve crossing the C_o curve for low chromium content.[3] This latter situation would require that a few percent chromium should appreciably change the heat of transfer of carbon from gamma to alpha phase, a possibility that cannot be ruled out, in view of the anomalous effect of chromium on pure iron.

2. Gamma-Carbide Equilibrium.

For low chromium contents there are two carbides which have stable ranges in contact with the gamma-phase, ortharhombic $(Fe,Cr)_3C$, (cementite), and trigonal $(Cr,Fe)_7C_3$. As is indicated, iron and chromium are found in both forms, at least within limits. In Figure 2 are plotted observations on microstructure by Tofaute, Sponheuer and Bennek,[2] corrected for the given contents of manganese and silicon. Making use of the cementite points under Cr = 1.60 % we obtain $\Delta H = 13,000$, giving the calculated curve as drawn. For higher chromium contents the points observed are of trigonal carbide, and, in fact, the calculated curves fall increasingly to the right of the observations, as is required by theory. The heavy dotted lines represent approximate positions for the γ-trigonal carbide boundary, increasingly encroaching on the γ-cementite boundary as the chromium content increases. Wever and Jellinghaus[1] using X ray analysis, found cementite at Cr = 1.6% and C = 1.3%. At Cr = 3.0% they found cementite and trigonal carbide at C = 0.5%, and cementite alone at .92% C. These fit fairly well with the diagrams of Figure 2.

It appears that ΔH = 13,000 is applicable up to 2-2.5% chromium.

B. Copper

1. Alpha-Gamma Equilibrium.

Copper is known to lower the temperature of this transformation, in its alloys with iron, but the few experimental data on the iron-copper-carbon system[4] indicate a marked rise of Ac_3 temperature with copper content.

2. Gamma-Carbide Equilibrium.

The authors mentioned above published three series of experimental data. Four points, with Cu = 1%, are plotted in Figure 3, with a line calculated for ΔG_{Cu} = 20,000. The agreement appears fairly good. This promise, however, is not fulfilled with the other two series. In Table 3 the calculated value of carbon assumes ΔG_{Cu} = 20,000. It is seen that in one series the calculated values fall consistently well above the observations, and in the other, equally far below. In the absence of further data the free energy of transfer cannot be determined with any certainty.

TABLE III

		% C				% C	
T	% Cu	obs	calc	T	% Cu	obs	calc
850	2.08	0.48	0.72	980	2.08	1.27	0.99
900	3.25	0.55	0.65	980	2.53	1.16	0.92
990	4.10	0.49	0.72	990	3.11	1.14	0.84
1020	4.97	0.48	0.70	1060	4.14	1.24	0.89
1050	5.80	0.54	0.68	1100	4.85	1.11	0.90

C. Manganese

1. Gamma-Alpha Equilibrium.

Inspection of results on the iron-manganese system[5] indicate a value for ΔG_{Mn} -1400 cal. The only observed points for the iron-manganese-carbon system, at low concentrations, are those of Gensamer,[6] which are listed in Table IV.

TABLE IV

% Mn	% C	α present	no α present	ΔC calc	ΔC obs
2.5	.16	770	795	-.21	-.24
4.5	.19	755	775	-.41	-.32
4.5	.45	710	730	-.41	-.42

ΔC gives the calculated and observed distances from the iron-carbon curve of points midway in the observed temperature range of dilatometric change. ΔG_{Mn} was taken as -1000 cal, which roughly fits the points. One approximate point is given for Mn = 7%[7] and two for Mn = 10%[8], all of which indicate ΔG_{Mn} as approximately -2500. It may be noted that recent observations by Troiano and McGuire[9] on the iron-manganese system indicate a very similar ΔG_{Mn} with a similar increase at higher manganese concentrations and lower temperatures. The limited evidence, then, points to a free energy of transfer of -1000 cal for low percentages of manganese and temperatures near 900°.

2. Gamma-Carbide Equilibrium.

Three series of experimental results exist for this boundary, two by Gensamer[6] for 2.5 and 4.5% Mn, and one by Wells and Walters for 7% Mn.[7] These are plotted in Figure 4, together with the C_1 line for the iron-carbon system, and a line calculated by Equation (35), using $\Delta G_{Mn} = 11,000$. This value gives the best fit that can be obtained, although the observational lines, especially those of Gensamer, show appreciably less slope than the calculated. The agreement is better at 7% Mn, where the equation might not be expected to apply so well.

D. Molybdenum

1. Gamma-Alpha Equilibrium.

The iron-molybdenum system forms a gamma-loop, but estimates of the value of C_α^* vary from less than 3% to more than 4%[10], corresponding to values of ΔG from 1500 to 1000. The only available data from the iron-molybdenum carbon system is from a set of curves by Svetchnikoff and Alferova.[11] Reading from these curves for Mo = 1% we obtain the points plotted in Figure 5. A calculated curve with $\Delta G_{Mo} = 1750$ is seen to fit the points fairly well. No information is available as to the methods employed by these authors.

2. Gamma-Carbide Equilibrium.

The gamma phase is in equilibrium with complex carbides other than cementite in concentration ranges for which observations are available.

E. Nickel

1. Gamma-Alpha Equilibrium.

Attempts to calculate ΔG_{Ni} from the Fe-Ni diagram fail, due to the wide divergence of experimental results obtained on heating and on cooling, the interpretation of this being uncertain.[12] The diagram widely accepted as of practical use is that showing two wide bands, representing gamma-alpha transformation ranges on cooling and heating respectively.

Marsh[12] quotes three investigators whose results indicate that the true upper and lower boundaries of the alpha-gamma two-phase region lie, respectively, in the heating and cooling transformation bands. There is, however, disagreement as to the exact position of these lines.

Few experimental results exist for the iron-nickel-carbon system. Kase[13] gives a few values of Ar_3, which correspond to $\Delta G_{Ni} = -2500$ or more, with considerable divergences. Bain (reference[12], page 74) reported points on the gamma $\rightleftharpoons$ gamma + alpha boundary which give fairly consistent results of $\Delta G_{Ni} = -2000$ or less. Jones[14] reported a long series of Ac_3 and Ar_3 points for nickel steels containing up to 1% Mn. When corrected for the effect of the manganese, which is somewhat uncertain, the Ac_3 points indicate $\Delta G_{Ni} \cong -1000$. No mention was made of Si, which was almost certainly present, and which may have been in fact responsible for this low result. It may be noted that his Ar_3 points fell 60° - 140° below the Ac_3, indicating that the previously mentioned effect of nickel on this transformation persists in the presence of at least some other alloying elements.

A series of observations on the ternary system iron-nickel-tungsten[15] provides an opportunity to determine ΔG_{Ni} at temperatures where the delayed transformation may be less troublesome. As will be shown later, ΔG_W for tungsten appears to be known with sufficient accuracy. Using ΔG_W = 1250, and applying equation (32) modified for a substitutional alloying element (nickel) in place of an interstitial element (carbon), we obtain the calculated curve as shown, with $\Delta G_{Ni} = -1050$ (Fig.6). Agreement is good with the experimental data of Winkler and Vogel. This would indicate that the true two-phase region for the iron-nickel system lies inside the heating range of transformation as the latter is shown on current diagrams.

2. Gamma-Carbide Equilibrium.

No experimental data exist on this transformation.

F. Silicon

1. Gamma-Alpha Equilibrium.

The gamma-loop for iron-silicon alloys is known fairly accurately[16] and from it we find $C_\alpha^* = 2.5\%$, giving $\Delta G_{Si} = 485$. As is indicated by the magnitude of ΔG, silicon has a rather small effect on the boundary of the gamma phase. It takes nearly 0.5% Si to change the amount of carbon by 0.05%, an effect produced by 10° change in temperature over most of the temperature range involved, which means that the uncertainty to be expected in thermal analysis will be at least a considerable fraction of the effects to be observed.

In Table V are given the results of three observers[17, 18,19] for Ac_3 for this system. ΔC, the distance of the point to the right of the curve for the iron-carbon diagram, was calculated from equation (32), using $\Delta G = 450$. The results of Kriz and Poboril and of Wilhelm and Reschka, were corrected for manganese content, that is the carbon contents were increased to compensate for the effects of the given percentages of manganese. Other elements present had small effects and practically cancelled each other. Sato did not give the complete analysis of his specimens, although it seems highly probable that manganese was present.

On inspecting the columns showing divergences, we find that the results of Kriz and Poboril are nearly all high, but irregular, those of Wilhelm and Reschka also high, but not by large amounts, while those of Sato average low but show no great divergence. In view of the fact that the manganese probably present in Sato's specimens would make his results too low the above seem to show good concordance with theory.

2. Gamma-Carbide Equilibrium.

A few observations are given by Hanson[20] and also some by Kriz and Poboril[17], but in view of the small amount of data and of the uncertainty regarding the relationship of carbides and graphite in this system, it does not seem worth-while to attempt a theoretical analysis.

G. Tungsten

1. Gamma-Alpha Equilibrium.

The iron-tungsten diagram shows a gamma-loop for which convincing data are available[21], with $C^{\alpha} = 6.5$ and $C^{\gamma} = 3.2$ at the maximum. We obtain $\Delta G_W = 1250$. When observed points[22] for the iron-tungsten-carbon system are plotted (Figure 7) it is found that curves calculated from $\Delta G_W = 1250$ fit the points as well as can be expected.

2. Gamma-Carbide Equilibrium.

Complex carbides only are present at the concentration ranges available.

H. Vanadium

1. Gamma-Alpha Equilibrium.

Since this element, with iron, forms a gamma-loop, it is possible to calculate ΔG from the maximum carbon concentration (C^{α}) in equilibrium with the gamma phase. There is some uncertainty regarding this value, different observers' estimates varying from 1.2% V to about 2.0%,[5] giving corresponding ΔG's of 2300 and 1200 respectively, with the probability favoring the former. Experimental data[23,24,25] on the boundary of the gamma phase in the Fe-V-C system was

TABLE V

Ac_3 for Silicon Alloys

Calculated (ΔG = 450 cal)

Observed (corrected; see text)

Kriz and Poboril

T	%Si	calc	obs	div.
910	.74	.08	.31	+.23
800	1.25	.13	.22	+.09
965	1.25	.12	.20	+.08
935	1.70	.17	.50	+.33
900	2.33	.23	.40	+.17
950	3.65	.36	.51	+.15
1090	3.93	.36	.34	-.02

Wilhelm and Reschka

T	%Si	calc	obs	div.
840	.30	.04	.12	+.08
825	.43	.05	.07	+.02
832	.64	.07	.15	+.08
860	.88	.10	.20	+.10
847	.99	.11	.13	+.02
852	1.08	.12	.14	+.02
850	1.17	.13	.16	+.03
775	1.13	.13	.21	+.08

Sato

T	%Si	calc	obs	div.
890	.26	.02	.04	+.02
828	.54	.06	.02	-.04
814	.50	.06	.00	-.06
804	.51	.06	.04	-.02
790	.71	.08	.02	-.06
762	.54	.06	.08	+.02
751	.53	.06	.11	+.05
900	.97	.10	.11	+.01
831	.99	.11	.08	-.03
823	.98	.11	.09	-.02
780	1.05	.11	.08	-.03
768	1.26	.14	.02	-.12
965	1.34	.13	.17	+.04
924	1.63	.17	.15	-.02
830	1.58	.18	.11	-.07
800	1.45	.17	.11	-.06
782	1.60	.18	.11	-.07
923	2.25	.22	.22	0
810	1.80	.20	.15	-.05
790	2.16	.24	.13	-.11

plotted in Figure 8 and it was found that $\Delta G_{\gamma} = 2000$, from which the theoretical curves were calculated, gave as good a fit as could be obtained. Although the number of points is not large, it represents three different observers, and no set shows systematic divergence.

2. Gamma-Carbide Equilibrium.

In this system the gamma phase is considered to be in equilibrium with V_4C_3 even at quite low vanadium concentrations.

I. Iron-Nickel-Phosphorus

1. Gamma-Alpha Equilibrium.

As was mentioned previously, the iron-chromium system is an exception to the theory, in that the A_3 point is first lowered and then raised as increasing (but small) amounts of chromium are added. The present ternary system is of interest, since it does much the same thing with increasing addition of phosphorus, although phosphorus alone produces a normal type of gamma-loop with iron.

In Figure 9 are plotted the results of Vogel and Bauer[26] for this system, with Ni = 2%. The calculated curves are based on $\Delta G_{Ni} = -1050$ (as used in Figure 6), and $\Delta G_P = 3100$, as determined from the gamma-loop of the iron-phosphorus system, and the curves were calculated by equation (49) modified for a substitutional solute, and by the corresponding equation for the alpha boundary. It is seen that the latter gives fairly good agreement, but the gamma boundary shows great distortion as compared with the theoretical curve. Apparently there is a marked interaction of nickel and phosphorus of such nature as to affect the solubility relationships in the gamma phase.

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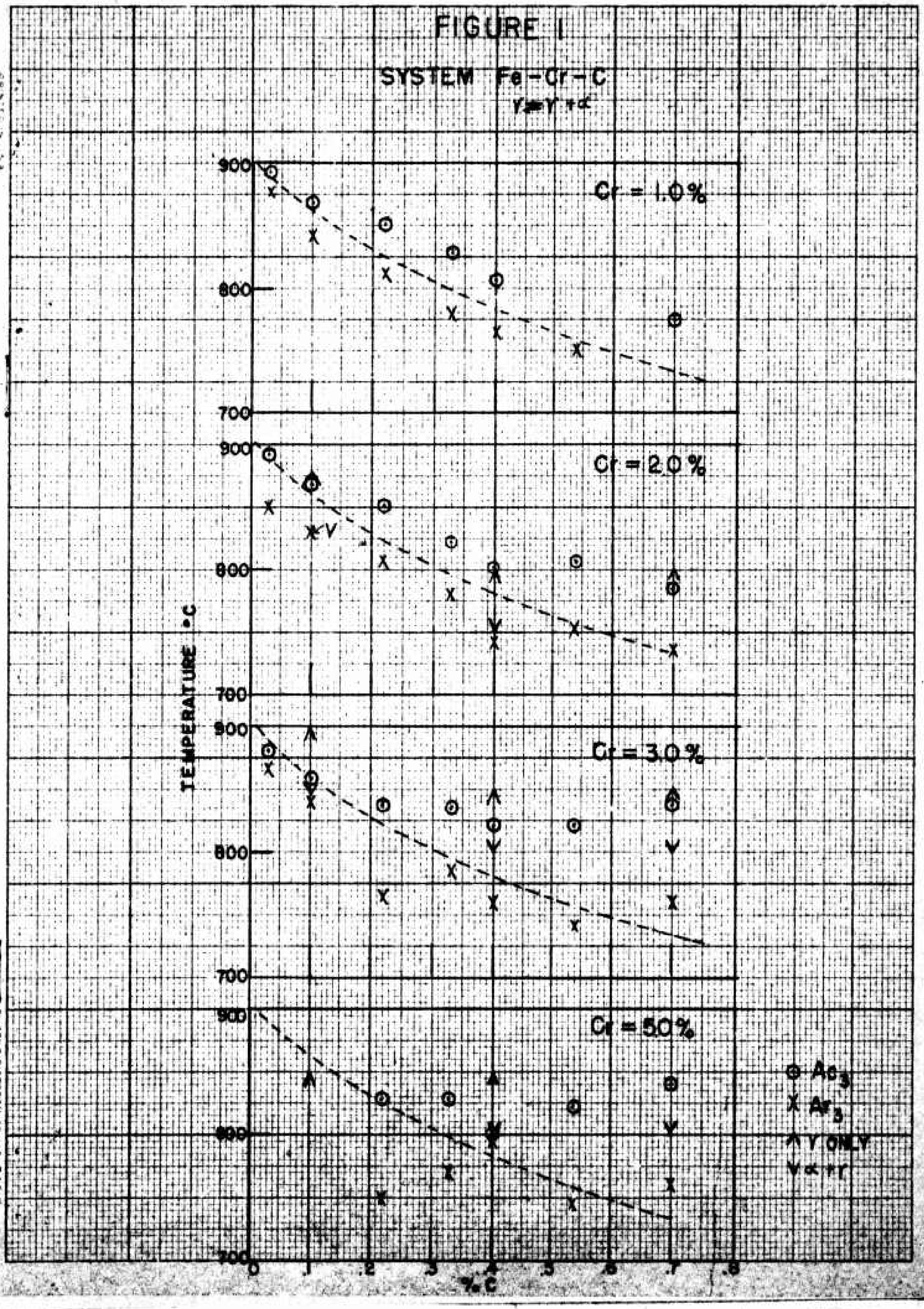


FIGURE I

SYSTEM Fe – Cr – C

$\gamma \rightleftharpoons \gamma + \alpha$

FIGURE 2

SYSTEM Fe – Cr – C

$\gamma \rightleftharpoons \gamma$ + CARBIDE

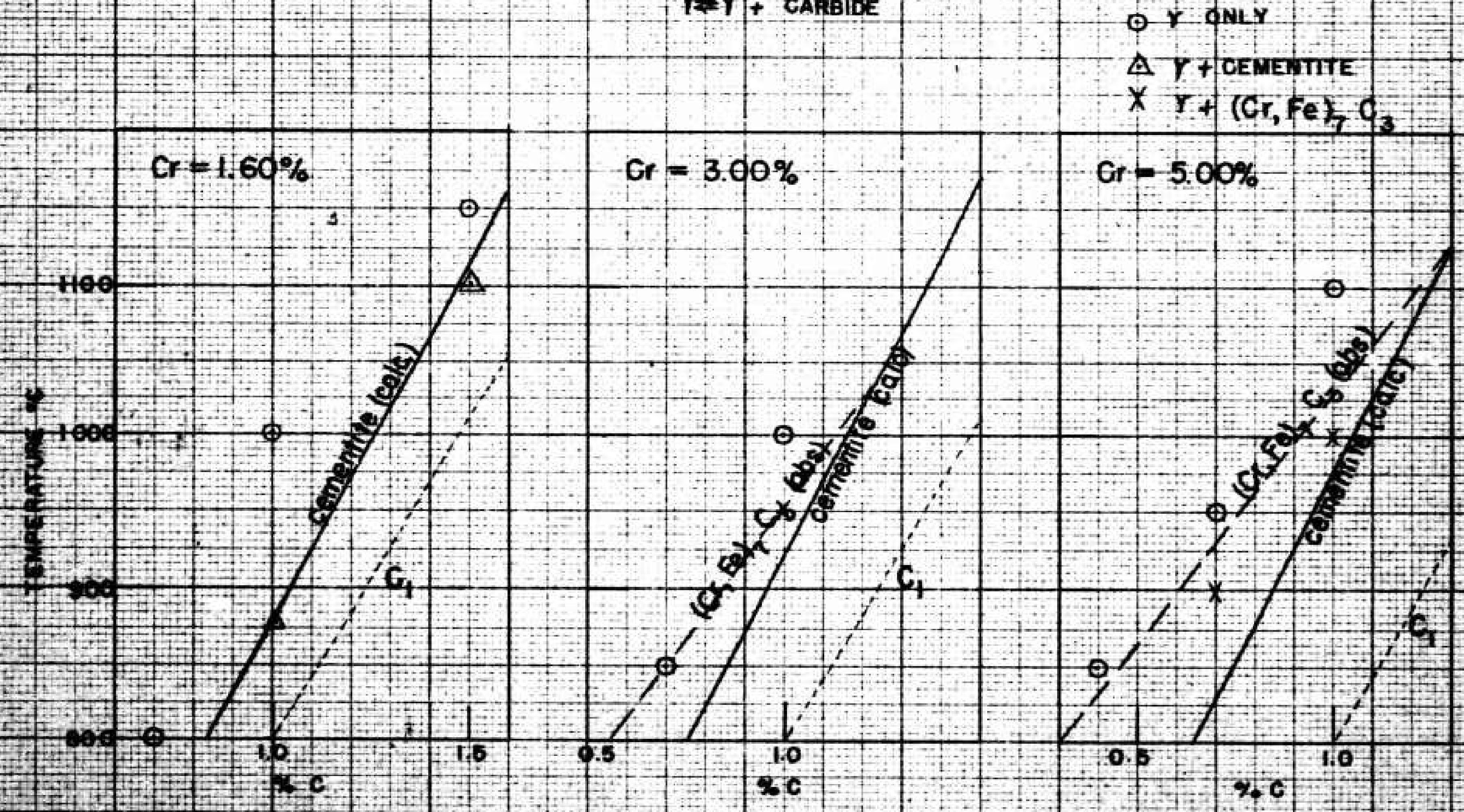


FIGURE 3

SYSTEM Fe—Cu—C
$\gamma \rightleftharpoons \gamma$ + carbide

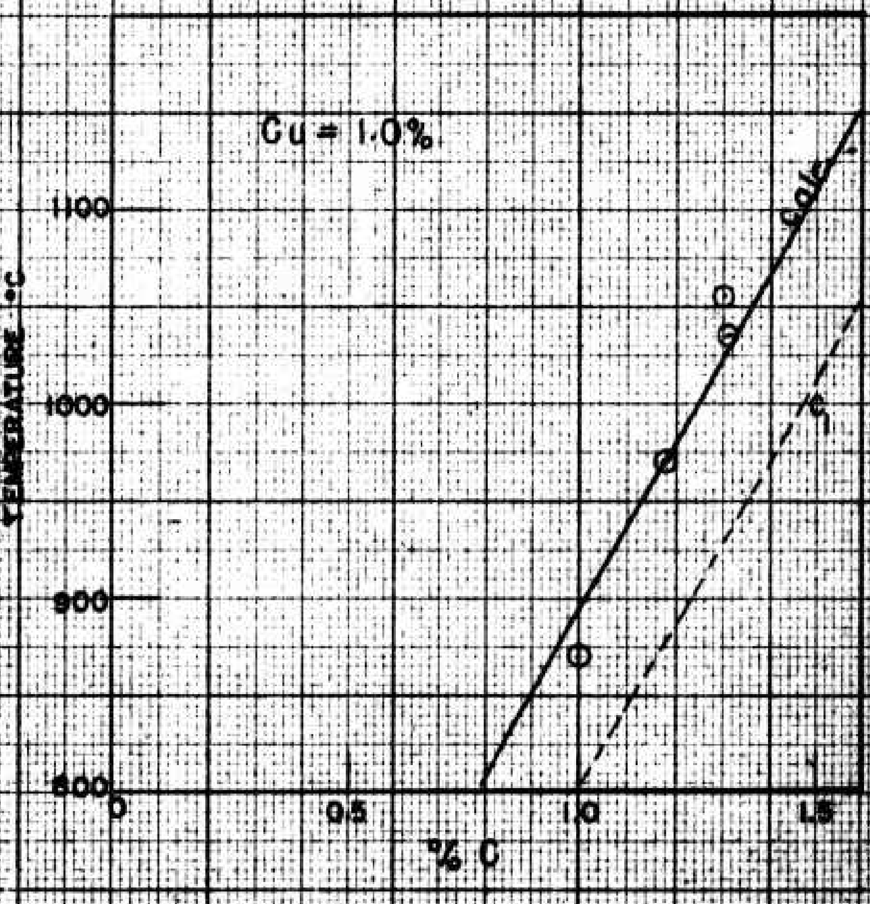


FIGURE 4

SYSTEM Fe – Mn – C

$\gamma \rightleftharpoons \gamma + \text{carbide}$

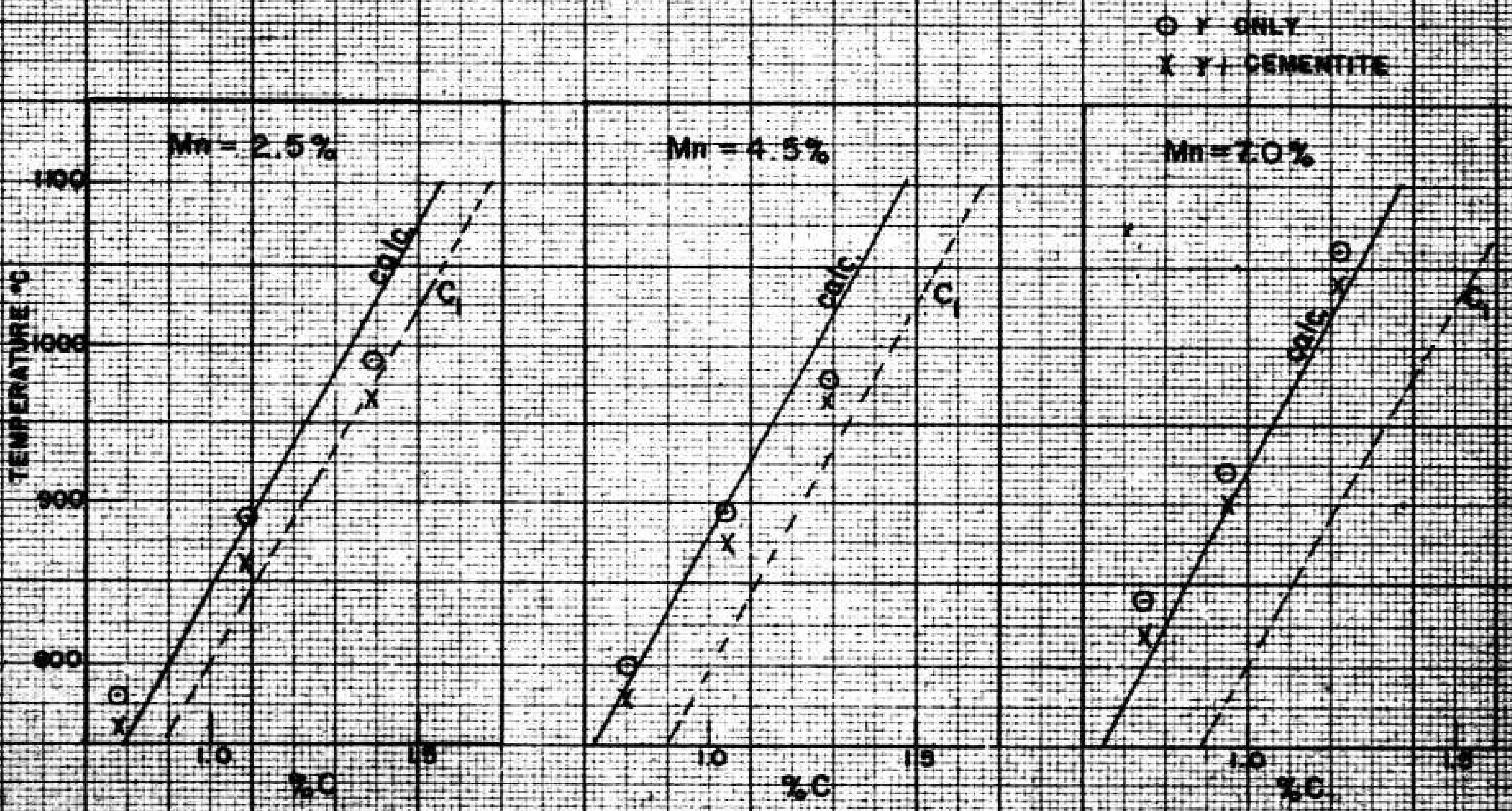


FIGURE 5

SYSTEM Fe-Mo-C

$\gamma \rightleftharpoons \alpha + \gamma$

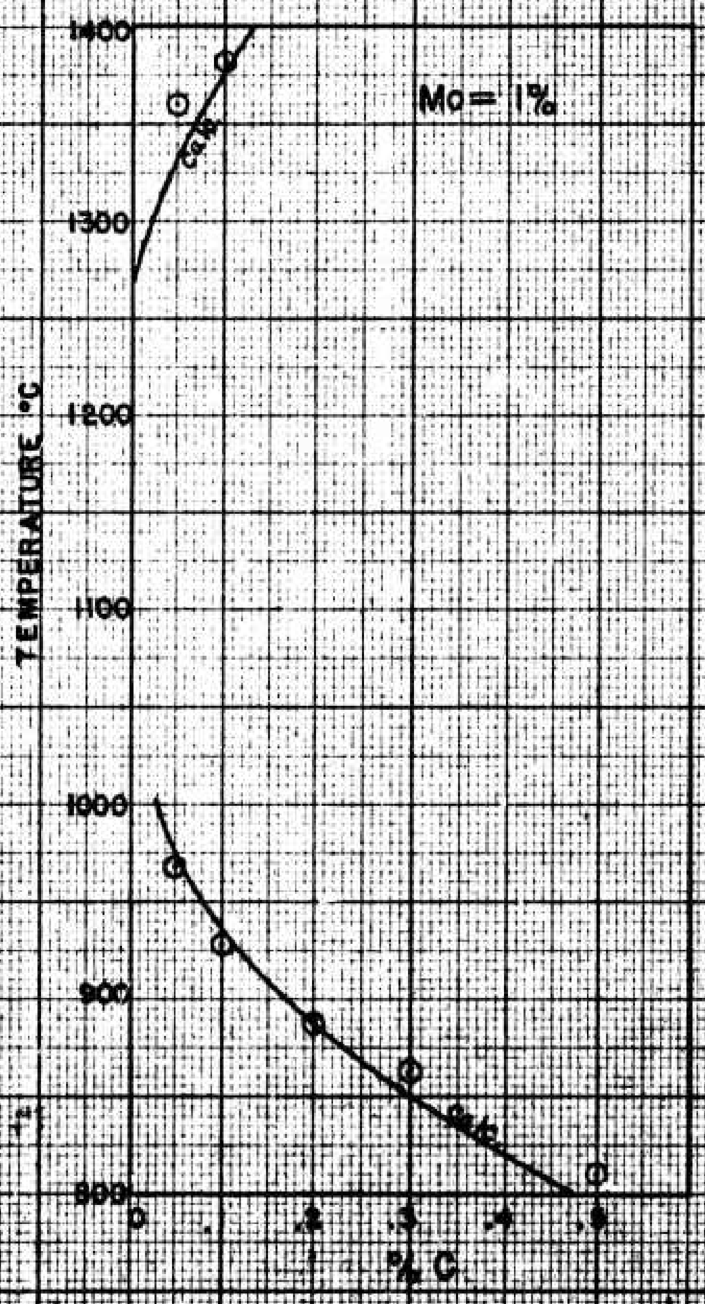


FIGURE 6

SYSTEM Fe-Ni-W
$\gamma \rightleftharpoons \gamma + \alpha$

Fe:Ni = 92.5:7.5

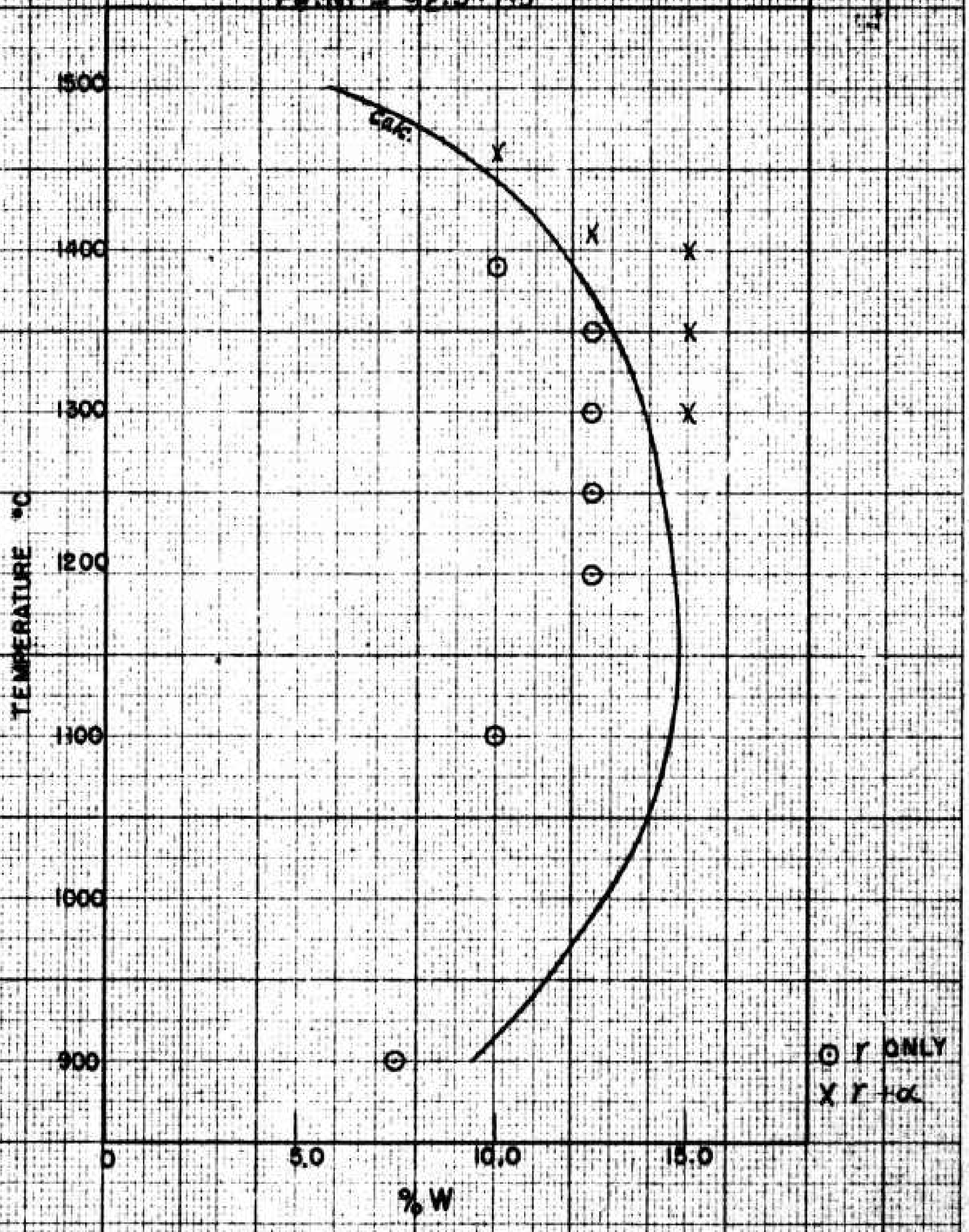


FIGURE 7

SYSTEM Fe-W-C

$\gamma \rightleftharpoons \alpha + \gamma$

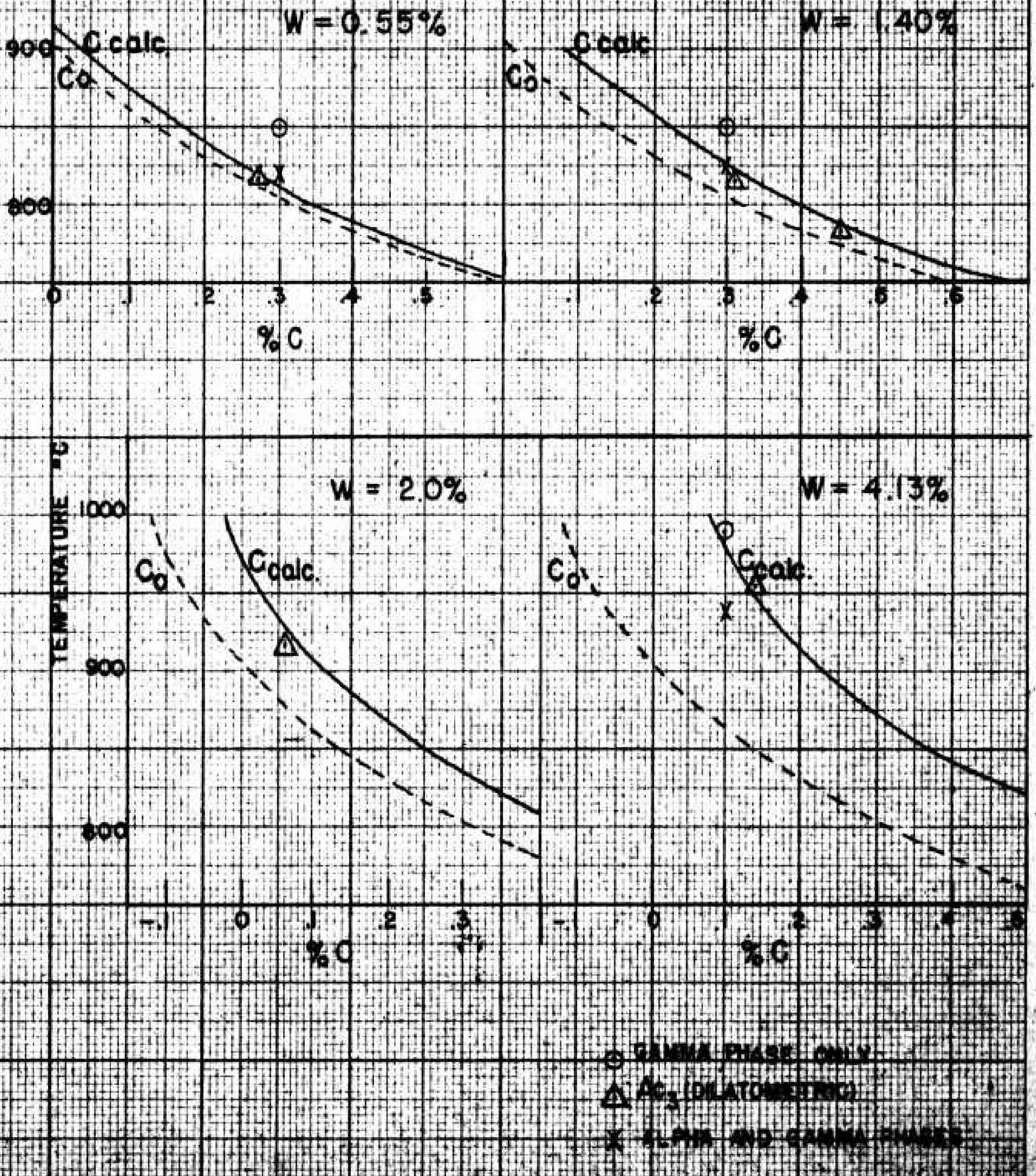
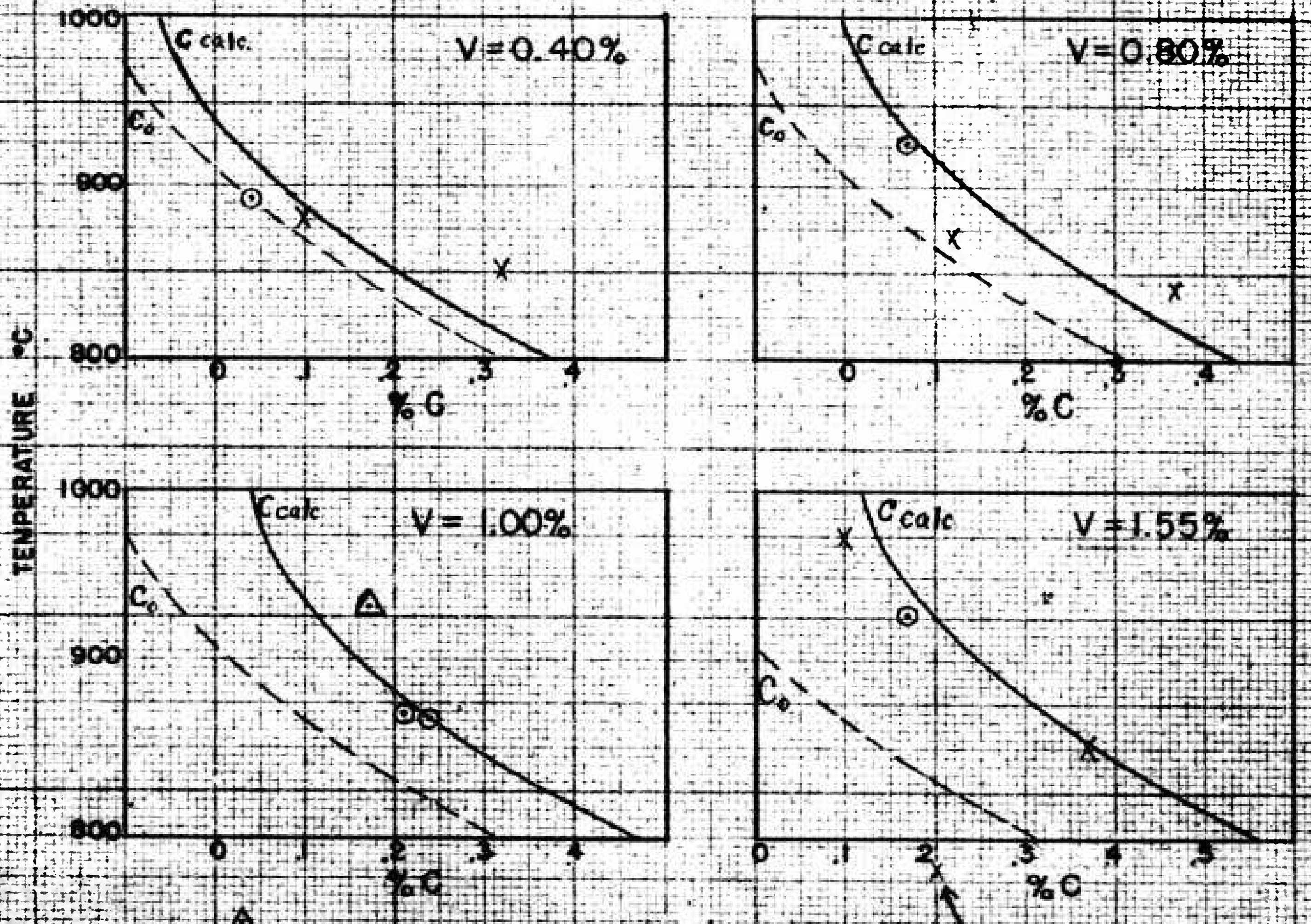
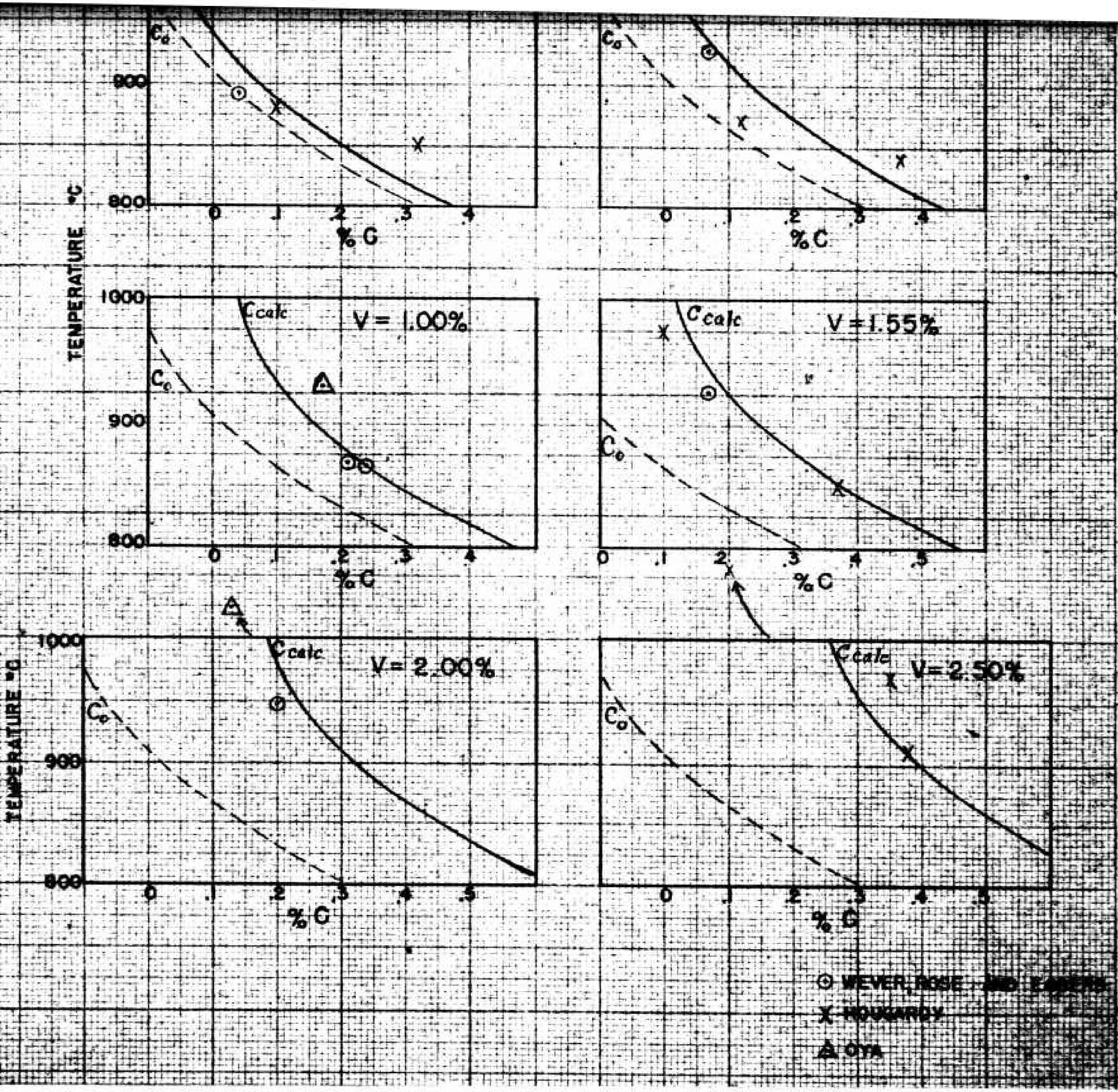


FIGURE 8

SYSTEM Fe – V – C

$\gamma \rightleftarrows \gamma + \alpha$

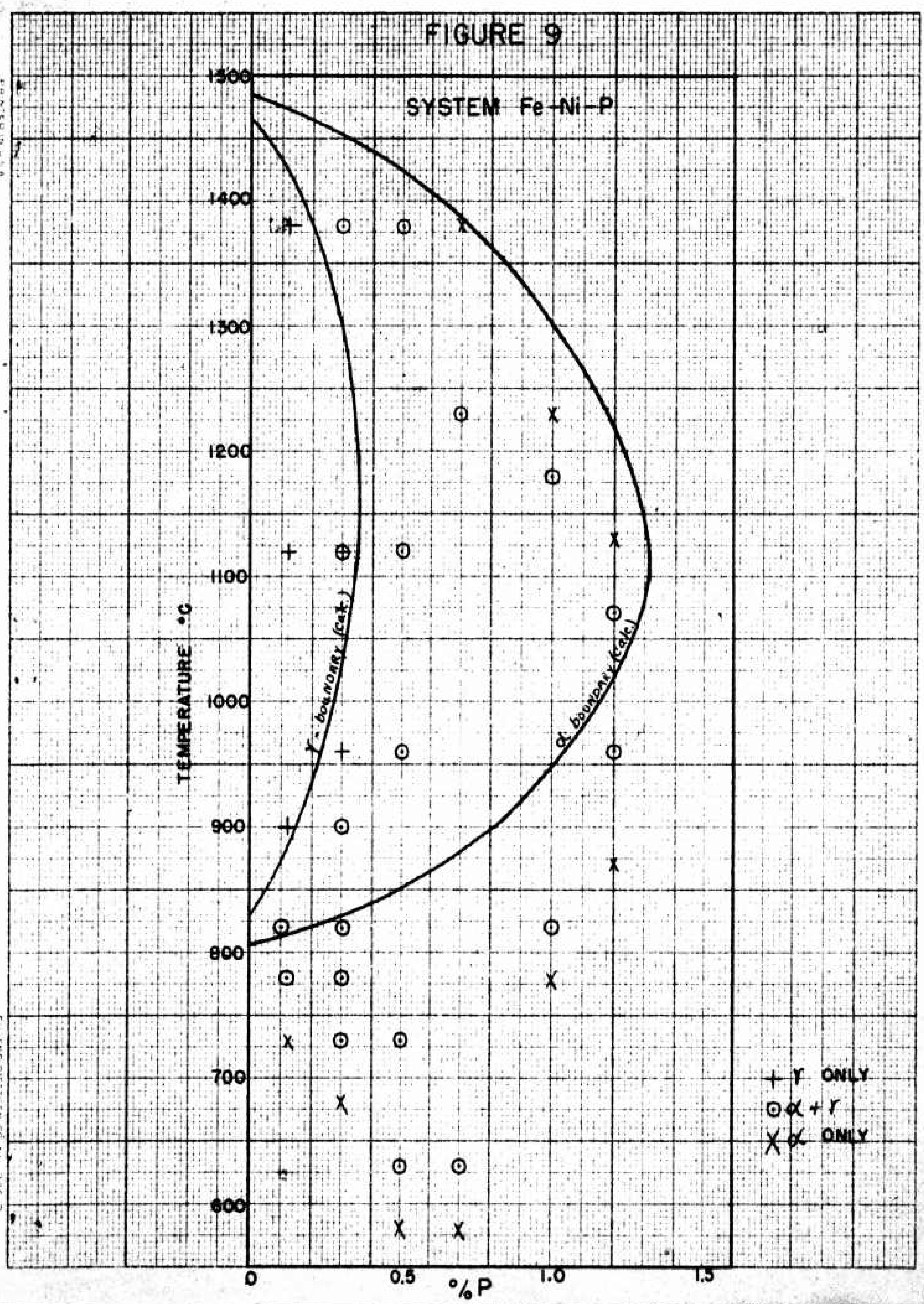



C₀
900
800
0
.1
.2
.3
.4
% C
TEMPERATURE °C
C₀
0
.1
.2
.3
.4
% C
1000
Ccalc
V = 1.00%
C₀
900
800
0
.1
.2
.3
.4
% C
Ccalc
V = 1.55%
C₀
0
.1
.2
.3
.4
.5
% C
TEMPERATURE °C
1000
Ccalc
V = 2.00%
C₀
900
800
0
.1
.2
.3
.4
.5
% C
Ccalc
V = 2.50%
C₀
0
.1
.2
.3
.4
.5
% C
⊙ WEVER, ROSE, AND EILENDER
X HOUGARDY
△ OYA

1

2

FIGURE 9



SYSTEM Fe-Ni-P
TEMPERATURE °C
1500
1400
1300
1200
1100
1000
900
800
700
600
0
0.5
1.0
1.5
% P
γ - boundary (calc.)
α boundary (calc.)
+ γ ONLY
⊙ α + γ
X α ONLY