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NIOBIUM PHASE DIAGRAMS

Manuscript Report
on
Niobium-Carbon System

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for

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NIOBIUM-CARBON SYSTEM

by

Rodney P. Elliott*

ABSTRACT

The niobium-carbon system has been determined by X-ray and metallographic examination of sintered and arc-cast alloys. Two carbides exist: hexagonal Nb_2C with a limited range of homogeneity, and cubic NbC with a solubility range from 8.25 to 10.25 weight per cent carbon. Dilute alloys freeze by eutectic reaction at 2230°C. The solubility of carbon in niobium is 0.80 at the eutectic temperature, but this decreases rapidly with temperature. Metallographic evidence indicates a peritectic reaction between melt, Nb_2C, and NbC; alloys richer in carbon than NbC freeze by eutectic reaction.

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EXISTING KNOWLEDGE

The carbides of niobium have been investigated with regard to number, formula, crystal structure, and range of homogeneity. A comprehensive review has recently been published by Hansen (1). Two intermediate phases, each with a solubility range, are accepted: an hexagonal subcarbide, Nb_2C, and the cubic NbC. The melting point of NbC has been found to be 3500° - 3800°C (2,3). Goldschmidt (4) published a complete phase diagram showing a single carbide and a melting temperature of 1950°C for niobium. The solid solubility of carbon in niobium has been determined as 0.0025 weight per cent (5).

Brauer et al. (5) initially determined the homogeneity ranges of Nb_2C and NbC as 4.32 to 5.98 and 8.52 to 11.44 weight per cent carbon, respectively. In a redetermination by Brauer and Lesser (6) the lattice constants were revised upward and homogeneity limits of 4.45 to 6.06 and 8.28 to 10.51 weight per cent carbon established for Nb_2C and NbC, respectively.

A complete phase diagram has been determined by Pochon et al. (7). Salient features of this determination are (a) a low solubility of carbon in niobium, varying from 0.03 weight per cent at the eutectic temperature to less than 0.01 weight per cent at room temperature; (b) a eutectic freezing reaction at 2335°C: $L_{1.5\%C} \rightarrow Nb_{ss} + Nb_2C$; (c) a peritectic reaction at 3265°C: $L + NbC \rightarrow Nb_2C$. The solubility ranges of the compounds were not checked; the values originally reported by Brauer (5) were incorporated into the diagram that was constructed.

EXPERIMENTAL PROGRAM

Alloys

The nature of the niobium-carbon system necessitated three separate techniques to be employed in the production of alloys: (a) arc melting of niobium with a master alloy to produce the more dilute alloys;

(b) sintering of niobium powder with lampblack to produce alloys for X-ray examination; and (c) arc-melting of sintered compacts for as-cast structures in the higher carbon region.

Attempts to produce alloys in the range 6-12 per cent carbon by arc melting niobium with spectrographic graphite rods were unsatisfactory because of excessive losses of carbon by vaporization. A 6 per cent carbon master alloy was produced by such a technique, crushed to a homogeneous mass, and used to prepare alloys from 0.1 to 5.5 per cent carbon. A 1.5 per cent carbon alloy was used to produce the very dilute carbon alloys. In all cases, electron-gun-refined niobium metal low in interstitial content was used in the alloy preparation.

For the production of alloys containing over 5 per cent carbon, a sintering technique was employed. Nominal compositions were prepared from niobium powder and lampblack. Niobium powder was supplied by either Murex or Shieldalloy. The former type was contaminated with hydrogen as evidenced by a body-centered cubic pattern of NbH which disappeared on annealing at relatively low temperatures in vacuum. The Shieldalloy was a higher grade product containing a small amount of residual carbon from the reduction process. Monsanto No. 10 lampblack was used throughout.

A high-temperature induction furnace was constructed for the sintering operations. A schematic drawing of the final design is shown in Figure 1. Temperatures up to 3450°C have been attained with this equipment. The system is evacuated beforehand and flushed with argon twice. An argon atmosphere is maintained during operation.

Powder aggregates for compacts were thoroughly milled by mortar and pestle and then were ball-milled overnight. Half-inch diameter compacts were then pressed. Preliminary chemical analyses indicated a tendency for the briquettes to carburize. To minimize the deviation from the nominal composition, compacts were wrapped in 0.001 in. niobium foil. The sintering operation consisted of a five-minute hold at 2000°C. The temperature was followed during the heat-up time. At approximately 1300°C there was a sudden evolution of heat as a result of the exothermic formation of the carbide. The sample would suddenly attain a temperature estimated to be 2000°C. It is questionable that the subsequent hold at 2000°C was needed to sinter the specimen.

Losses of carbon in arc melting of sintered powder compacts are not as serious as in preparing alloys from niobium and graphite. Presumably this is because the carbon is already chemically combined in the sintered compacts.

A summary of arc-cast alloys is presented in Table I, together with their analyzed compositions. Chemical analyses were made by standard combustion techniques in which the resulting CO_2 is either weighed or its volume determined under known conditions. At very low nominal carbon levels the alloys have gained carbon on arc melting. This is rationalized on the basis that the niobium melting stock contains residual carbon of this order of magnitude. Alloys containing more than 1.50 per cent carbon have a tendency to lose carbon by vaporization on arc melting.

Heat Treatment

Heat-treating procedures were carried out at temperatures up to 2000°C. At 1500° and 2000°C an evacuated resistance furnace was employed. Specimens were suspended in a molybdenum wire basket during treatment. Quenching is effected by allowing the contents of the basket to drop to the water-cooled hearth of the furnace. At 1500° and 2000°C the treating times were three hours and one-half hour, respectively. Below 1500°C, specimens were encapsulated in Vycor or quartz tubes and heat treated in resistance-heated tube furnaces.

X-Ray Examination

Sintered powdered compacts were crushed to -200 + 325 mesh for X-ray powder pattern determinations. Straumanis-type cameras of 114.59 mm diameter were used throughout with nickel-filtered copper K α radiation.

INTERPRETATION OF DATA

Metallography

The solid solubility of carbon in niobium at elevated temperatures is far in excess of that previously reported. Alloys containing 0.60 per cent carbon and less give metallographic evidence of being single-phase at elevated temperatures. On subsequent cooling to room temperature, Nb_2C precipitates. This is illustrated by Figures 2 to 6. The fields of these photos have been selected to show the as-cast grain structure. Precipitating Nb_2C does not preferentially agglomerate at grain boundaries. Grain boundaries are delineated by a relatively minor portion of the precipitating Nb_2C; the bulk precipitates on preferential planes within the grain. More dilute alloys result in a very fine precipitate, while richer compositions produce larger platelets of Nb_2C. Annealing at elevated temperatures causes Nb_2C to spheroidize (Figure 7).

The dilute carbon alloys (0.005 to 0.035 per cent nominal carbon) were annealed at 750°, 1000°, and 1500°C for 15 days, 2 days, and 3 hours, respectively. No change in solubility was detected.

Freezing of dilute niobium-carbon alloys is by the eutectic reaction: $L_{1.5\%C} \rightarrow Nb_2C + Nb_{ss}$. The series of photomicrographs in Figure 8 through 14 documents this. Figures 8 and 9 show pro-eutectic niobium in a matrix of Nb-Nb_2C eutectic. A homogeneous eutectic structure is shown in Figure 10. As the carbon content of the alloy increases, there is an increasing amount of pro-eutectic Nb_2C.

Examination of the arc-cast, high-carbon alloys shown in Figures 16 and 17 discloses no evidence of an eutectic reaction between Nb_2C and NbC. Alloys in this composition range are very inhomogeneous in the arc-cast state. The microstructure of Figure 14 gives evidence of nucleation of Nb_2C on prior NbC. These observations support the peritectic reaction $L + NbC \rightarrow Nb_2C$ as reported by Pochon et al. (7)

Arc-cast Nb_2C develops typical Widmanstätten patterns, as shown in Figures 16 and 17. A possible rationalization of this is the precipitation of NbC on preferential planes of Nb_2C. As is discussed in the following section, Nb_2C does not exist at the stoichiometric composition at lower temperatures. At elevated temperatures the composition range probably extends to the stoichiometric composition. On cooling, NbC is rejected, producing these characteristic striations.

At carbon contents higher than the solubility region of NbC, there is an eutectic between NbC and graphite, as shown in Figures 18 and 19. The eutectic composition is greater than 14.12 weight per cent carbon.

Solubility Limits of Nb_2C and NbC

Solubility limits of Nb_2C and NbC have been established by X-ray diffraction methods. Both structures have a compositional range and a resulting parametric variation. In all instances the K α doublet was resolved and sharply defined in the back-reflection region, indicating that compositional variation of the sintered compacts was minor.

Data presented in Table II indicate that the solubility limits of Nb_2C lie between 5.43 and 5.83 weight per cent carbon. These boundaries are much more restricted than either set of published data by Brauer and his co-workers (5,6). These compositions are carbon deficient with respect to stoichiometric Nb_2C (6.07 weight per cent carbon). The X-ray diffraction pattern of Nb_2C is recorded in Table III.

Experimental data of lattice parameters of NbC as a function of analyzed carbon composition are summarized in Figure 20. These data indicate a solubility of carbon extending from 8.25 to 10.25 weight per cent. The diffraction pattern of NbC is given in Table IV.

At the time when the present investigation was being performed the latest data of the solubility limits of NbC (6) were unpublished. Consequently the sharp disagreement of the present data, both as to composition limits and lattice parameter, with Brauer's original work were points of concern. Extra effort was expended to verify the present data. These are in close agreement with Brauer's revised data.

It was considered that the composition limit of 10.25 per cent carbon represented the equilibrium of 2000°C and that stoichiometric NbC was existent at temperatures near the graphite eutectic or melting temperature. A portion of arc-cast ingot that contained NbC and NbC-graphite eutectic was prepared for X-ray examination. The lattice parameter of the NbC was identical to the maximum solubility limit determined in the sintering experiments. Such an arc-cast specimen represents the ultimate in quenching from the molten state. Since the K α doublet of the back-reflection lines was resolved and sharp, it can be assumed that the NbC is homogeneous. No metallographic data demonstrate precipitation of graphite from the NbC. It is therefore indicative that 10.25 per cent represents the true solubility limit of NbC.

On the basis of a persistent diffraction line at $\theta_{Cu} = 19.70°$, Brauer and Lesser (6) have hypothesized a ζ niobium-carbon phase at compositions intermediate to NbC and Nb_2C. A careful scrutiny of similar patterns in the present investigation gave no indication of such a phase.

Incipient Melting

The eutectic temperature was determined by incipient melting techniques in the furnace shown in Figure 1. The nominal one per cent alloy was used since the eutectic alloy had served as a master alloy in producing the very dilute alloys.

Pieces of alloy were wrapped in tantalum foil and supported in the graphite susceptor by tantalum wire. Such compacts were held for five minutes at various temperature levels, after which the sample was examined for visible signs of melting. (Prior to the use of tantalum, molybdenum foil and wire were used. This was impractical since the eutectic in the molybdenum-carbon system is at 2200°C. Sufficient carbon vaporizes from the susceptor, forming a liquid on the wire and foil. As reported by Reference 1, the eutectic in the tantalum-carbon system is at 2800°C and so did not interfere with the present determination.) Incipient melting data are summarized in Table V. The calibration temperature approaches a negligible correction at the observed eutectic melting temperature. These data support a value of 2230 ± 10°C.

Attempts to measure the eutectic temperature of the NbC-graphite eutectic were less satisfactory. Uncorrected data obtained with a Leeds and Northrup optical pyrometer with an extended range adaptor indicate that this eutectic temperature is approximately 3250°C.

No attempts were made to verify the reported temperature of 3265°C for the peritectic reaction.

Solid Solubility of Carbon in Niobium

The extended solid solubility of carbon in niobium has been verified by direct experimental evidence. Pieces of niobium sheet 0.046 in. thick were packed loosely in lampblack and held for fifteen minutes at 1800°, 1900°, 2000°, 2100°, and 2200°C in the furnace described in Figure 1. Temperature was controlled manually with the aid of an optical pyrometer. It is estimated that the temperature was held constant within a ten-degree range.

Such a carburizing treatment is sufficient for the equilibrium saturation of carbon to be established. After the carburizing treatment the entire apparatus was allowed to cool to room temperature. The surface layer of Nb_2C and NbC was extremely thin. Samples were nevertheless etched in a mixture of 40 cc HF, 10 cc HNO_3, and 50 cc H_2O. Duplicate specimens were sent to separate analytical laboratories for analysis.

Metallographic specimens of carburized samples are shown in Figures 21, 22, and 23. These photomicrographs indicate that the specimens at all temperatures were carburized homogeneously. The nature of precipitation is such that Nb_2C precipitates in situ. Thus, chemical analyses of the carburized specimens give data that correspond to the saturation of carbon in niobium at the carburizing temperature.

These data are plotted in Figure 24. Incorporated in this figure is the maximum extent of the solid solubility (between 0.60 and 0.83 weight per cent carbon) as indicated by the as-cast metallographic analysis. These data are in good agreement. As is indicated, the solid solubility decreases rapidly with temperature to approximately 0.1 weight per cent carbon at 1800°C. An extrapolation of these data gives a solid solubility of 0.01 weight per cent carbon at approximately 1500°C. This is in agreement with the inconclusive nature of annealing the very dilute alloys.

In one instance during these carburizing treatments the specimen overheated to 2220°C. Subsequent examination indicated that there had been surface melting. This observation corroborates the previously documented temperature of 2230°C for the eutectic temperature.

PHASE DIAGRAM

The phase diagram presented in Figure 25 incorporates the experimental data previously discussed in this paper. Salient features of the niobium-carbon system are as follows.

1. Two carbides of niobium exist. These are the hexagonal subcarbide Nb_2C, having a limited region of solubility between 5.43 and 5.83 weight per cent carbon, and the face-centered

cubic monocarbide with a wide range of solubility from 8.25 to 10.25 weight per cent carbon.

2. The solid solubility of carbon is 0.80 weight per cent at the eutectic temperature. This solubility decreases rapidly to 0.10 at 1800°C.

3. Dilute carbon alloys freeze at 2230°C by eutectic reaction:

$$L_{1.5\%C} \rightarrow Nb_{0.80\%C} + Nb_2C$$

4. Metallographic evidence indicates the existence of the peritectic reaction $L + NbC \rightarrow Nb_2C$ at some undetermined temperature.

5. Alloys richer in carbon than the NbC phase freeze by the eutectic reaction $L \rightarrow NbC + \text{Graphite}$ at a temperature of approximately 3250°C.

ACKNOWLEDGMENT

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REFERENCES

1. M. Hansen, Constitution of Binary Alloys, McGraw-Hill Book Co., New York, 1958.

2. E. Friederich and L. Sittig, "The Melting Points of Inorganic Compounds and Those of the Elements," Z. anorg. Chem., Vol. 145 (1925), p. 251.

   E. Friederich, "Some Previously Unknown Properties of Simple Compounds and Remarks on the Kinds of Solid State," Z. Physik, Vol. 31 (1925), p. 814.

3. C. Agte and H. Alterthum, "Systems of High-Melting Carbides; Contributions to the Problem of Carbon Fusion," Z. tech. Physik, Vol. 11 (1930), p. 182.

4. H. J. Goldschmidt, "The Structure of Carbides in Alloy Steel," J. Iron and Steel Inst., Vol. 160 (1948), p. 345.

5. G. Brauer, H. Renner, and J. Wernet, "Carbides of Niobium," Z. anorg. Chem., Vol. 277 (1954), p. 249.

6. G. Brauer and R. Lesser, "Carbide Phases of Niobium," Z. Metallkunde, Vol. 50 (1959), p. 8.

7. M. L. Pochon, C. R. McKinsey, R. A. Perkins, and W. D. Foreng, "Solubility of Carbon and Structure of Carbide Phases in Tantalum and Columbium," presented at AIME Reactive Metals Conference, Buffalo, N. Y., May, 1958.

TABLE I

ARC-MELTED NIOBIUM-CARBON ALLOYS

Nominal Composition w/o C	Analyzed Composition w/o C
Arc-Melted from Niobium and Master Alloy	
0.005	0.011
0.010	0.035
0.015	0.023
0.020	0.029
0.025	0.031
0.030	0.035
0.035	0.040
0.10	0.11
0.25	0.26
0.50	0.52
0.75	0.60
0.85	0.88
1.00	0.95
1.50	1.50
2.00	2.00
2.50	2.31
3.00	2.96
3.50	3.38
4.50	4.34
5.50	5.27
Arc-Melted Sintered Compacts	
5.0	4.58
6.0	6.33
7.0	6.81
8.0	7.86
9.0	8.27
10.0	9.32
12.0	10.30
14.0	12.69
-	14.12

TABLE II

SOLUBILITY LIMITS OF Nb_2C

Alloy, w/o Carbon	Patterns of Phase(s) Detected Visually	Lattice Constants Nb_2C c, Å	a, Å	c/a
4.80	$Nb + Nb_2C$			
4.89	$Nb + Nb_2C$	4.955_4	3.114_7	1.591
5.28	$Nb + Nb_2C$	4.955_3	3.114_9	1.591
5.43	$Nb + Nb_2C$	4.954_0	3.115_3	1.590
5.63	Nb_2C	4.962_0	3.117_8	1.592
5.83	$Nb_2C + NbC$	4.966_3	3.119_4	1.592
5.87	$Nb_2C + NbC$	4.967_8	3.127_2	1.592
6.10	$Nb_2C + NbC$			

TABLE III

INTERPLANER SPACING OF HEXAGONAL CLOSE-PACKED Nb_2C PHASE

hkl	I*	In Equilibrium with Nb_{ss} d, Å	Single-phase 5.63%C d, Å	In Equilibrium with NbC d, Å
100	M	2.678	2.676	2.682
002	M	2.461	2.455	2.474
101	S	2.349	2.350	2.361
102	M	1.816	1.820	1.824
110	M	1.553	1.552	1.558
103	M	1.404	1.405	1.411
200	W	1.345	1.346	1.349
112	M	1.316	1.316	1.321
201	M	1.298	1.299	1.302
004	W	1.235	1.238	1.240
202	W	1.183	1.183	1.186
104	W	1.124	1.125	1.127
203	W	1.043	1.044	1.046
210	VW	1.018	1.019	1.021
211	M	0.9984	0.9984	0.9998
114	M	0.9687	0.9696	0.9713
212	W	0.9423	0.9426	0.9444
105	W	0.9293	0.9310	0.9318
204	VW	0.9117	0.9127	0.9137
300	W	0.8987	0.8994	0.9002
213	M	0.8670	0.8682	0.8688
302	M	0.8451	0.8457	0.8463
006	VW	0.8252	0.8268	0.8271
205+	M	0.7986	0.7995	0.8002
303+	W	0.7894	0.7908	0.7911
124+	M	0.7873	0.7881	0.7886
220+	M	0.7790	0.7793	0.7798
	c	4.954_0	4.962_0	4.966_3
	a	3.115_3	3.117_8	3.119_4
	c/a	1.590	1.592	1.592

+ Lines used for making least-squares solution of parameters

* S = strong, M = medium, W = weak, VW = very weak

TABLE IV

INTERPLANAR SPACING OF FACE-CENTERED CUBIC NbC PHASE

hkl	I*	In Equilibrium with Nb_2C d, Å	In Equilibrium with Graphite d, Å
111	S	2.543	2.564
200	S	2.209	2.221
220	S	1.562	1.576
311	S	1.334	1.345
222	M	1.277	1.287
400	M	1.107	1.116
331	S	1.016	1.025
420	S	0.9910	0.9991
422	S	0.9043	0.9124
511/333	S	0.8533	0.8602
440	S	0.7836	0.7902
a_o^+		4.432_7	4.470_1

* S = strong, M = medium

+ Extrapolated to $\theta = 90°$

TABLE V

DETERMINATION OF $Nb-Nb_2C$ EUTECTIC TEMPERATURE

Sample	Observed Temperature, °C	Observation
Nb-1%C	2300	Melted
Nb-1%C	2200	Not Melted
Nb-1%C	2250	Melted
Nb-1%C	2215	Not Melted
Nb-1%C	2230	Not Melted

CALIBRATION:

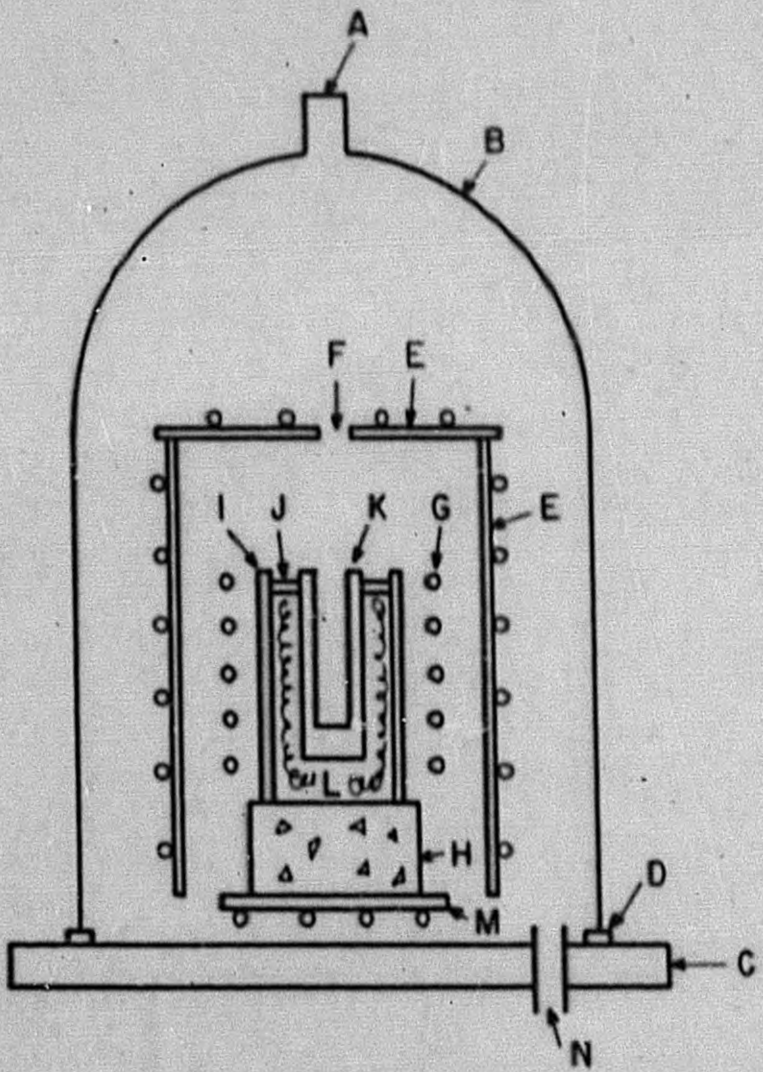
Metal	Accepted M.P., °C*	Observed M.P., °C
Pt	1769 ± 1	1740
Pt	1769 ± 1	1755
Rh	1960 ± 3	1950
Rh	1960 ± 3	1950

* 1948 Temperature Scale

LIST OF ILLUSTRATIONS

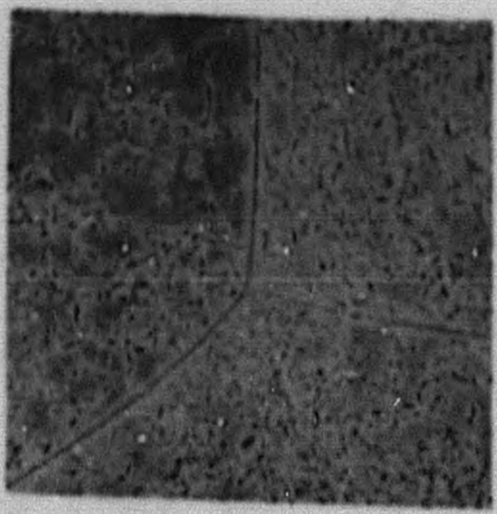
LIST OF ILLUSTRATIONS

(continued)



A Optical Flat Sight Glass
B Glass Bell Jar
C Formica Base
D Neoprene Seal
E Water Cooled Copper Heat Shields
F Sight Hole
G Induction Coil
H Fire Brick
I Vycor Cylinder
J Graphite Retainer
K Graphite Susceptor
L Thermax Insulating Material
M Water-Cooled Copper Pedestal
N Vacuum - Gas Inlet

FIG. 1 SCHEMATIC DIAGRAM OF HIGH-TEMPERATURE INDUCTION FURNACE



X 250 Etched

FIG. 2

Nb-0.01%C. As cast.
Nb_2C precipitate in niobium solid solution.

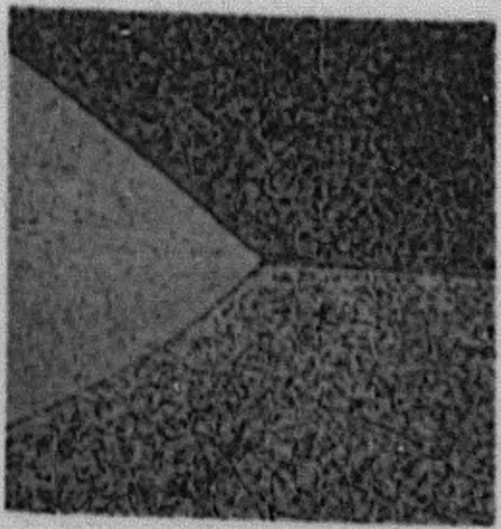


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FIG. 3

Nb-0.11%C. As cast.
Nb_2C precipitate in niobium solid solution.

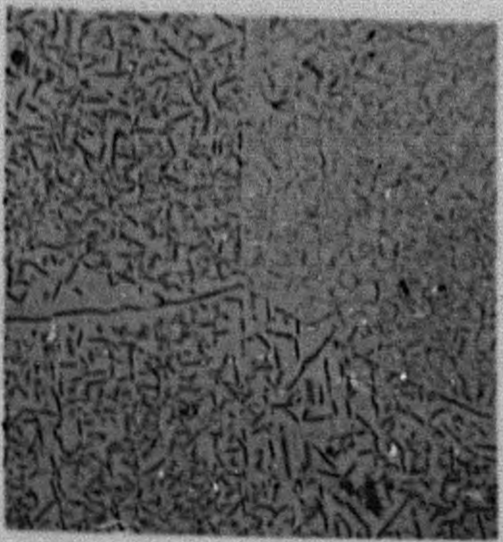

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FIG. 4

Nb-0.26%C. As cast.
Nb_2C precipitate in niobium solid solution.

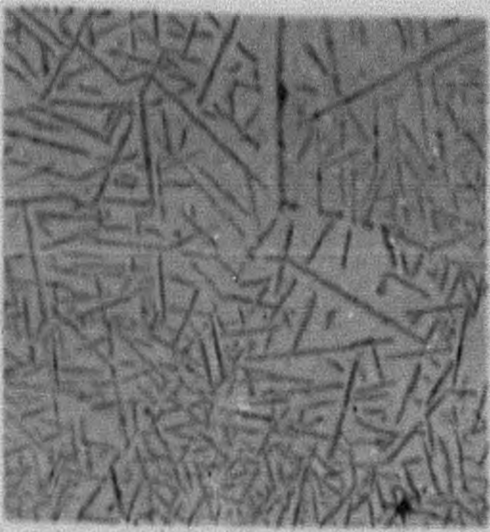

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FIG. 5

Nb-0.52%C. As cast.
Nb_2C precipitate in niobium solid solution.

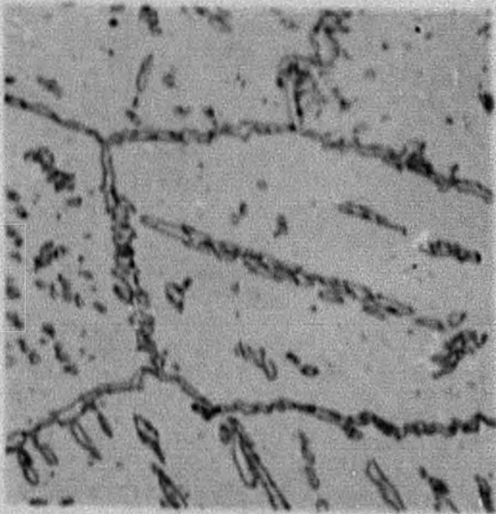

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FIG. 6

Nb-0.60%C. As cast
Nb_2C precipitate in niobium solid solution.

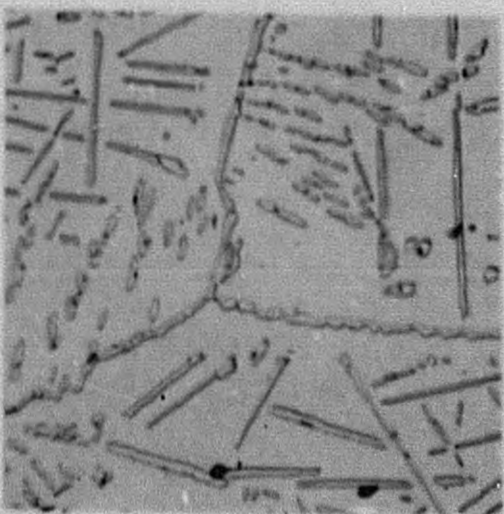

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FIG. 7

Nb-0.60%C. Annealed 1800°C 20 minutes. Spheroidized Nb_2C in niobium solid solution.

063 021

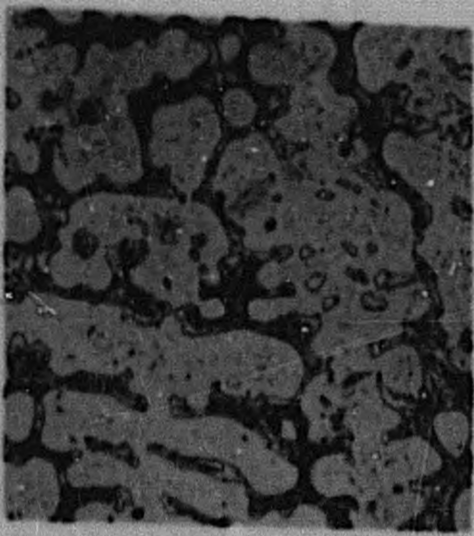

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FIG. 8

Nb-0.88%C. As cast.
Pro-eutectic niobium in matrix of $Nb-Nb_2C$ eutectic.

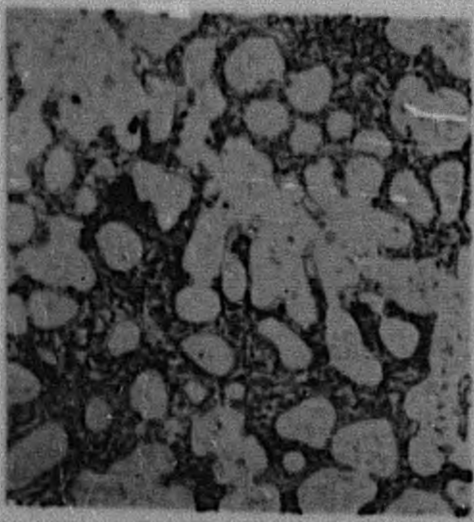

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FIG. 9

Nb-0.95%C. As cast.
Pro-eutectic niobium in matrix of $Nb-Nb_2C$ eutectic.

X 250 Etched

FIG. 10

Nb-1.50%C. As cast.
$Nb-Nb_2C$ eutectic.

X 250 Etched

FIG. 11

Nb-2.00%C. As cast.
Pro-eutectic Nb_2C in matrix of
$Nb-Nb_2C$ eutectic.

X 250 Etched

FIG. 12

Nb-2.31%C. As cast.
Pro-eutectic Nb_2C in matrix of
$Nb-Nb_2C$ eutectic.

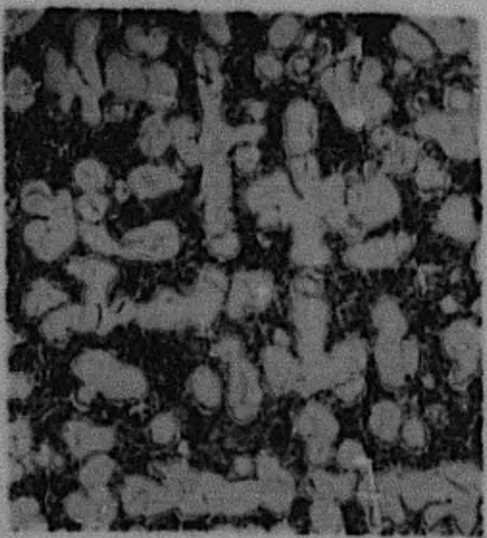

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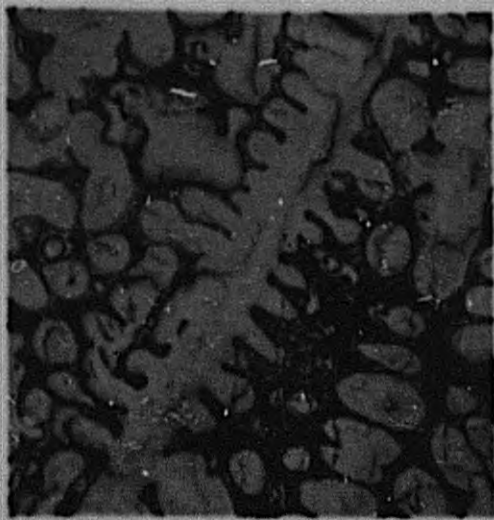
FIG. 13

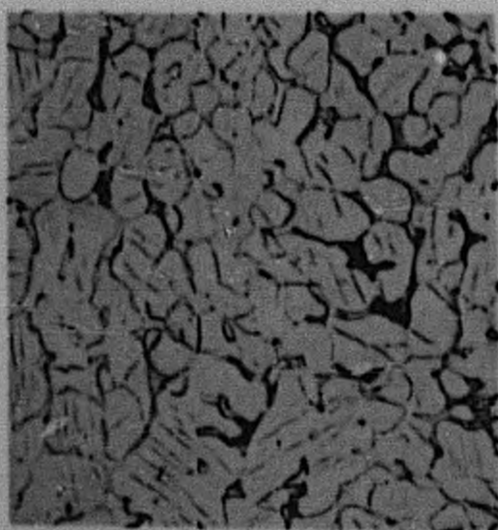
Nb-3.38%C. As cast.
Pro-eutectic Nb_2C in matrix of
$Nb-Nb_2C$ eutectic.



X 250 Etched

FIG. 14

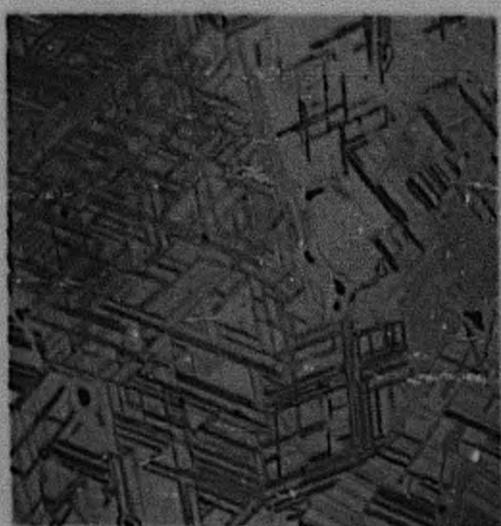
Nb-4.34%C. As cast. Pro-eutectic Nb_2C in matrix of Nb-Nb_2C eutectic. Evidence of peritectic reaction.



X 250 Etched

FIG. 15

Nb-4.58%C. As cast. Pro-eutectic Nb_2C. [illegible]ast traces of Nb-Nb_2C eutecti[illegible]



X 250 Etched

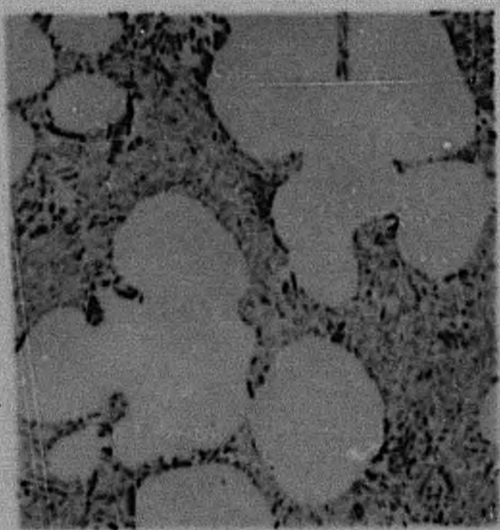
FIG. 16

Nb-6.33%C. As cast. Nb_2C with NbC.

X 250 Etched

FIG. 17

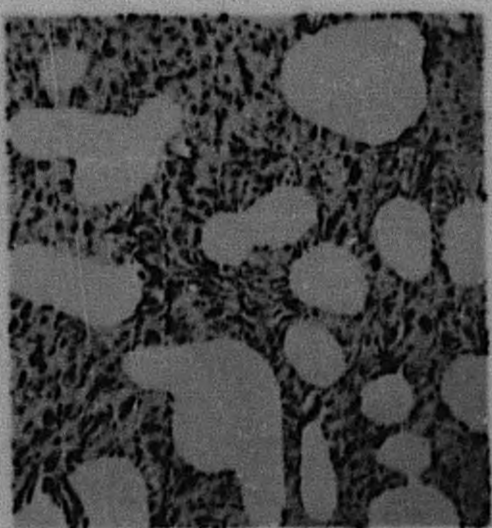
Nb-6.80%C. As cast.
Nb_2C with NbC.



X 500 Unetched

FIG. 18

Nb-12.7%C. As cast.
Pro-eutectic NbC in NbC-Graphite eutectic.



X 500 Unetched

FIG. 19

Nb-14.1%C. As cast.
Pro-eutectic NbC in NbC-Graphite eutectic.

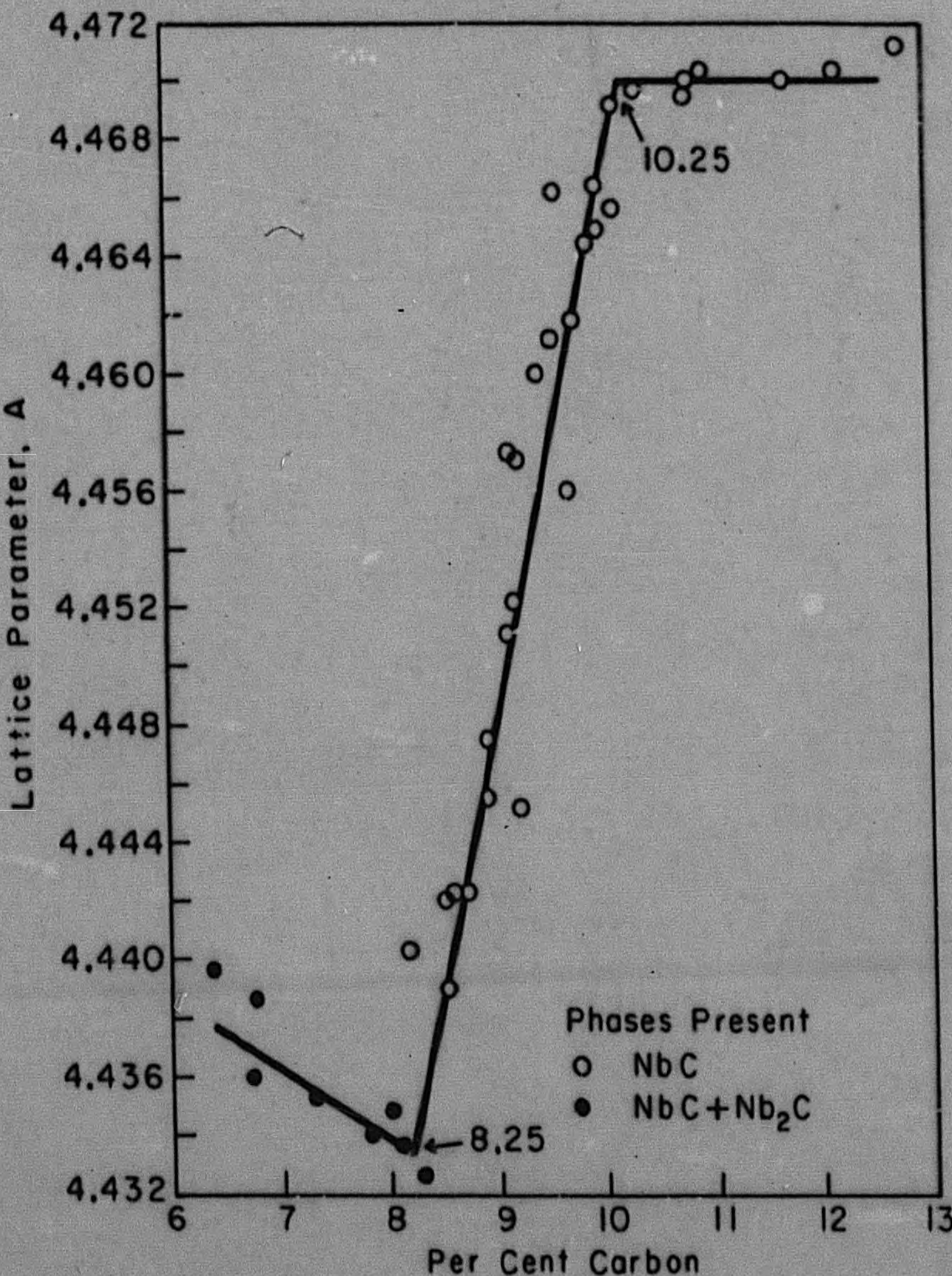
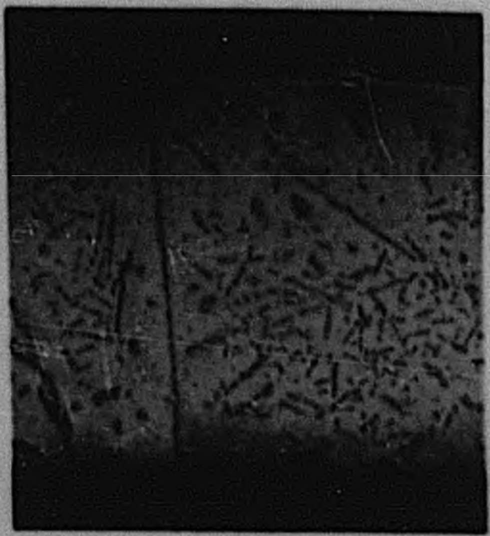


FIG. 20 LATTICE PARAMETERS OF NbC PHASE



X 50 Etched

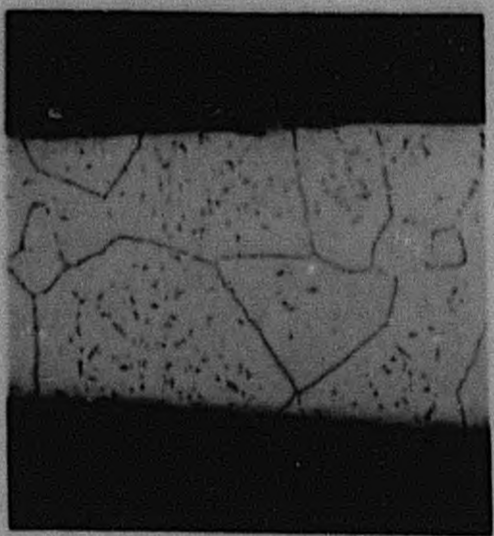
FIG. 21

0.046 in. Nb sheet carburized at 2200 °C.

X 50 Etched

FIG. 22

0.046 in. Nb sheet carburized at 2000 °C.



X 50 Etched

FIG. 23

0.046 in. Nb sheet carburized at 1800 °C.

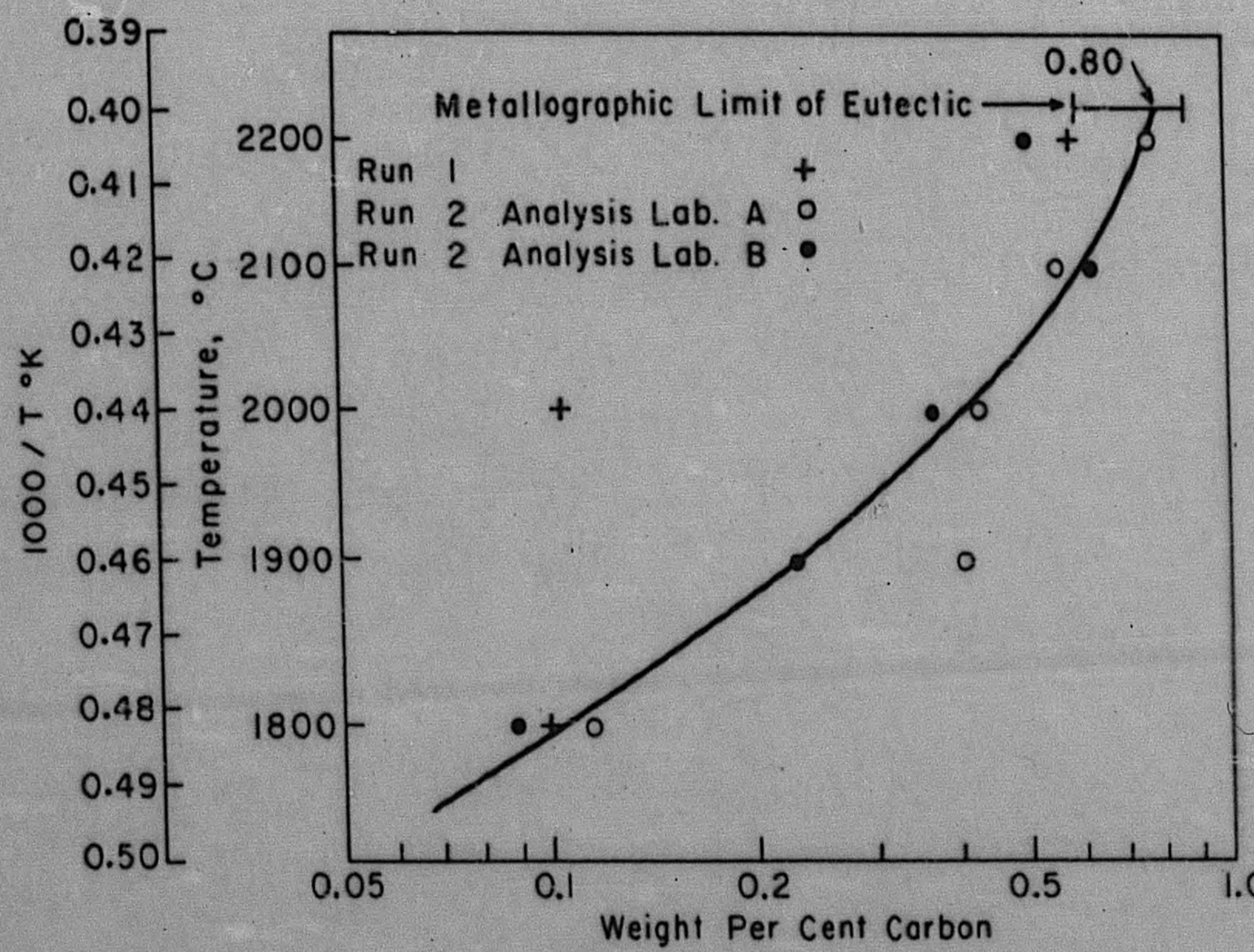


FIG. 24 SOLID SOLUBILITY OF CARBON IN NIOBIUM

063 028

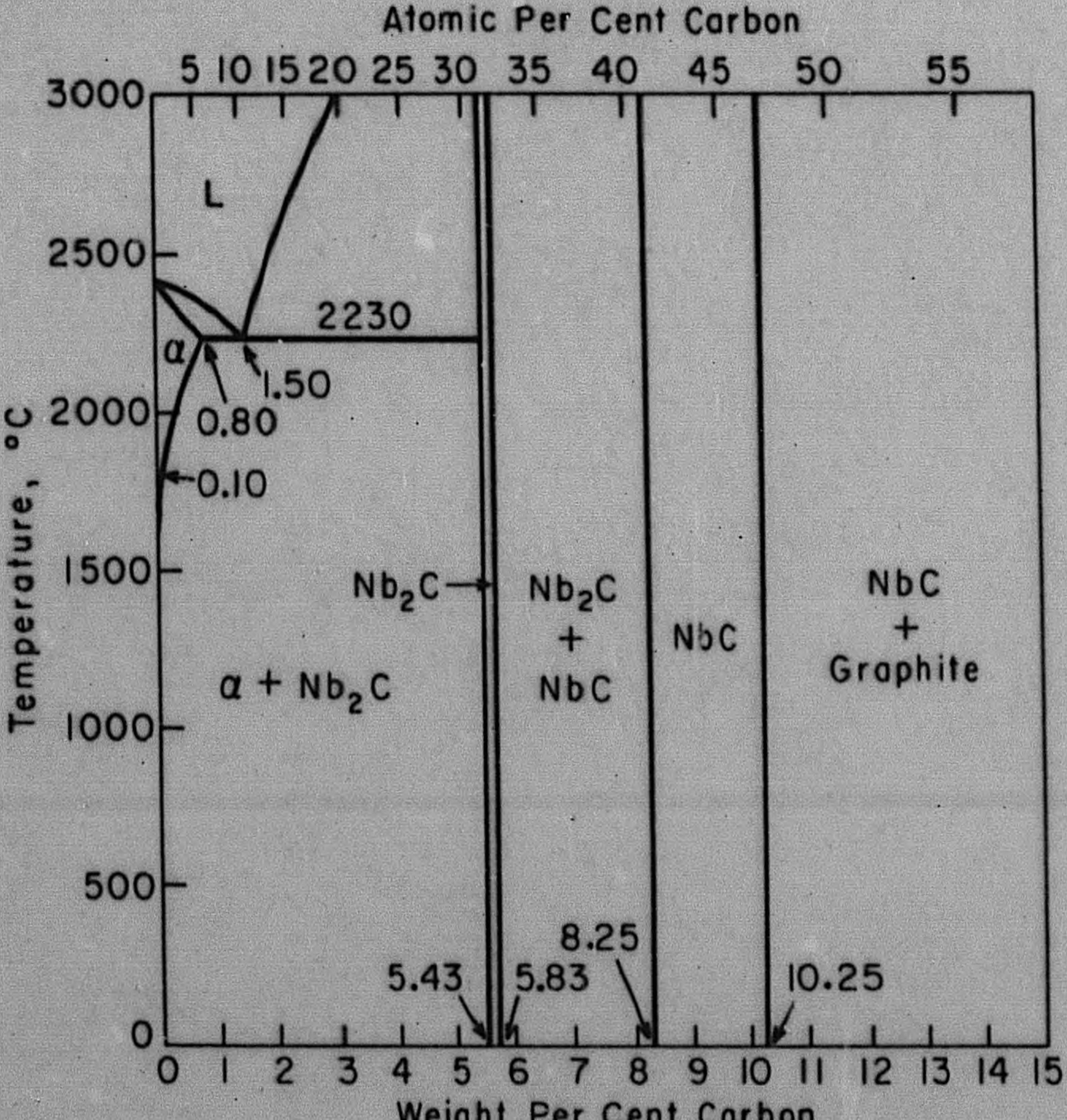


FIG. 25 NIOBIUM-CARBON PHASE DIAGRAM