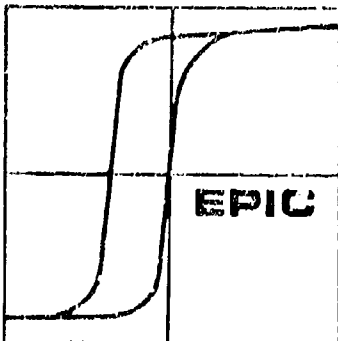


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# NIOBIUM ALLOYS and COMPOUNDS

DONALD L. GRIGSBY

DATA SHEET DS-148  
JANUARY 28, 1966



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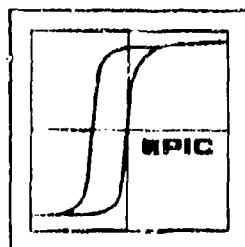
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## FOREWORD

The Electronic Properties Information Center (EPIC) was established in June 1961, at Hughes Aircraft Company, Culver City, California. It is operated under contract with the Air Force Materials Laboratory, Research and Technology Division, Wright-Patterson Air Force Base, Ohio. The contract was initiated under Project No. 7381, Task No. 738103, with Mr. R.F. Klinger acting as Project Engineer.

The EPIC Information Analysis Center is a center for the collection, review and analysis of the scientific and technical literature on the electrical and electronic properties of materials. Its major function is to evaluate, compile and publish the experimental data from that literature. Through the medium of a series of publications such as Data Sheets, Special Reports, State-of-the-Art Reports, Computer Bibliographies, and services including special studies, answers to technical inquiries, research support is provided to the DoD community. EPIC input is primarily from the open literature. A large number of abstract journals, in addition to about 40 other journals, and the unclassified report literature are completely searched.

This report consists of the compiled data sheets on niobium alloys and compounds. A full list of EPIC publications to date appears at the end of the report.

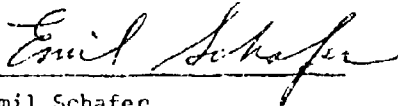
The author wishes to acknowledge the contribution of Mr. E. Schafer in the pre-publication review of the compilation. The supporting assistance of other members of the EPIC staff, in particular, Mrs. J. Forest, Miss Sharon Bender, Mr. W.S. Hodge, and Mrs. Meta Neuberger, is gratefully acknowledged.



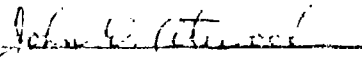
## ALSTRACT

These data sheets present a compilation of electronic properties for superconducting properties including transition temperature, critical field, critical current, electrical resistivity, and magnetic hysteresis. Electrical properties include conductivity, dielectric constant, Hall coefficient, mobility, and thermoelectric effects. Emission data have been broken down into the varied electron and photon emissions. Work functions, absorption, magnetic susceptibility, specific heat, Debye temperature and thermal conductivity data are also given. Each property is compiled over the widest possible range of parameters including bulk and film form, from references obtained in a thorough literature search.

This report has been reviewed and is approved for publication.



Emil Schafer  
Assistant Head, Electronic Properties Information Center



John W. Atwood  
Project Manager

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## INTRODUCTION

The data given for niobium alloys and compounds in this publication are presented according to the period, rather than the group, of those elements added to niobium. Within the periodic nature of the organization some of the systems have been grouped together, such as niobium boride and niobium carbide. This has been done where the data on systems of neighboring elements are suitable for comparison. Most of the data are on the binary systems; however, available data on ternary niobium systems are given when available and pertinent.

The superconducting properties of these systems are of primary concern and are presented first, followed by other data available. Some systems such as niobium-tellurium do not show evidence of being superconducting at any temperature, still the semiconducting data are given for completeness.

None of the data on niobium-tin or niobium-zirconium are included in this publication. Each of these systems is being compiled separately and will be issued later.

As the data on these various systems are presented, every effort has been made to provide sample specifications where they are available. One particular method is used for niobium-metal alloys; that is where the samples are arc melted on a water cooled copper hearth and then remelted several times to obtain homogeneity. This has been referred to as the "standard" sample preparation in some of the captions.

One other method of sample preparation has been used to investigate the forming of materials with B-tungsten structure and with a high density of states. The HCl transport method started with sintered  $Nb_3M$  materials. The cold zone was kept at 800-900°C and the hot zone at 1000-1100°C. The results are given below for two niobium compounds, the other data are presented in the body of this publication.

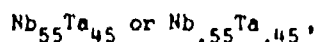
| Compound           | Crystal type       | Lattice constant $a_0$ (Å) | $T_c$ °K |
|--------------------|--------------------|----------------------------|----------|
| Nb <sub>3</sub> Ag | Cu <sub>3</sub> Au | 4.207                      | -        |
| Nb <sub>3</sub> Cu | "                  | "                          | <4.2     |

[Ref. 21843]

Compiling these data from as many sources as possible, it has often been necessary to change some parameters so that they are compatible with others. One example of this is in the method of measuring the amount of the element added to niobium. The two most common methods are weight percent and atomic percent, the conversion factors between these are taken from ASM Metals Handbook, 1948.

$$y = \frac{100x}{x + \frac{A}{B}(100-x)}, \quad x = \frac{100y}{y + \frac{B}{A}(100-y)}$$

where  $x$  is the weight percent and  $y$  is the atomic percent. A common notation for atomic percentage is as follows:



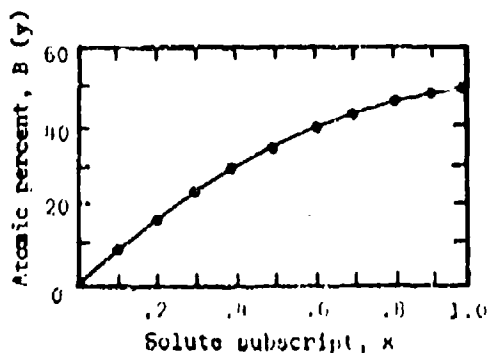
other than this, at % or wt.% is used.

The generalized subscript  $x$  is often used to replace the numerical values; Nb<sub>1-x</sub>Ge<sub>x</sub> is just another method of using atomic percent notation when  $x$  takes on specific values. However, when the notation NbC<sub>x</sub> is used, this is not the atomic percent notation; when  $x = .5$ , i.e. Nb<sub>1.0</sub>C<sub>.5</sub>, the carbon content is in reality 33 at.%. The following nomogram aids in these conversions.

Nomogram for conversion to atomic percent B in A<sub>1-x</sub>B<sub>x</sub>:

$$x = \frac{y}{1+y}, \quad y = \frac{x}{1-x}$$

where  $x$  is the subscript for the solute, and  $y$  is the atomic percent.

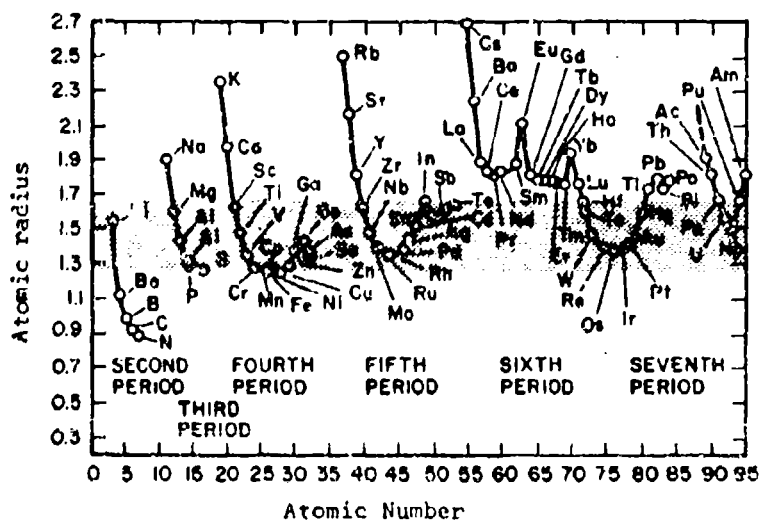


Another notation used in reporting the composition of niobium alloys and compounds is the ratio of the additional element to niobium; an example of this is C/Nb. If this is the atomic ratio, the value is easily converted to atomic percent, an atomic ratio C/Nb of .5 is 50 at.% carbon. Occasionally mole ratio C/Nb may be given when in reality atomic ratio is intended, when this is done, an attempt has been made to clarify.

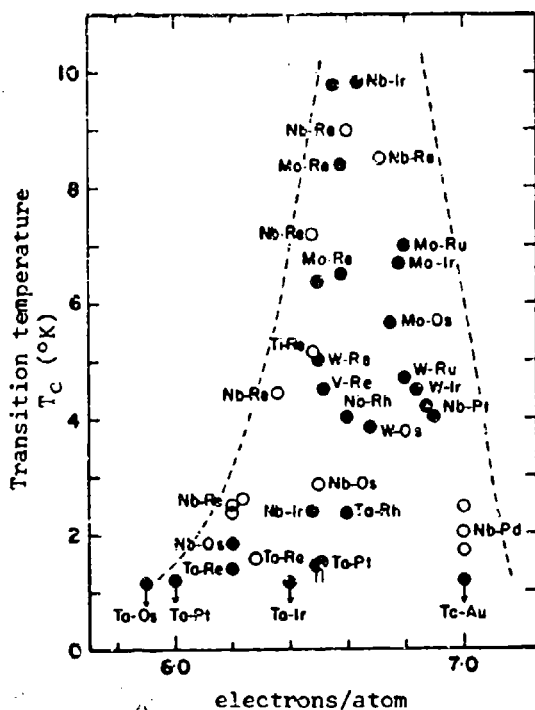
The crystalline nature of the niobium systems is of great importance in determining the properties they exhibit. This is one of the reasons why much attention has been given to phase diagrams and lattice parameters. The three main crystalline structures which show superconductivity are  $\beta$ -tungsten,  $\alpha$ -manganese, and sigma. Below is a graph which shows those elements which are favorable for solid solubility in niobium.

The shaded band covers the range of radii favorable for extensive solid solubility in niobium

[Ref. 21851]



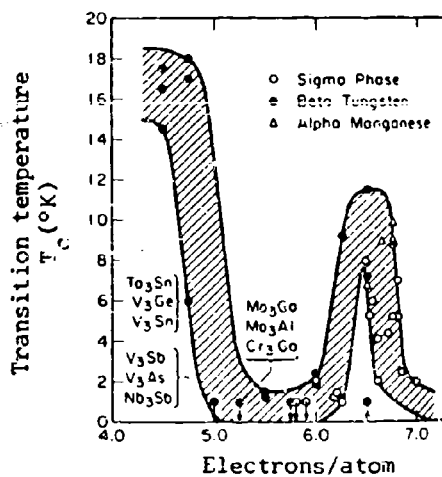
Directly correlated to the composition and crystalline structure of the niobium systems is the valence electron/atom ratio. The two following graphs show the transition temperatures as a function of this ratio for various systems in different structures.



- $\sigma$  structure
- $\alpha$ -Mn structure

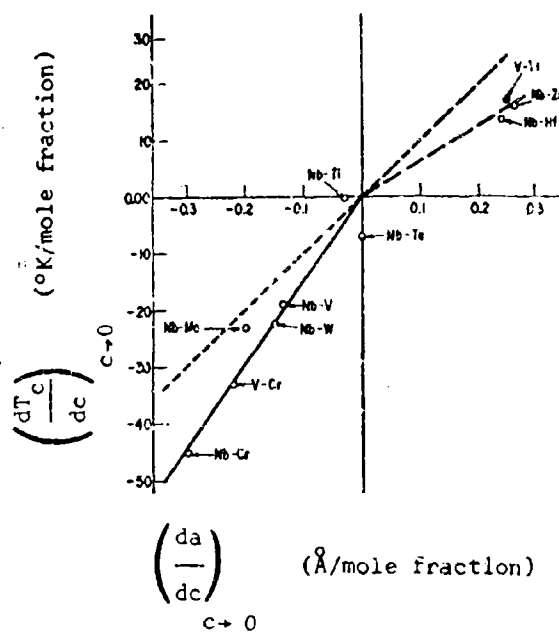
[Ref. 15323]

Transition temperature as a function of  $e/a$  ratio.



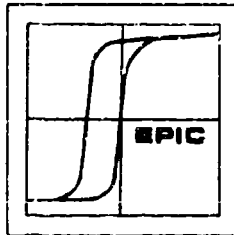
[Ref. 7548]

In a 1963 paper, DeSorbo reports the effects of composition and structure on superconducting properties. The following graph shows  $dT_c/dc$  plotted against  $da/dc$  where  $c$  is the concentration and  $a$  is the lattice parameter. The size of the solute atom is one of the factors affecting the properties of the system.



The rate of change of transition temperature with composition as a function of change of lattice parameter.

[Ref. 10778]



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Section 1  
NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-HYDROGEN

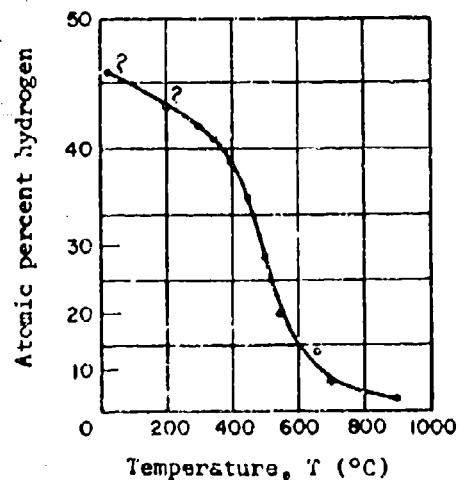
GENERAL

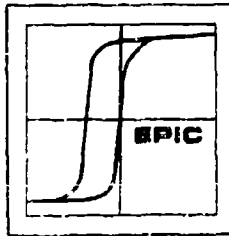
Niobium hydride shows a transition temperature near 9°K with low hydrogen content. This temperature value decreases as the hydrogen content is increased and has a value of about 12°K at  $Nb_{1.0}H_{1.0}$ .

Two distinct phases are found for the niobium-hydrogen system, an  $\alpha$  phase up to 10 at.% hydrogen and  $\beta$ -niobium hydride phase above 41 at.% hydrogen. The ranges represented by these phases are given by Brauer and Herman [Ref. 20328] and Trzebiatowski and Stalinski [Ref. 20575].

Some disagreement exists over the nature of the  $\beta$  phase. Brauer and Herman [Ref. 20328] cite the lattice constants for an orthorhombic structure, but also interpret this phase as distended cubic. Samsonov and Anmonova [Ref. 20333] substantiate this latter symmetry in the 44 to 51 at.% hydrogen region.

Solubility isobar for hydrogen at 1 atmosphere, in niobium (98.5 wt.% pure) [Hansen Fig. 434; taken from: Sieverts, A. and H. Moritz. Z FUER ANORG. UND ALLGEM. CHEM., v. 247, 1941. p. 124.]





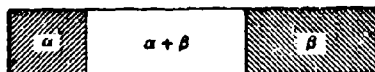
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# NIوبيUM-HYDROGEN

## GENERAL

Mole ratio H/Nb

|   |      |      |       |
|---|------|------|-------|
| 0 | 0.10 | 0.57 | 0.86† |
| 0 | 0.11 | 0.7  | 0.94* |



|   |      |      |       |
|---|------|------|-------|
| 0 | 10.0 | 41.0 | 48.5* |
| 0 | 9.1  | 36.4 | 46.0† |

Phase diagram for niobium-hydrogen system.  
48.5 at.% H is the maximum hydrogen content used by Brauer and Herman.

\* Brauer and Herman [Ref. 20328]

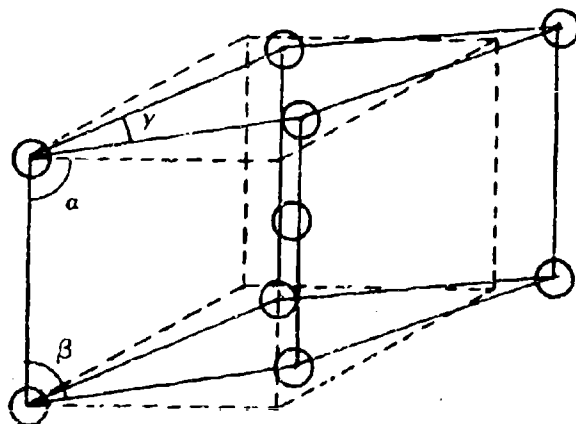
† Trzebiatowski and Stalinski [Ref. 20575]

Pseudo cubic (orthorhombic) drawing  
of  $\beta$ -niobium hydride structure, NbH<sub>0.89</sub>.

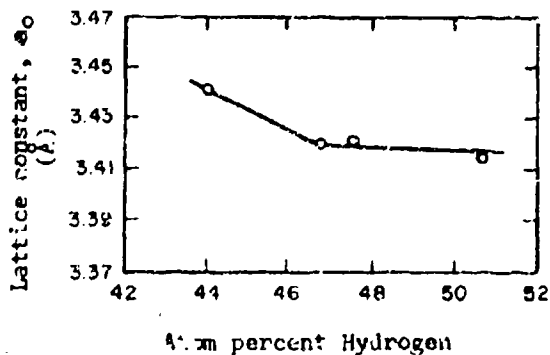
$$\alpha = \beta = 90^\circ,$$

$$\gamma = 89.4^\circ$$

$$c_0 = 3.45$$



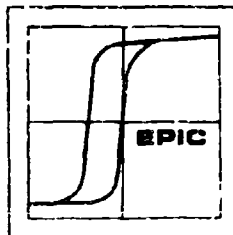
[Ref. 20328]



Lattice constant for the cubic  $\beta$ -NbH  
as a function of hydrogen content.

[Ref. 20333]





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Section 1

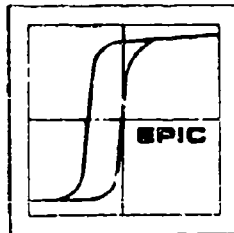
NIObIUM-HYDROGEN

TRANSITION TEMPERATURE

Lattice Constants and Transition Temperature

| At. % H | Crystallography | Lattice constants (Å) |                |                | Transition temperature (°K) |       | Samples                                                  | Ref.  |
|---------|-----------------|-----------------------|----------------|----------------|-----------------------------|-------|----------------------------------------------------------|-------|
|         |                 | a <sub>0</sub>        | b <sub>0</sub> | c <sub>0</sub> | Midpoint                    | Range |                                                          |       |
| 0       | bcc             | 3.3004*               | -              | -              | 9.98                        | 0.90  | -                                                        | 9299  |
| 5.06    | α-bcc           | 3.311±.004            | -              | -              | 7.83                        | 2.27  | Cooled from 800°C in calibrated volume of H <sub>2</sub> | "     |
| 8.5     | β-bcc           | 3.308±.002            | -              | -              | -                           | -     | -                                                        | 20329 |
| 8.5     | α-bcc           | 3.427±.005            | -              | -              | -                           | -     | -                                                        | "     |
| 9.89    | "               | 3.327±.003            | -              | -              | 7.38                        | 3.25  | See preceding note.                                      | 9299  |
| 17.0    | "               | 3.312±.002            | -              | -              | -                           | -     | -                                                        | 20329 |
| 17.0    | β-bcc           | 3.44                  | -              | -              | -                           | -     | -                                                        | "     |
| 32.76   | α-bcc           | -                     | -              | -              | 7.28                        | 3.17  | See preceding note                                       | 9299  |
| 32.76   | "               | 3.330±.003            | -              | -              | -                           | -     | -                                                        | 20329 |
| 40.2    | "               | 3.308±.002            | -              | -              | -                           | -     | -                                                        | -     |
| 40.2    | β-bcc           | 3.42                  | -              | -              | -                           | -     | -                                                        | -     |
| 47.0    | "               | 3.45                  | -              | -              | -                           | -     | -                                                        | -     |
| 47.0    | β-orthorhombic  | 4.84                  | 4.90           | 3.45           | -                           | -     | -                                                        | 20326 |
| 50.0    | β-bcc           | 3.43                  | -              | -              | -                           | -     | -                                                        | 20333 |
| 50.0    | -               | -                     | -              | -              | 12.7                        | -     | -                                                        | 20330 |
| 50.0    | -               | -                     | -              | -              | 14.8                        | -     | NbC sheath                                               | "     |
| 67.0    | -               | 4.55                  | -              | -              | -                           | -     | -                                                        | 20333 |

\* This lattice constant taken from J. APPL. PHYS., v. 22, p. 424 (1951).

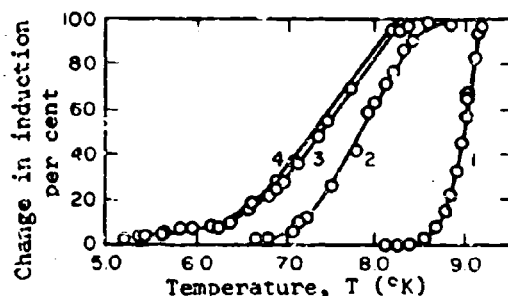


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# Section 1

## NIOBIUM-HYDROGEN

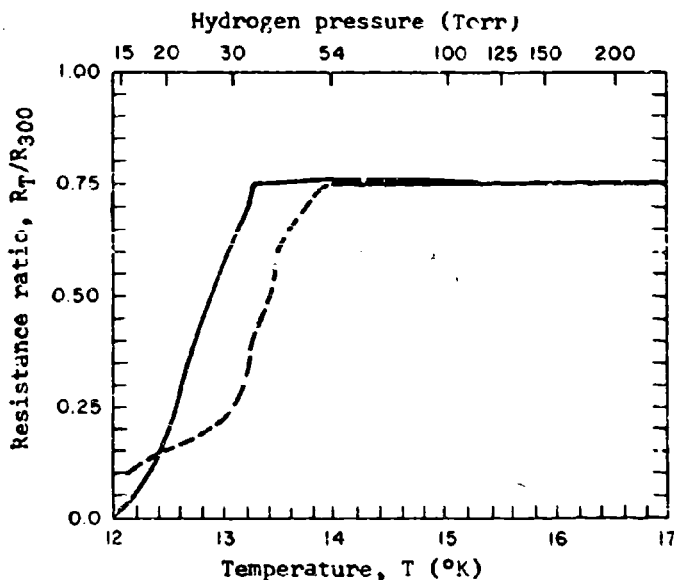
### TRANSITION TEMPERATURE



Transition curves of four niobium-hydrogen systems.

- |                |                 |
|----------------|-----------------|
| 1) 0 at.% H    | 3) 9.89 at.% H  |
| 2) 5.06 at.% H | 4) 32.76 at.% H |

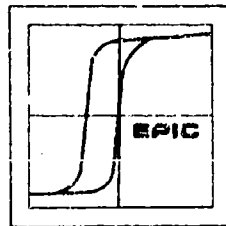
[Ref. 9299]



Transition curves for niobium hydride,  $I = 4$  milliAmp,  $H = 0$ .

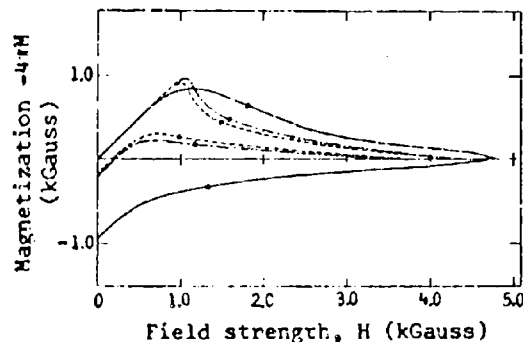
- rising, superconducting→normal  
— falling, normal→superconducting

[Ref. 20330]



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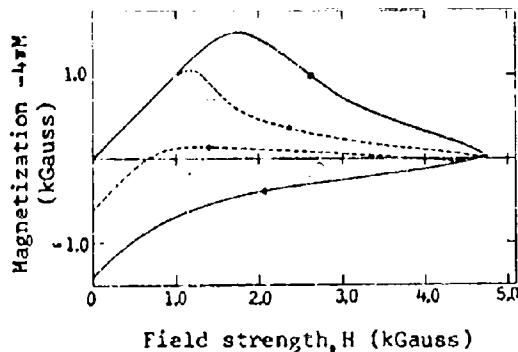
Section 1  
NIOBIUM-HYDROGEN  
MAGNETIC HYSTERESIS



Magnetization for niobium-hydride. Data taken at 4.2°K. Sample preparation: niobium heated in 10-80 mm Hg at 800°C.

--- H/Nb < 0.30  
- - - H/Nb = 0.28  
— H/Nb = 0.45

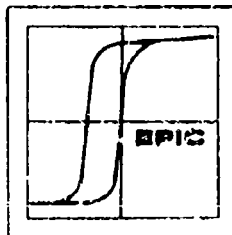
[Ref. 21040]



Magnetization for niobium hydride sample prepared by cathodic polarization.

--- 0.16 Amp/cm, 25 hours: single crystal  
— 0.16 Amp/cm, 25 hours: polycrystalline

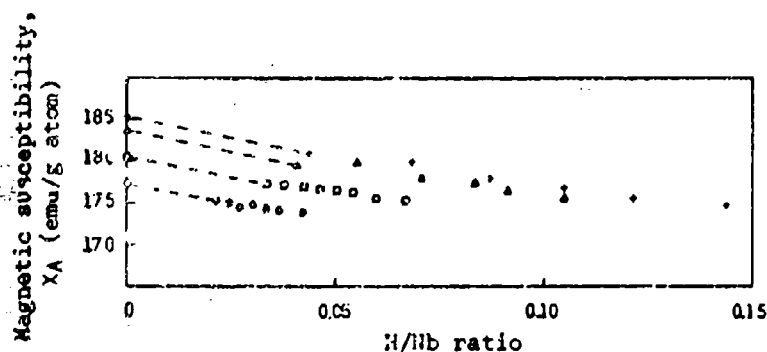
[Ref. 21040]



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# NIOBIUM-HYDROGEN

## MAGNETIC SUSCEPTIBILITY



Atomic susceptibility of niobium-hydrides as a function of hydrogen content. Samples were arc-melted under reduced argon pressure.

- 800°C
- 700
- △ 600
- † 550

[Ref. 19871]

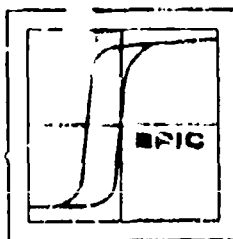
# NIOBIUM HYDROGEN

## SPECTRAL EMISSION

Integral intensity of  $L_{\beta 2}$  bands for a niobium hydrogen compound, taking  $L_{\beta 2}$  line for Nb as unity.

| Compound | Intensity |
|----------|-----------|
| $NbH_x$  | 1.06      |

[Ref. 16347]



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Section 2

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-BERYLLIUM

Electrical Resistivity and Thermal Conductivity

| Compound                         | Electrical Resistivity<br>( $\mu\Omega$ -cm) |                |                   | Thermal Conductivity, K<br>(W/cm $^{\circ}$ K) |                   | Melting Point<br>$T_m$ ( $^{\circ}$ C) |
|----------------------------------|----------------------------------------------|----------------|-------------------|------------------------------------------------|-------------------|----------------------------------------|
|                                  | 25 $^{\circ}$                                | 650 $^{\circ}$ | 1260 $^{\circ}$ C | 760 $^{\circ}$ C                               | 1480 $^{\circ}$ C |                                        |
| NbBe <sub>12</sub>               | 55.5                                         | 166.6          | 200.0             | 0.301                                          | 0.326             | 1690                                   |
| Nb <sub>2</sub> Be <sub>17</sub> | -                                            | -              | -                 | 3.261                                          | 0.343             | 1705                                   |
| Nb <sub>2</sub> Be <sub>19</sub> | -                                            | -              | -                 | -                                              | -                 | 1765                                   |

[Ref. 10169]

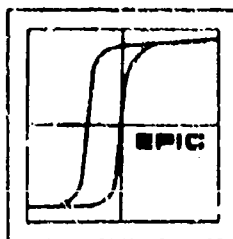
NIOBIUM-ZIRCONIUM-BERYLLIUM

Transition Temperature

Nb<sub>5</sub>Zr<sub>2</sub>Be<sub>8</sub>

$T_c = 5.2^{\circ}$ K

[Ref. 10784]



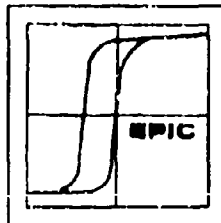
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Section 2  
NIOBIUM ALLOYS AND COMPOUNDS  
NIOBIUM-BORON AND NIOBIUM-CARBON SYSTEMS  
GENERAL

Nb-B Niobium combines with boron and forms three distinct compounds,  $NbB$ ,  $Nb_3B_4$ , and  $NbB_2$ . Only the monoboride shows a favorable transition temperature in the 3-8°K range.

Anderson and Klesning [Ref. 19932] have identified two phases at about 10 at.% boron which they call  $\beta$  and  $\beta'$ . The first of these seems to be stable at room temperature while the latter is stable only at higher temperatures. These authors claim a primitive cubic lattice for the  $\beta'$  phase with  $a_0 = 4.210 \text{ \AA}$ . Another phase,  $\beta''$  is identified by Anderson and Klesning between 20 and 35 at.% boron. Brewer, et al [Ref. 19752] suggest that this  $\beta''$  might be a  $NbB_m$  phase containing 25 at.% boron.  $NbB_m$  was noted along with Nb and NbB after heating a 25 at.% boron sample for 8 minutes at 1650°C, but was not found in two other samples with 20 and 33 at.% boron heated for 47 minutes at 1980°C and 10 minutes at 1820°C respectively. In further experiments as the boron approached the 40 at.% level a  $NbB_n$  phase was identified by Brewer, et al, in samples prepared at 1530°C for 21 minutes and 1810°C for 9 minutes. The boron component m and n is not identifiable in either of these phases and no lattice constants are given for either of them or for  $Nb_3B_4$ .

The monoboride in the niobium-boron system shows an orthorhombic structure and is isotypic with CrB and TaB. This same orthorhombic structure carries on through to the  $Nb_3B_4$  compound which is isotypic with  $Ta_3B_4$ . As the boron content increases, the system reaches the  $NbB_2$  compound with a hexagonal structure of the  $AlB_2$  (C 32) type.



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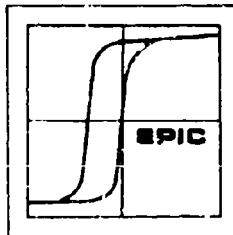
Section 2  
NIOBIUM-CARBON

GENERAL

Nb-C Both the "mono" and "sub" carbides of niobium have transition temperatures in the 6-10°K range, and show strong dependence on the carbon content. Near the 33 at.% carbon region ( $\text{NbC}_{0.5}$ ) an increase in the carbon percentage by 0.66 at.% sends the transition temperature to less than 2°K. Likewise near the 50 at.% region a decrease in the carbon percentage to about 45 at.% ( $\text{NbC}_{0.885}$ ) drops the transition temperature to less than 4°K. This dependence upon carbon content is noted even though these two compounds exhibit different crystalline structures.

Brauer, et al<sup>\*</sup> claim  $\text{Nb}_2\text{C}$  to be homogeneous between 25.9-33.3 at.% carbon and NbC to be homogeneous between 41.9-50.0 at.% carbon. The transition temperatures, however, do not reflect the homogeneity of these phases.

\* Brauer, G., H. Renner, and J. Wernet. Carbides of Niobium. Z. FÜR ANORG. UND ALLGEM. CHEM., v. 177, 1934. p. 249-257.

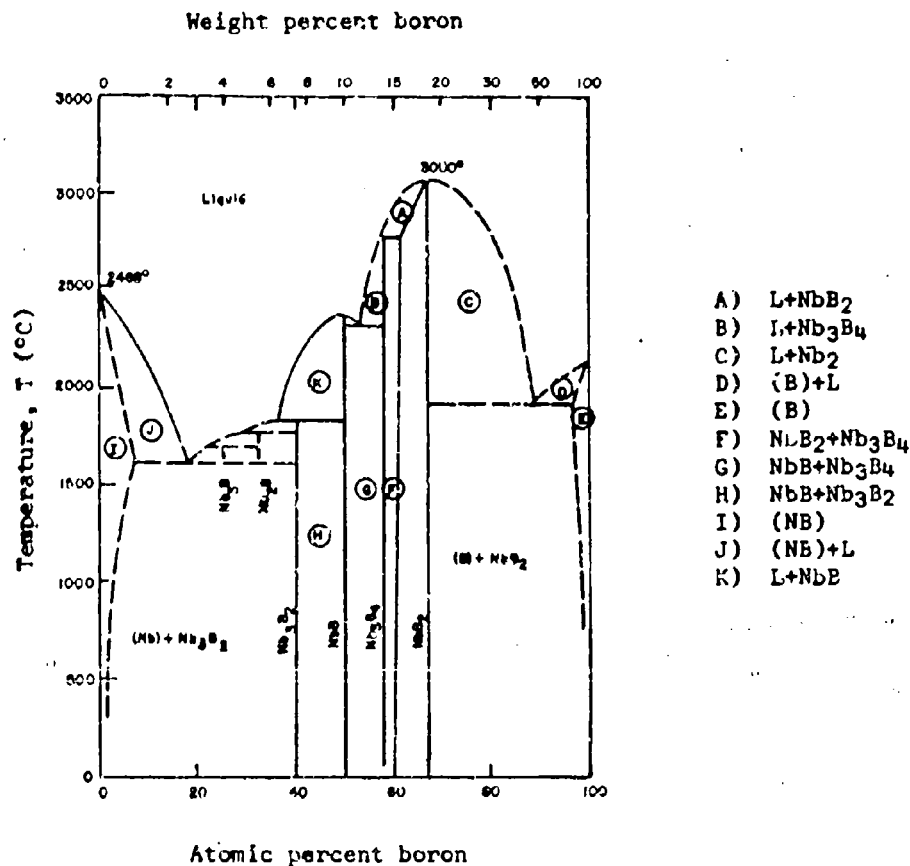


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Section 2

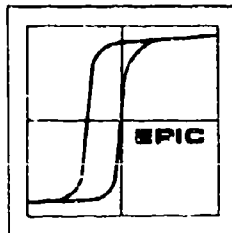
NIOBIUM-BORON

GENERAL



\* W.F. SHEELY. Alloying Behavior. In COLUMBIUM AND TANTALUM. Ed. by: FRANK T. SISCO and EDWARD EPREMIAN, New York, Wiley, 1963. p. 444. Sheely has added to the Kieffer and Benovsky phase diagram.





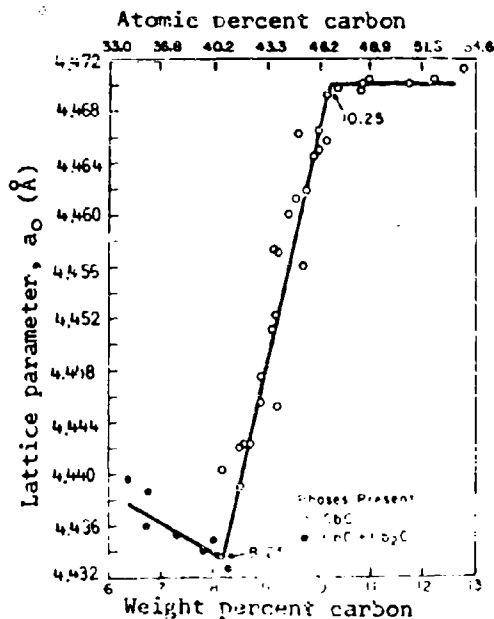
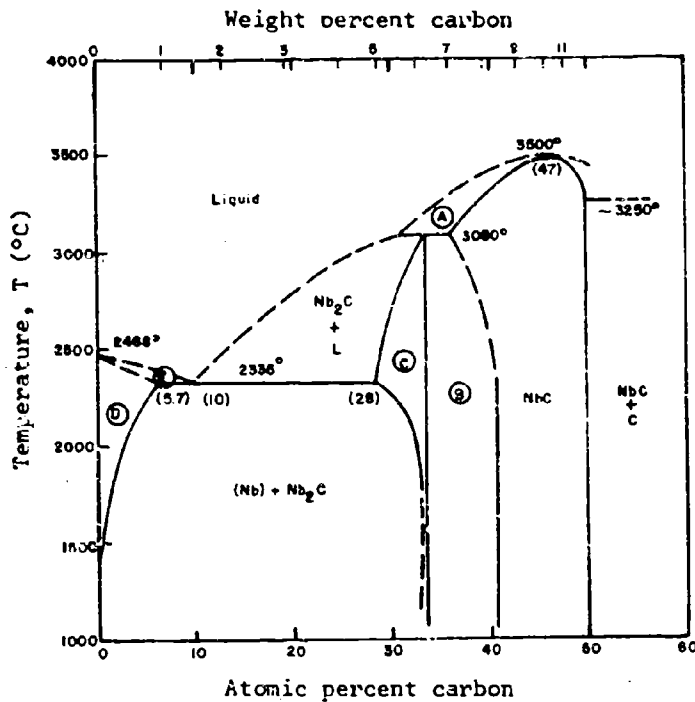
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Section 2  
NIOBIUM-CARBON

GENERAL

Phase diagram of niobium-carbon system. [Ref. 19<sup>0</sup>.]

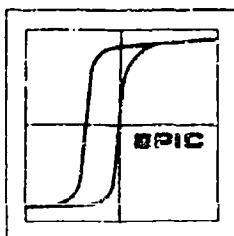
- A) NbC+L
- B) Nb<sub>2</sub>C+NbC
- C) Nb<sub>2</sub>C
- D) (Nb)
- E)  $\alpha$ -Nb+L



Lattice parameters for niobium carbide, arc-cast samples:

- single phase NbC
- double phase NbC+Nb<sub>2</sub>C.

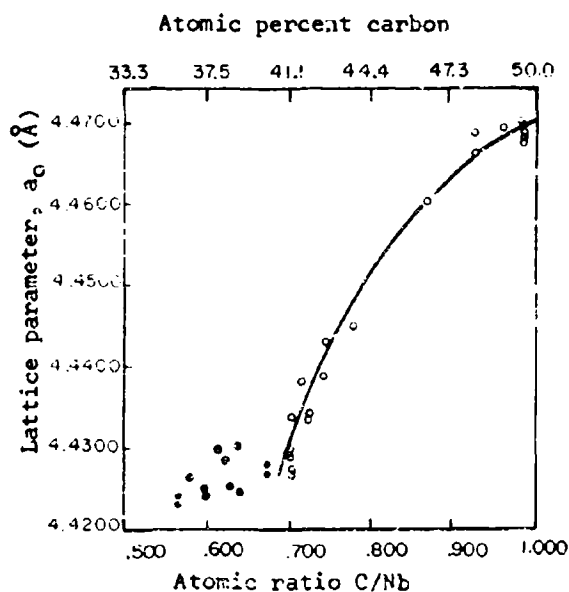
[Ref. 20<sup>0</sup>31]



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Section 2 |  
NIOBIUM-CARBON

GENERAL



Lattice parameters for powdered niobium carbide. The curve is a least squares fit of the data and follows the equation:

$$a_0 = 4.4704 - 0.0239(1-x) - 0.3586(1-x)^2$$

where  $x$  is the atomic ratio C/Nb.

Sample Preparation

pressed: 100k - 200K psi  
sintered: 3000°C for .5 hrs., or  
1800°C for 38 hrs.

- single phase NbC
- double phase NbC+Nb₂C

[Ref. 20532]

Section 2  
NIOBIUM-BORON

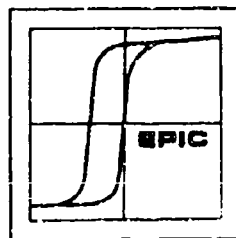
TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

| At. % B        | Phase                                            | Lattice Constant (Å) |       |            | Transition Temperature $T_c$ (°K) | Symmetry | Notes                                | Ref.  |
|----------------|--------------------------------------------------|----------------------|-------|------------|-----------------------------------|----------|--------------------------------------|-------|
|                |                                                  | $a_0$                | $b_0$ | $c_0$      |                                   |          | Samples                              |       |
| 10             | B                                                | 4.210                | -     | -          | -                                 | n.i.**   | -                                    | 19932 |
| 10             | B'                                               | -                    | -     | -          | -                                 | cubic    | -                                    | "     |
| 25             | B"                                               | -                    | -     | -          | -                                 | n.i.**   | -                                    | "     |
| 25             | NbB <sub>m</sub>                                 | -                    | -     | -          | -                                 | -        | 8 min., 1650°C.                      | 19752 |
| 40             | Nb <sub>3</sub> B <sub>2</sub>                   | -                    | -     | -          | -                                 | -        | -                                    | 13014 |
| 50             | NbB <sub>n</sub>                                 | -                    | -     | -          | -                                 | -        | 21 min., 1530°C.                     | 19752 |
| 50             | "                                                | -                    | -     | -          | -                                 | -        | 9 min., 1810°C.                      | "     |
| 50             | NbB                                              | 3.298                | 8.724 | 3.166      | -                                 | ortho    | -                                    | 19625 |
| 50             | -                                                | -                    | -     | -          | 6.00                              | "        | No impurities.                       | 9697  |
|                |                                                  |                      |       |            | 8.25                              | -        | Purified of Mo impurities.*          | 7666  |
| 50             | -                                                | -                    | -     | -          | 6.94                              | -        | Electron-beam melted & zone-refined. | 15336 |
| (+3% excess B) | -                                                | -                    | -     | -          | 5.51                              | -        | "                                    | 15336 |
| 55             | -                                                | -                    | -     | -          | 6.1                               | -        | Sintered in argon, 1700-1750°C.      | 15335 |
| 57             | Nb <sub>3</sub> B <sub>4</sub>                   | 3.305                | 24.08 | 3.137      | -                                 | -        | -                                    | 19625 |
| 57             | -                                                | -                    | -     | -          | <1.27                             | -        | -                                    | 9697  |
| 59.3           | Nb <sub>2</sub> NbB <sub>2</sub>                 | -                    | -     | -          | 4.60                              | -        | "                                    | 15336 |
| 67.0           | NbB <sub>2</sub> +Nb <sub>3</sub> B <sub>4</sub> | 3.110±.002           | -     | 3.264±.002 | -                                 | -        | Heated w/86% B, 22 min., 1565°C.     | 19752 |
| 67.0           | NbB <sub>2</sub>                                 | 3.085±.002           | -     | 3.311±.002 | -                                 | hex      | -                                    | "     |
| 67.0           | "                                                | -                    | -     | -          | <1.27                             | "        | -                                    | 9697  |

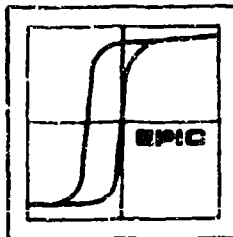
\*Hulm and Mathias obtained  $T_c = 6.0^\circ\text{K}$  [9697] and in a latter work [7666] removed the molybdenum impurities and obtained  $T_c = 8.25^\circ\text{K}$ .  
\*\*n.i. = not identified.

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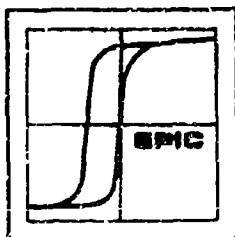
Section 2

NIOBIUM-CARBON

TRANSITION TEMPERATURE

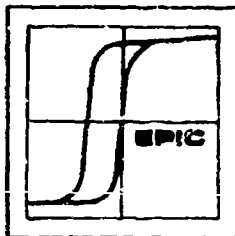
Lattice Constants and Transition Temperatures

| At. % C | Phases                              | Symmetry  | Lattice Constants (Å) |                | Transition Temperature $T_C$ (°K) | Notes                                                                                  | Ref.   |
|---------|-------------------------------------|-----------|-----------------------|----------------|-----------------------------------|----------------------------------------------------------------------------------------|--------|
|         |                                     |           | $a_0$                 | $c_0$          |                                   |                                                                                        |        |
| 25.9    | Nb+Nb <sub>2</sub> C                | hexagonal | 3.117                 | 4.955          | -                                 | -                                                                                      | Hansen |
| 28.5    | -                                   | -         | -                     | -              | 9.2                               | Arc melted                                                                             | 9696   |
| 30.5    | Nb <sub>2</sub> C+Nb <sub>2</sub> C | -         | 3.126 ± .001          | 4.965 ± .001   | -                                 | -                                                                                      | 20533  |
| 32.4    | Nb <sub>2</sub> C+NbC               | -         | 3.1194                | 4.9663         | -                                 | -                                                                                      | 20531  |
| 32.4    | -                                   | -         | -                     | -              | 9.2                               | Arc melted                                                                             | 9696   |
| 33.0    | Nb <sub>2</sub> C                   | -         | -                     | -              | 9.18                              | Induction measurement.                                                                 | 9695   |
| 33.5    | NbC .51                             | -         | -                     | -              | <1.98                             | Heated at 2000°C.                                                                      | 9695   |
| 36.2    | Nb <sub>2</sub> C+NbC               | -         | 3.1280 ± .0002        | 4.9722 ± .0003 | -                                 | -                                                                                      | 20533  |
| 36.4    | NbC+Nb <sub>2</sub> C               | cubic     | 4.4244                | -              | -                                 | -                                                                                      | 20532  |
| 39.7    | Nb <sub>2</sub> C+NbC               | hexagonal | 3.1270 ± .0007        | 4.9710 ± .0005 | -                                 | -                                                                                      | 20533  |
| 40.9    | NbC                                 | cubic     | 4.4281 ± .0001        | -              | -                                 | -                                                                                      | "      |
| 42.1    | -                                   | -         | -                     | -              | 1.05                              | Susceptibility measurement on powders heated 2000°C, 10 <sup>-5</sup> mmHg 2-24 hours. | 18737  |
| 42.9    | -                                   | -         | -                     | -              | -                                 | -                                                                                      | -      |
| 43.6    | -                                   | -         | -                     | -              | -                                 | -                                                                                      | -      |
| 44.1    | -                                   | -         | -                     | -              | -                                 | -                                                                                      | -      |
| 44.7    | -                                   | -         | -                     | -              | 1.05                              | -                                                                                      | -      |



Lattice Constants and Transition Temperatures  
(Continued)

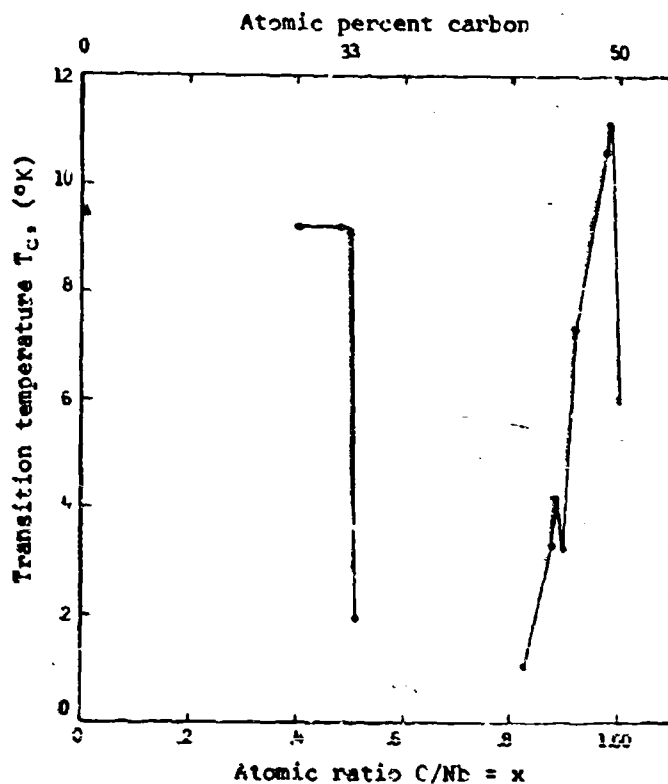
| At. % C                         | Phases | Symmetry | Lattice Constants<br>$a_0$  | Lattice Constants<br>$c_0$ | Transition<br>Temperature<br>$T_c$ (°K) | Notes                                                                                                   | Ref.           |
|---------------------------------|--------|----------|-----------------------------|----------------------------|-----------------------------------------|---------------------------------------------------------------------------------------------------------|----------------|
| 46.5<br>46.75                   | NbC    | cubic    | 4.4605<br>-                 | -<br>-                     | -<br>3.5                                | -<br>Susceptibility<br>measurement on<br>powders heated<br>2000°C, 10 <sup>-5</sup> mmHg<br>2-24 hours. | 20533<br>18737 |
| 46.83<br>46.89                  |        |          | -<br>-                      | -<br>-                     | 4.2<br>3.2                              |                                                                                                         |                |
| 47.9                            |        |          | -                           | -                          | 7.3                                     |                                                                                                         |                |
| 49.18<br>49.36<br>49.41<br>49.8 |        |          | -<br>-<br>-<br>-            | -<br>-<br>-<br>-           | 10.6<br>11.1<br>"<br>-                  |                                                                                                         | 20533          |
| 50.0<br>50.0                    |        |          | 4.4702 ± .0001<br>4.61<br>- | -<br>-<br>-                | -<br>6.0                                | -<br>Induction<br>measured                                                                              | 13014<br>9695  |



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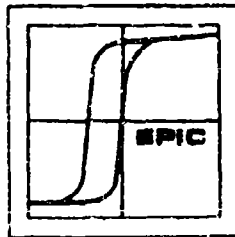
Section 2  
NIOBIUM-CARBON

TRANSITION TEMPERATURE



Plot of the data in the preceding table. Measurements are not available at  $x = .4$ ; between  $x = .51$  and  $x = .70$  no transition temperature is reported. Data in this graph represents the following authors:

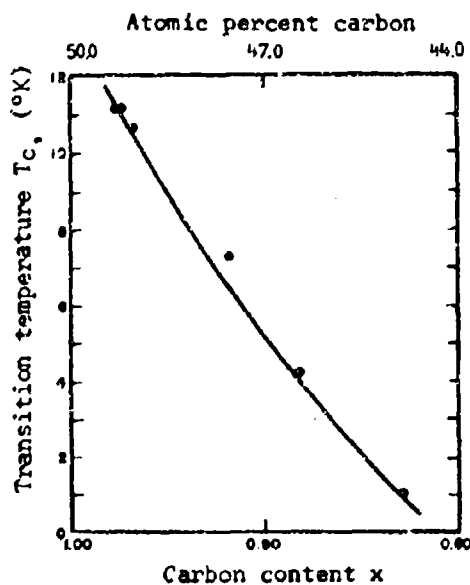
- Δ De Sorbo, W. [Ref. 13366]
- Giorgi, A.W., et al. [Ref. 9696]
- Giorgi, A.W., et al. [Ref. 18737]
- x Hardy, G.F. and J.K. Hulm [Ref. 9695]



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Section 2  
NIOBIUM-CARBON

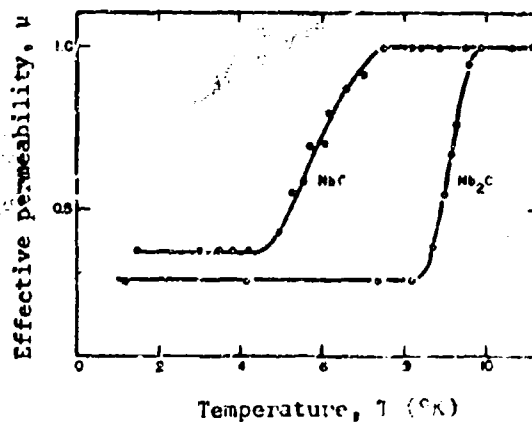
TRANSITION TEMPERATURE



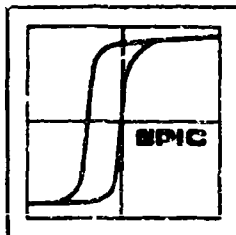
Transition temperature of niobium carbide as a function of the carbon content  $x$ ,  $\text{NbC}_x$ .

Plot of Giorgi's data [Ref. 18737]

Transition curves for arc-melted  $\text{NbC}$  and  $\text{Nb}_2\text{C}$  samples, measured in a 26 Oe field.



[Ref. 9695]



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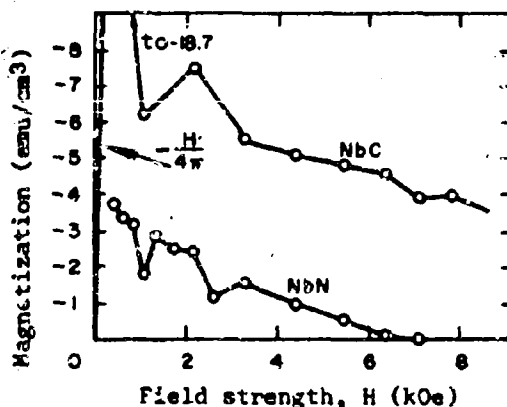
Section 2  
NIOBIUM-BORON  
CRITICAL FIELD

Critical Field

| At.% B              | H <sub>c</sub> , kGauss<br>(4.2°K) | Symmetry                   | Notes                                                                                        | Samples | Ref.  |
|---------------------|------------------------------------|----------------------------|----------------------------------------------------------------------------------------------|---------|-------|
| 50                  | 4.45                               | orthorhombic<br>B-MoB type | Electron beam melted<br>& zone refined.<br>Impurities: Ta 2000<br>ppm, others <100 each.     | "       | 12621 |
| 50(+3%<br>excess B) | 5.95                               | "                          |                                                                                              |         |       |
| 55                  | 8.00                               | Nb, NbB                    | Sintered in argon at<br>1700-1750°C. Impuri-<br>ties: Ta 500 ppm Fe<br>100, others <50 each. | "       |       |
| 59.3                | 4.8                                | N, NbB <sub>2</sub>        |                                                                                              |         |       |

NIOBIUM-CARBON

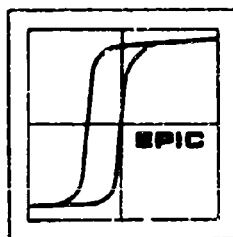
MAGNETIZATION



Magnetization as a function of applied field. Niobium carbide sample at 4.2°K. NbN curve is shown for comparison.

[Ref. 21847]



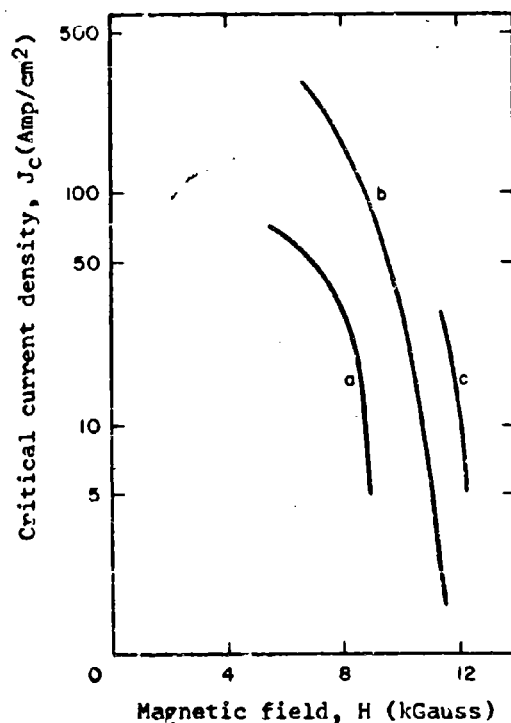


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Section 2

NIOBIUM-CARBON

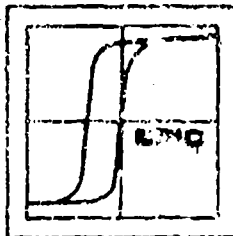
CURRENT DENSITY



Critical current density for two  $\text{NbC}_{0.995}$  samples, as a function of external field. The samples were prepared by hot pressing of powders.

| Impurities | $T_c$ ( $^{\circ}\text{K}$ ) |
|------------|------------------------------|
| a) 0.6%    | 1.4                          |
| b) 0.3%    | 4.2                          |
| c) 0.6%    | 4.2                          |

[Ref. 21780]



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Section 2

NIOBIUM-BORON AND NIOBIUM-CARBON

SEMICONDUCTING PROPERTIES

Electrical and Thermal Properties

| Electrical Resistivity<br>$\rho$ ( $\mu\Omega$ -cm) | Thermal Conductivity<br>K (W/cm <sup>2</sup> K) | Thermoelectric emf<br>$\mu$ V/°C | Hall Coefficient<br>R (10 <sup>-4</sup> cm <sup>3</sup> /coul) | Notes                                          | Ref.  |
|-----------------------------------------------------|-------------------------------------------------|----------------------------------|----------------------------------------------------------------|------------------------------------------------|-------|
| <u>NbB<sub>2</sub></u>                              |                                                 |                                  |                                                                |                                                |       |
| 12                                                  | -                                               | -                                | -1.0                                                           | -                                              | 3803  |
| 12-65                                               | -                                               | (a) 4.3                          | -                                                              | -                                              | "     |
| 28-65                                               | 0.17                                            | -                                | -                                                              | -                                              | 18179 |
| 32                                                  | -                                               | -                                | -                                                              | -                                              | 11599 |
| 34                                                  | -                                               | (a)-1.4                          | -2.1+                                                          | -                                              | 3803  |
| 35                                                  | 0.167                                           | -                                | -                                                              | 25°C                                           | 18169 |
| -                                                   | 0.197-0.259                                     | -                                | -                                                              | 200°C                                          | "     |
| 65.5*                                               | -                                               | -                                | -                                                              | -                                              | 6778  |
| -                                                   | -                                               | (S)-3.7                          | -                                                              | Arc melted                                     | 14991 |
| -                                                   | -                                               | (S)-1.2                          | -                                                              | Annealed                                       | "     |
| <u>NbB</u>                                          |                                                 |                                  |                                                                |                                                |       |
| 64                                                  | -                                               | -                                | -                                                              | -                                              | 11599 |
| <u>NbC</u>                                          |                                                 |                                  |                                                                |                                                |       |
| 51.1                                                | -                                               | (a)-4.0                          | -1.32**                                                        | -                                              | 3803  |
| 74.0                                                | 0.14                                            | -                                | -                                                              | 25°C, sin-<br>tered powder.                    | 18179 |
| 150.0                                               | -                                               | -                                | -                                                              | -                                              | 6778  |
| 204.0                                               | 0.134                                           | -                                | -                                                              | a-axis, poly-<br>crystalline,<br>dense powder. | 12288 |
| -                                                   | 0.14                                            | -                                | -                                                              | 25°C, sin-<br>tered powder.                    | 18169 |
| -                                                   | 0.37                                            | -                                | -                                                              | 1900°, S.P.                                    | "     |
| -                                                   | -                                               | (S)-9.4                          | -                                                              | Arc melted.                                    | 14991 |
| -                                                   | -                                               | "                                | -                                                              | Annealed.                                      | "     |

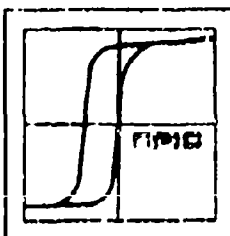
+  $\delta = +51.1 \times 10^{-23}$  (cm/V<sup>2</sup>sec<sup>2</sup>)

\*\*  $\delta = +11.4$  " "

$$\delta = \frac{R}{e\rho^2} = n_e \mu_e^2 - n_h \mu_h^2$$

n is the carrier concentration and  $\mu$  is the mobility

\* Thermal coefficient of resistivity.  $\alpha = +0.12$  (%/deg)



Section 2  
NIOBIUM-DORON

SEMICONDUCTING PROPERTIES

Electrical Resistivity

| At. % B             | ( $\mu\Omega$ -cm) | $\rho_{T_C}/\rho_{300}$ | Notes<br>Crystallography          | Samples                                                                                       | Ref.  |
|---------------------|--------------------|-------------------------|-----------------------------------|-----------------------------------------------------------------------------------------------|-------|
| 50                  | 9.72               | .0261                   | orthorhombic<br>$\beta$ -NbB type | Electron beam melted<br>& zone refined.<br>Impurities: Ta 2000<br>ppm, others <100 each.      | 12621 |
| 50(+3%<br>excess B) | 10.57              | .0279                   | "                                 | "                                                                                             |       |
| 55                  | 8.120              | .0345                   | Nb, NbB                           | Sintered in argon at<br>1700-1750°C. Impuri-<br>ties: Ta 500 ppm, Fe<br>100, others <50 each. |       |
| 59.3                | 14.76              | .0366                   | N, NbB <sub>2</sub>               | "                                                                                             |       |

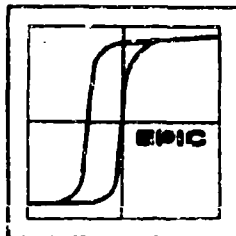
NIOBIUM-CARBON

SEMICONDUCTING PROPERTIES

Electrical and Thermal Properties

| Formula              | Lattice Constant<br>$a_0(\text{\AA})$ | Electrical<br>Resistivity<br>( $\mu\Omega$ -cm) | Thermal<br>Conductivity<br>$\kappa$ ( $10^{-2}$ W/cm <sup>2</sup> °K) | Thermoelectric Effect<br>( $\mu$ V/°K) |
|----------------------|---------------------------------------|-------------------------------------------------|-----------------------------------------------------------------------|----------------------------------------|
| NbC <sub>0.710</sub> | 4.431                                 | 171.7                                           | 9.0 $\pm$ 0.7                                                         | -1.9 $\pm$ 0.1                         |
| NbC <sub>0.750</sub> | -                                     | 150.0                                           | 9.7 $\pm$ 0.7                                                         | -2.1 $\pm$ 0.1                         |
| NbC <sub>0.808</sub> | -                                     | 151.9                                           | 10.2 $\pm$ 1.2                                                        | -3.4 $\pm$ 0.4                         |
| NbC <sub>0.855</sub> | -                                     | 135.2                                           | 10.7 $\pm$ 1.2                                                        | -5.8 $\pm$ 0.6                         |
| NbC <sub>0.908</sub> | 4.464                                 | 89.8                                            | 11.2 $\pm$ 0.7                                                        | -5.5 $\pm$ 0.3                         |

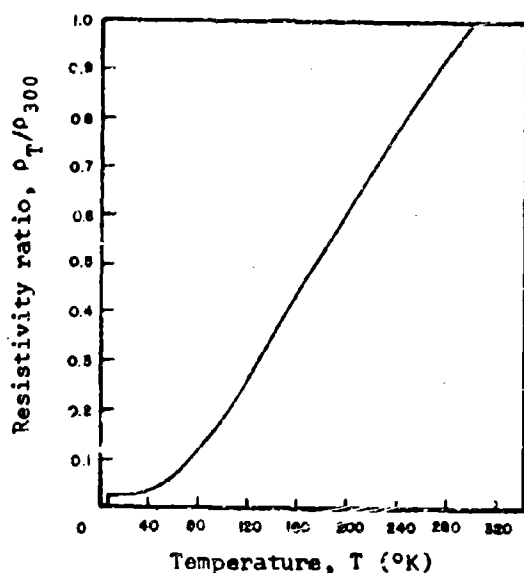
[Ref. 21271]



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Section 2  
NIOBIUM-BORON

ELECTRICAL RESISTIVITY



Resistivity ratio as a function of temperature for electron-beam melted, zone-refined NbB. Measurements on sintered samples show a similar curve.

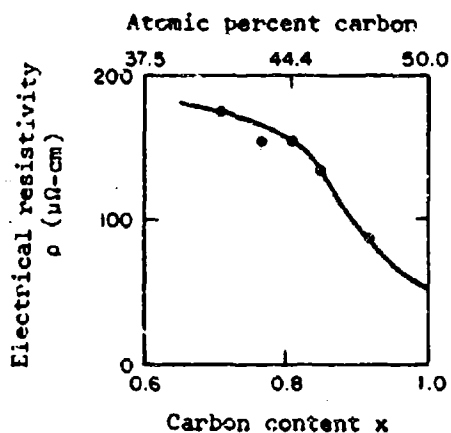
[Ref. 15336]

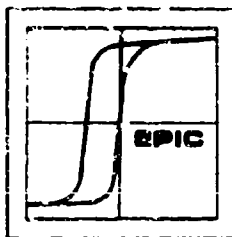
NIOBIUM-CARBON

ELECTRICAL RESISTIVITY

Electrical resistivity of  $NbC_x$ . Powders were pressed and sintered at  $10^{-4}$  -  $10^{-5}$  mm Hg and 2200-2400°C.

[Ref. 21271]



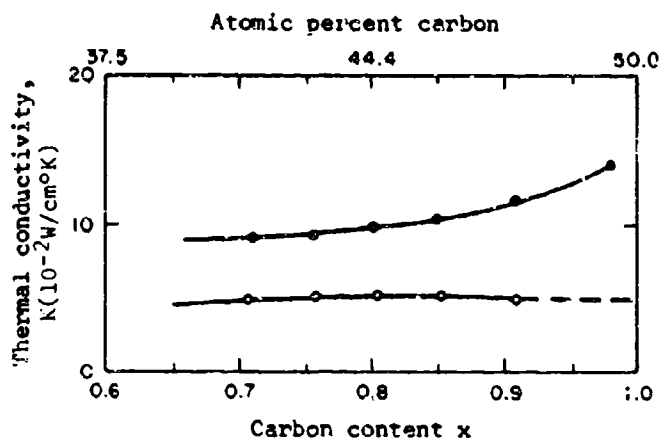


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## Section 2

### NIOBIUM-CARBON

#### THERMAL CONDUCTIVITY

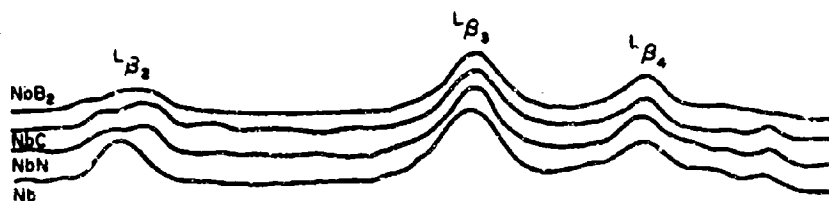


Thermal conductivity of  $\text{NbC}_x$  powders which were pressed and sintered at  $10^{-4}$  -  $10^{-5}$  mm Hg and  $2200$  -  $2400^\circ\text{C}$ .

[Ref. 21271]

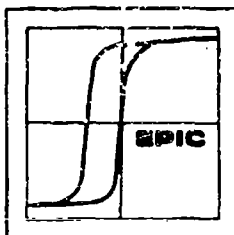
### NIOBIUM-BORON AND NIOBIUM-CARBON

#### PHOTON EMISSION PROPERTIES



The L series spectra for  $\text{NbB}_2$  and  $\text{NbC}$ . The curves for  $\text{NbN}$  and pure  $\text{Nb}$  are given for comparison.

[Ref. 16346]



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Section 2

NIOBIUM-BORON AND NIOBIUM-CARBON

PHOTON EMISSION PROPERTIES

L line intensities for Nb compounds.

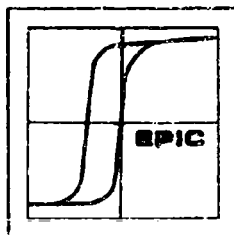
| <u>Line</u>                     | <u>Nb</u> | <u>NbN</u> | <u>NbC</u> | <u>NbB<sub>2</sub></u> |
|---------------------------------|-----------|------------|------------|------------------------|
| L <sub>c1</sub>                 | 100       | 100        | 100        | 100                    |
| L <sub>a2</sub>                 | 11        | 11         | 11         | 11                     |
| L <sub>β1</sub>                 | 60.0      | 60.5       | 61.0       | 62.0                   |
| L <sub>β3</sub>                 | 9.9       | 9.5        | 9.9        | 10.2                   |
| L <sub>β2</sub>                 | 5.3       | 4.0        | 4.0        | 3.5                    |
| L <sub>γ1</sub>                 | 2.0       | 1.47       | 1.48       | 1.40                   |
| N <sub>IV</sub>                 | 0.56      | 0.39       | 0.39       | 0.36                   |
| N <sub>V</sub>                  | 1.27      | 0.91       | 0.90       | 0.77                   |
| N <sub>IV</sub> +N <sub>V</sub> | 1.83      | 1.30       | 1.29       | 1.13                   |

[Ref. 16346]

Relative values of the variation of the L<sub>β2</sub> and L<sub>γ1</sub> lines for equal L<sub>β1</sub> intensities.

| <u>Line</u>     | <u>Nb</u> | <u>NbN</u> | <u>NbC</u> | <u>NbB<sub>2</sub></u> |
|-----------------|-----------|------------|------------|------------------------|
| L <sub>β2</sub> | 100       | 71.5       | 72.9       | 68.5                   |
| L <sub>γ1</sub> | 37        | 26.3       | 27         | 27.6                   |

[Ref. 16346]



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## Section 2

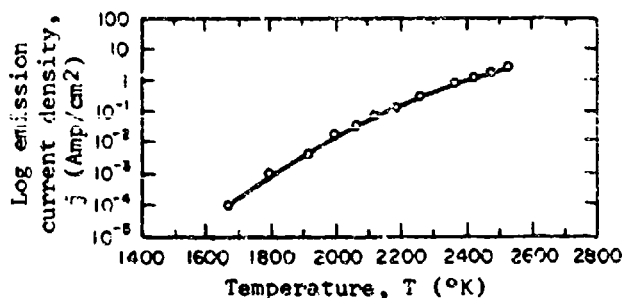
### NIOBIUM-BORON AND NIOBIUM-CARBON

#### THERMIONIC EMISSION PROPERTIES

| Work Function<br>$\phi$ (eV) | Richardson's Constant A<br>(Amp/cm <sup>2</sup> deg <sup>2</sup> ) | Current Density<br>$J_c$ (Amp/cm <sup>2</sup> ) | Notes  | Ref.  |
|------------------------------|--------------------------------------------------------------------|-------------------------------------------------|--------|-------|
| <u>NbC</u>                   |                                                                    |                                                 |        |       |
| 2.23                         | $\sim 10^{-5}$                                                     | -                                               | -      | 11031 |
| 4.02                         | -                                                                  | -                                               | 300°K  |       |
| 3.74                         | -                                                                  | -                                               | 1400°K |       |
| 3.72                         | -                                                                  | -                                               | 1800°K |       |
| 3.58                         | -                                                                  | 3.6                                             | 2000°K |       |
| <u>NbB<sub>2</sub></u>       |                                                                    |                                                 |        |       |
| 3.65                         | -                                                                  | -                                               | -      | 16424 |

### NIOBIUM-CARBON

#### THERMIONIC EMISSION PROPERTIES



Emission current density for niobium carbide  $\sim 100\mu$  thick, based on (1)  $30\mu$  strips of tungsten and tantalum and (2) tungsten and tungsten carbide wires. The properties show little dependence on the base. The samples were treated and measurements taken after heating to 2400°K.

#### Heating

1500 - 1800°K  
1800 - 2400°K

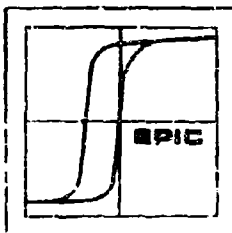
#### Work Function

reduced from 4.4 to 3.8 ev  
raised from 3.6 to 4.2 ev

[Ref. 19231]

SECTION 2  
NIOBIUM-CARBON-  
NITROGEN SYSTEMS



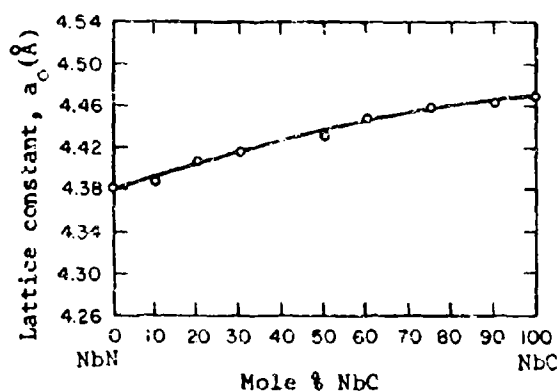


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## NIOBIUM ALLOYS AND COMPOUNDS

### NIOBIUM-CARBON-NITROGEN

#### GENERAL

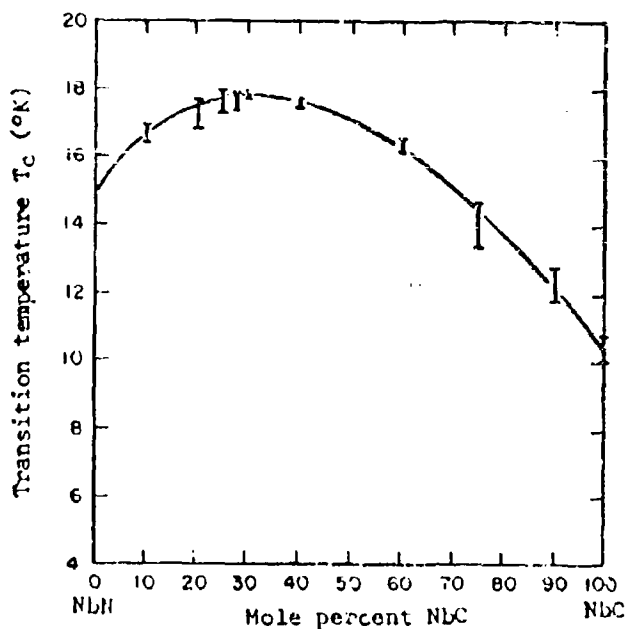


Lattice constants for the NbN-NbC system. The samples were cold pressed compacts, sintered between 2000-2400°C in nitrogen.

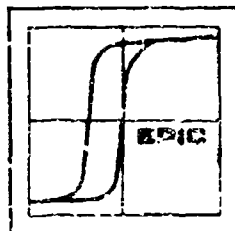
[Ref. 21840]

#### TRANSITION TEMPERATURE

Transition temperature for the system NbN-NbC. Samples were cold pressed and sintered 2000 - 2400°C in nitrogen.

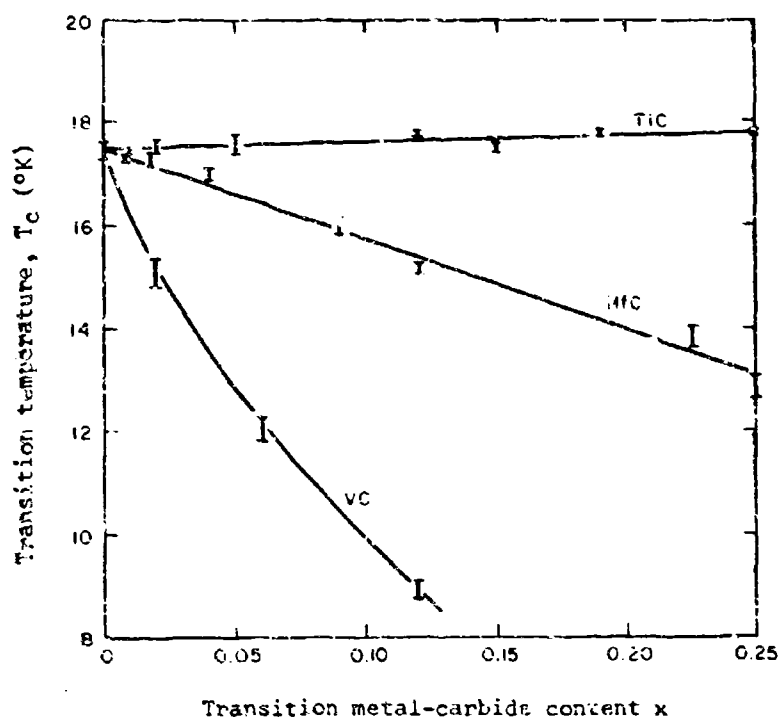


[Ref. 21844]



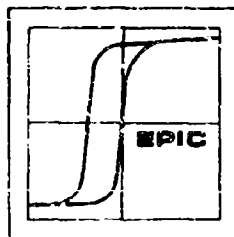
NIOBIUM-CARBON-NITROGEN-M

TRANSITION TEMPERATURE



Transition temperature for the system  
 $(\text{NbN})_{0.75}(\text{NbC})_{0.25-x}(\text{MC})_x$   
where M is Ti, Hf or V.

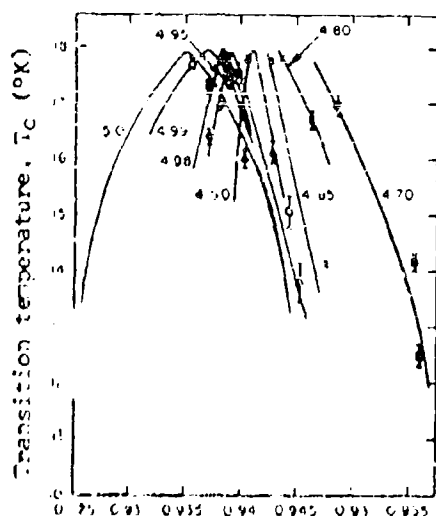
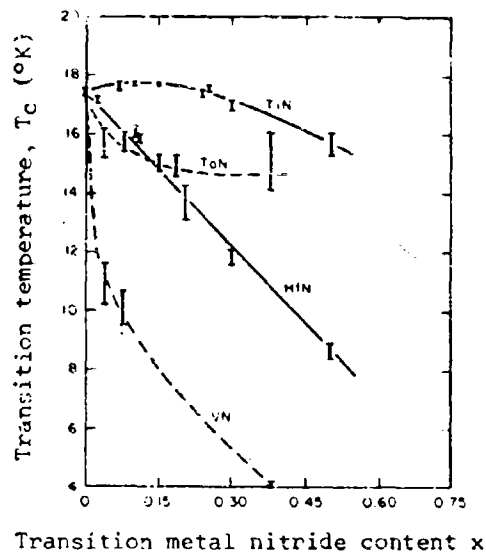
[Ref. 21844]



# NIOBIUM-CARBON-NITROGEN-M

## TRANSITION TEMPERATURE

Transition temperature for the system  
 $(\text{NbN})_{0.75-x}(\text{NbC})_{0.25}(\text{MN})_x$  where M is  
Ti, Ta, Hf, or V.



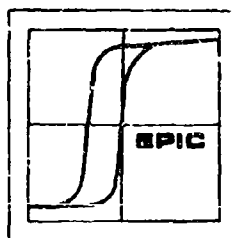
Transition temperature for pseudo-binary and  
ternary nitride-carbide compounds. The num-  
bers represent the e/a ratio for the compound.

### ALLOY SYSTEMS STUDIED      TRANSITION METAL e/a RATIO

|             |      |
|-------------|------|
| NbN-NbC-TiC | 4.99 |
| NbN-NbC-TiN | 4.98 |
| NbN-NbC-HfC | 4.95 |
| NbN-NbC-HfN | 4.90 |
| NbN-ZrN-TiN | 4.90 |
| NbN-ZrN     | 4.90 |
| NbN-TiC     | 4.85 |
| NbN-NbC     | 4.80 |
| NbN-NbC     | 4.70 |

Effective diam. of transition metal in compound

[Ref. 21844]



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# NIOSIUM-CARBON-NITROGEN

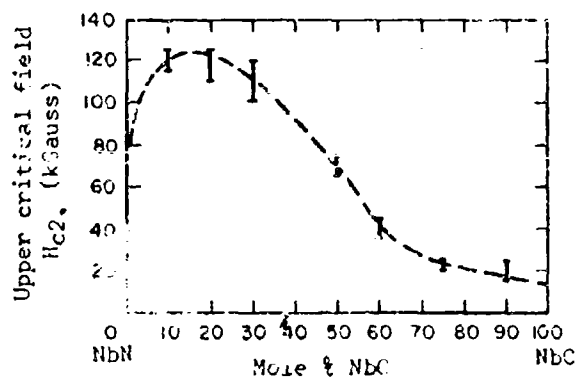
## TRANSITION TEMPERATURE

| Compound                            | Transition Temperature<br>$T_c(^{\circ}\text{K})$ | Notes                                                   | Ref.  |
|-------------------------------------|---------------------------------------------------|---------------------------------------------------------|-------|
| NbC/NbN†                            | 8.5 - 17.3                                        | Whiskers 2 $\mu$ -100 $\mu$ diam,<br>[111] orientation. | 21847 |
| NbC <sub>0.3</sub> N <sub>0.7</sub> | 17.8                                              | -                                                       | 21844 |
| NbN-NbC-NbO                         | >20                                               | Prepared by chemical<br>vapor deposition.               | 21843 |

†  $\rho(20^{\circ}\text{K}) = 6 \times 10^{-5} \Omega\text{-cm}$

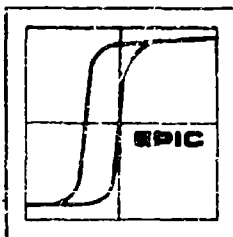
# NIOSIUM-CARBON-NITROGEN

## CRITICAL FIELD



Upper critical field for NbN-NbC system. The samples were cold pressed compacts, sintered between 2000-2400 $^{\circ}\text{C}$  in nitrogen.

[Ref. 21840]

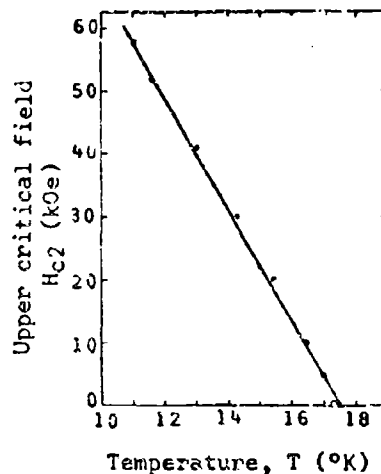


# NIOBIUM-CARBON-NITROGEN

## CRITICAL FIELD

Upper critical field for a 5.8μ diam. NbC/NbN whisker as a function of temperature. These mixed structures were formed in the [111] direction when carbon and nitrogen were both present. [Ref. 21847]

$$\left(\frac{dH_{C2}}{dT}\right)_{T_C} = -9 \text{ kOe/}^\circ\text{K}$$



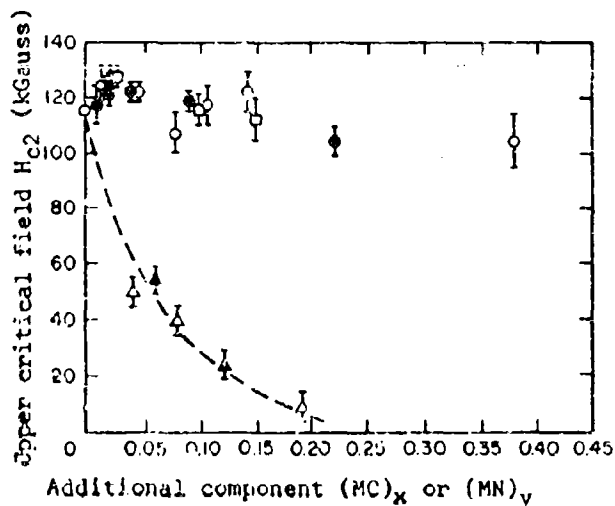
# NIOBIUM-CARBON-NITROGEN-M

## CRITICAL FIELD

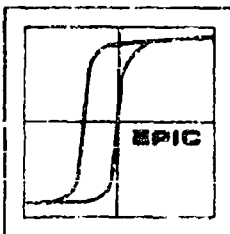
For the following graph the samples were cold pressed compacts, sintered between 2000-2400 in nitrogen.

The upper critical field for the following systems (NbN)<sub>0.75</sub>(NbC)<sub>0.25-x</sub>(MC)<sub>x</sub> or (NbN)<sub>0.75-y</sub>(NbC)<sub>0.25</sub>(MN)<sub>y</sub> as a function of the additional component.

|               |               |
|---------------|---------------|
| ○ NbN-NbC-HfN | ● NbN-NbC-HfC |
| ○ NbN-NbC-TiN | ● NbN-NbC-TiC |
| △ NbN-NbC-VN  | △ NbN-NbC-VC  |



[Ref. 21844]



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# NIOBIUM-CARBON-NITROGEN

## CRITICAL FIELD

| Compound                             | Critical Field (kOe) |       |              | Notes                                                   | Ref.  |
|--------------------------------------|----------------------|-------|--------------|---------------------------------------------------------|-------|
|                                      | $H_{c1}$             | $H_c$ | $H_{c2}$     |                                                         |       |
| NbC/NbN                              | .1                   | 1.7   | $\sim 110^*$ | Whiskers 2 $\mu$ -100 $\mu$ diam,<br>[111] orientation. | 21847 |
| NbC <sub>0.2</sub> Nb <sub>0.8</sub> | -                    | -     | 120          | -                                                       | 21847 |

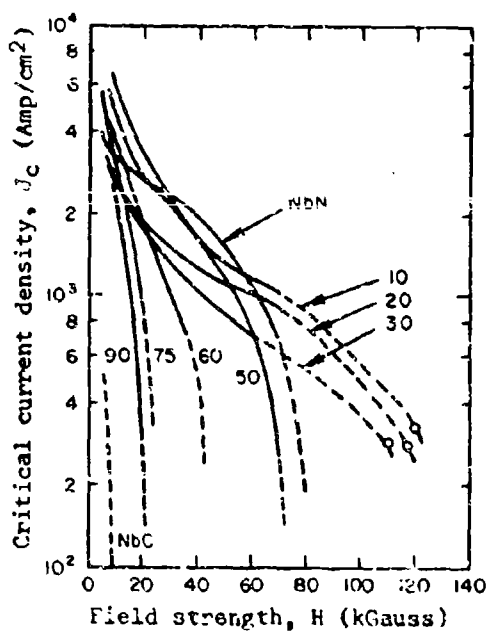
$$* \left( \frac{dH_{c2}}{dT} \right)_{T_c} = -9 \left( \frac{kOe}{^{\circ}K} \right)$$

# NIOBIUM- CARBON-NITROGEN

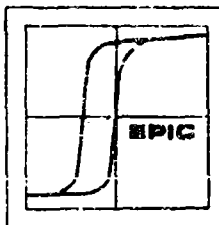
## CURRENT DENSITY

Critical current density for NbN-NbC system as a function of field strength for different mole percentages of NbC. The samples were cold-pressed compacts, sintered between 2000-2400°C in nitrogen atmosphere.

o pulsed field data



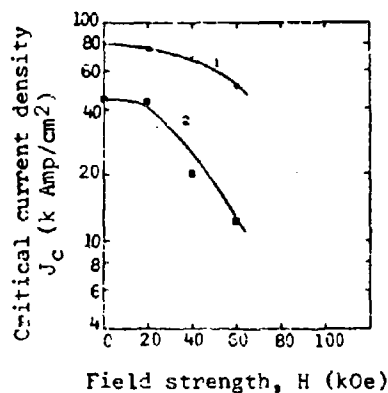
[Ref. 21840]



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# NIOBIUM-CARBON-NITROGEN

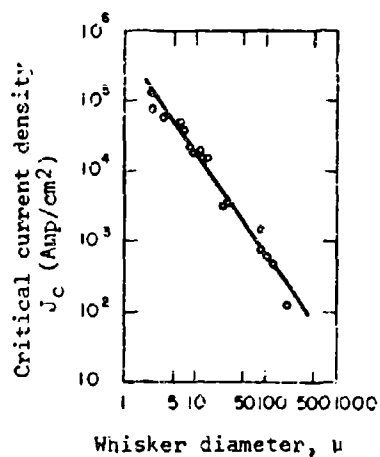
## CURRENT DENSITY



Critical current density as a function of field strength for NbC/NbN, [111] oriented whiskers. Data taken at 4.2°K.

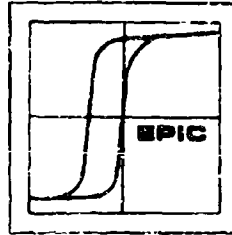
- 1) 3.5μ diameter
- 2) 5.8μ diameter

[Ref. 21847]



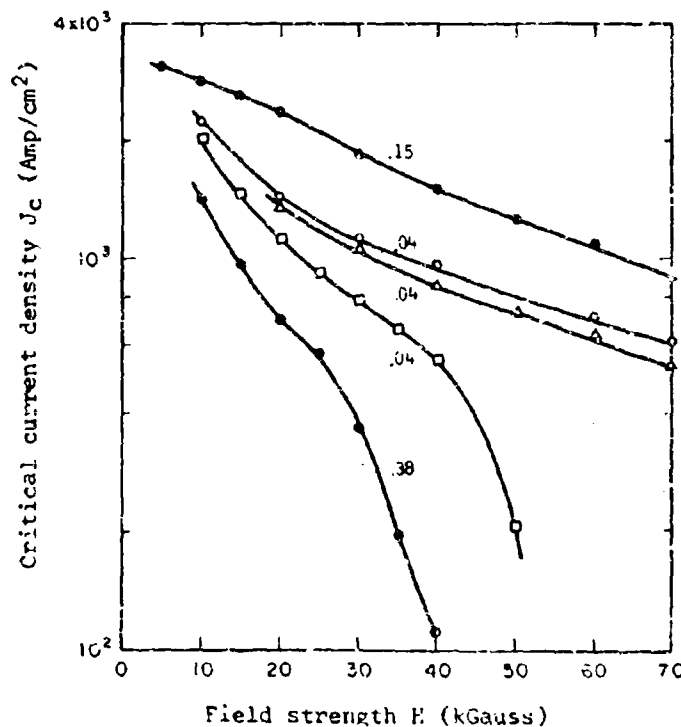
Critical current density for NbC/NbN, [111] oriented whiskers, as a function of sample diameter. Measurements are taken at 4.2°K.

[Ref. 21847]



NIOBIUM-NITRIDE-NITROGEN-M

CURRENT DENSITY

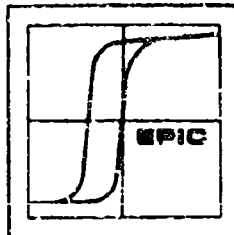


Critical current density for the system  $(\text{NbN})_{0.75-x}(\text{NbC})_{0.25}(\text{MN})_x$  as a function of field strength, where M is Hf, V or Ti. The numbers on the curves represent the transition metal nitride content in x.

- NbN-NbC
- △ NbN-NbC-HfN
- NbN-NbC-VN
- NbN-NbC-TiN

[Ref. 21644]



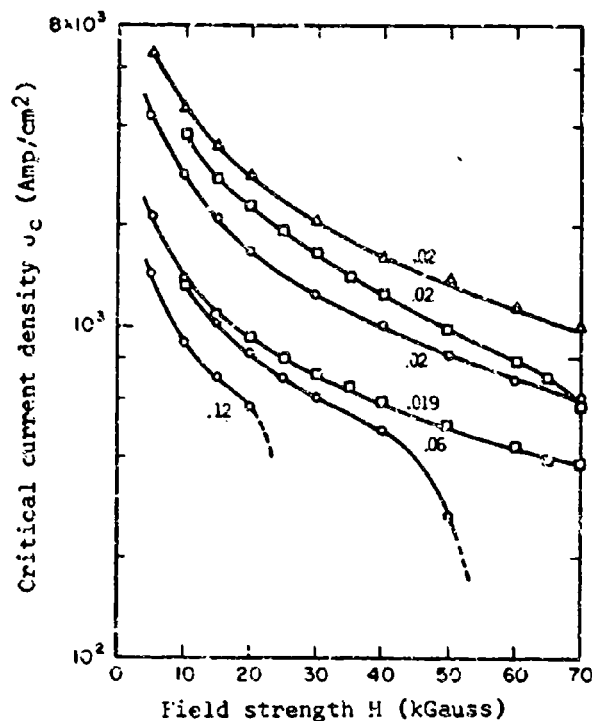


# NIOBIUM-CARBON-NITROGEN-M

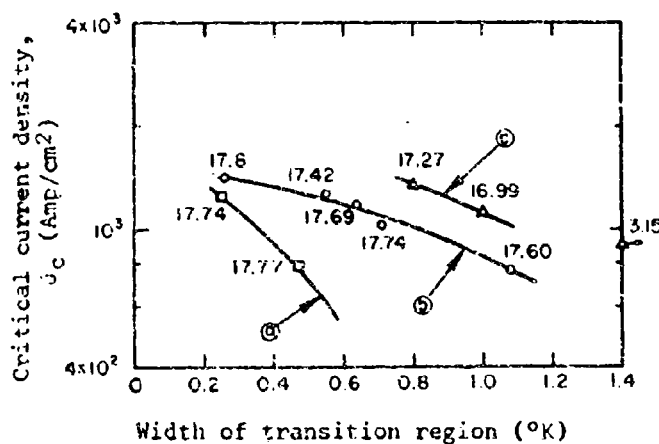
## CURRENT DENSITY

Critical current density for the system  $(\text{NbN})_{0.75}(\text{NbC})_{0.25-x}(\text{MC})_x$  where M is Ti, Hf or V. The numbers on the curves represent the transition metal carbide content in x.

- TiC
- △ HfC
- VC



[Ref. 21844]

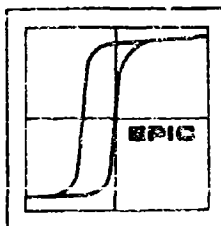


The critical current density is given for three pseudo-ternary compounds and is plotted against the width of the transition region. This region of transition is an indication of the deviation from stoichiometry. The numbers indicate the midpoints of the regions.

- (a) NbN-NbC-TiN
- (b) NbN-NbC-TiC
- (c) NbN-NbC-HfC

[Ref. 21844]

SECTION 2  
NIOSIUM-NITROGEN &  
NIOBIUM-OXYGEN SYSTEMS



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## NIOBIUM ALLOYS AND COMPOUNDS

### NIOBIUM-NITROGEN AND NIOBIUM-OXYGEN SYSTEMS

#### GENERAL

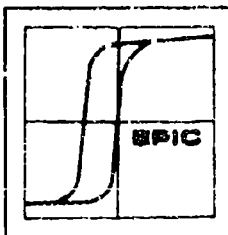
Nb-N The transition temperature for a niobium-nitrogen system in the  $Nb_{1.0}N_{1.0}$  region is near 16°K. As the nitrogen content is reduced to the  $Nb_2N$  region,  $T_c$  apparently decreases to zero. With further reduction of the nitrogen content, the transition temperature begins to rise and approaches that of pure niobium.

Two notations have been used to differentiate the various compounds in the niobium-nitrogen systems. Brauer and Jander (20714) in their 1952 work assign the following notations NbN(I), NbN(II), and NbN(III) to the compositions  $NbN_{1.0}$ ,  $NbN_{\sim 0.95}$ , and  $NbN_{\sim 0.87-0.94}$  respectively. Schoenberg in 1954 uses the following naming scheme:

|                |                        |
|----------------|------------------------|
| $\alpha$ phase | Nb+N                   |
| $\beta$        | $NbN_{0.40-0.50}$      |
| $\gamma$       | $NbN_{\sim 0.80-0.90}$ |
| $\delta$       | $NbN_{\sim 0.95}$      |
| $\epsilon$     | $NbN_{1.00}$           |

The exact nature of the transition from normal to superconducting state is in doubt in two composition regions. First near the  $NbN_{1.00}$  Schroeder [9655] claims that  $T_c$  drops below 1.94°K. Rogener composition data do not show this effect, and two earlier papers, Ziegler and Young (13390) and Milton (19468), can not claim an exact  $NbN_{1.00}$  composition for their samples. Schroeder cites data from Brauer stating that at lower temperatures of formation, the NbN(I), NbN(II) and NbN(III) regions are broadened by beginning the sample preparation at lower nitrogen content.

The other area of doubt is found in the  $Nb_2N$  region. No experimental evidence can be found for a transition temperature above 1.94°K [9655]. However,



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## NIBIUM-NITROGEN AND NIOBIUM-OXYGEN SYSTEMS

### GENERAL

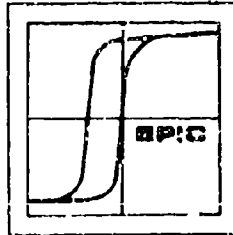
Samsonov and Neshpor [10725] predict  $T_c = 9.5^\circ\text{K}$  for  $\text{Nb}_2\text{N}$  based upon a relationship between  $T_c$  and  $\frac{1}{Nn}$  where  $N$  is the principle quantum number and  $n$  is the number of electrons of the incomplete d-level.

The following value is given for  $\text{NbN}$ , [21847]

$$\frac{dH_{c2}}{dT_c} = -10 \frac{\text{kOe}}{^\circ\text{K}}$$

**Nb-O** Three distinct niobium oxides are formed,  $\text{NbO}$  (14.69 wt.% O),  $\text{NbO}_2$  (25.89 wt.% O) and  $\text{Nb}_2\text{O}_5$  (30.09 wt.% O). However, none of these show any promise as superconducting materials. An attempt to find the transition temperature of  $\text{NbO}$  has failed to show a  $T_c$  above  $1.2^\circ\text{K}$  (9695). Below the solubility limit of oxygen in niobium, i.e., from .25 to 1.0 wt.% oxygen, the solid solution  $\text{Nb-O}$  shows superconducting characteristics.

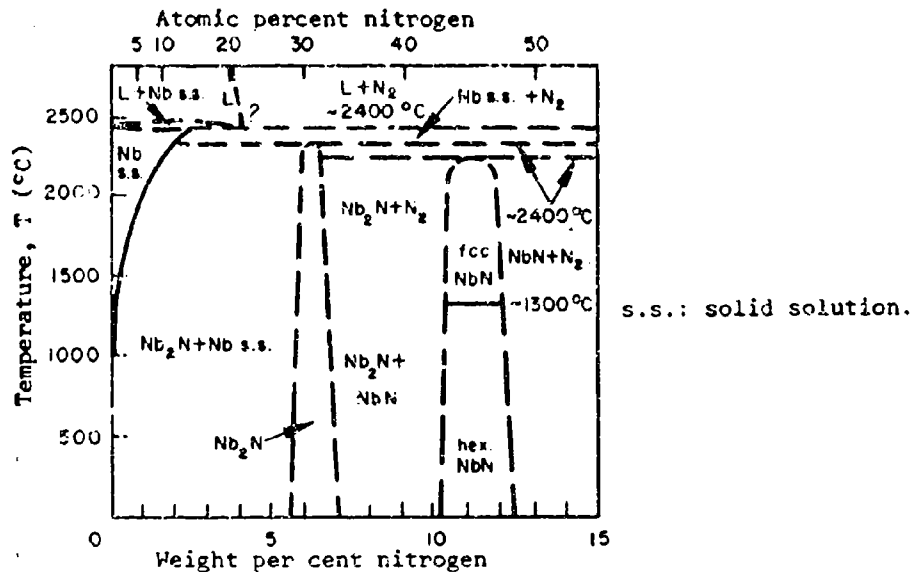
Samples up to .75 wt.% Oxygen were prepared by a gas absorption and diffusion technique. In the region of 1 wt.% O and above the samples were prepared by arc-melting  $\text{Nb}_2\text{O}_5$  with Nb.



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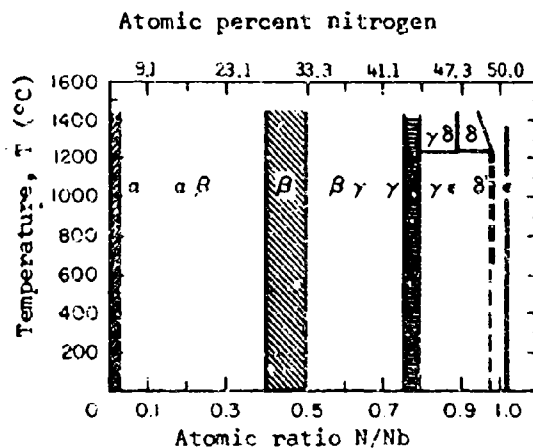
# NIOBIUM-NITROGEN

## GENERAL



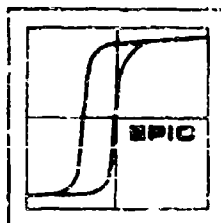
Probable phase diagram for niobium-nitrogen system  
at a pressure of one atmosphere nitrogen

[Ref. 19928]



Tentative phase diagram for the niobium-nitrogen system.

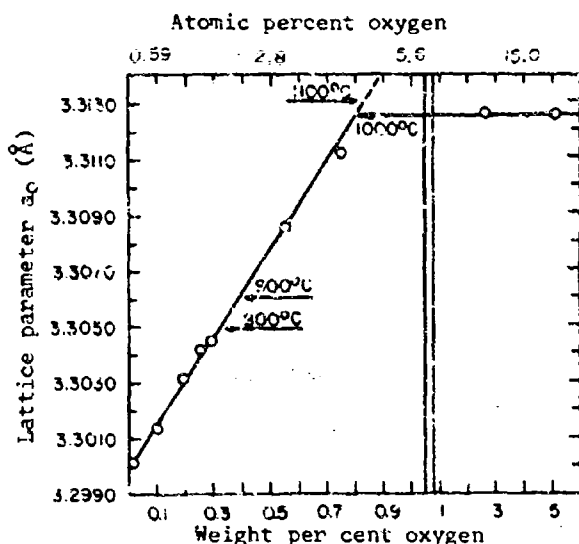
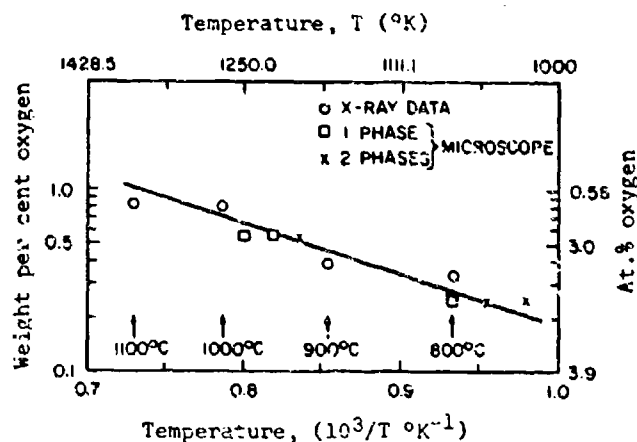
[Ref. 20719]



# NIOBIUM-OXYGEN

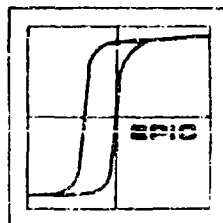
## GENERAL

Solubility of oxygen in niobium. The x-ray data were checked by metallographic examination on two samples: .25 wt.% O and .55 wt.% O.



Lattice parameters for the niobium-oxygen system. Up to .75% oxygen gas absorption and diffusion methods were used to prepare the samples. Above this region Nb and Nb<sub>2</sub>O<sub>5</sub> were melted together to form the samples.

[Ref. 21113]



# NIOBIUM-NITROGEN

## GENERAL

### Lattice Constants

| At. % N | Phase          | Symmetry      | Lattice Constants (Å) |        | Notes                                     | Ref.  |
|---------|----------------|---------------|-----------------------|--------|-------------------------------------------|-------|
|         |                |               | $a_0$                 | $c_0$  |                                           |       |
| 0       | $\alpha$       | bcc           | 3.3014 ± .0002        | -      | -                                         | 20714 |
| 15.9    | $\alpha+\beta$ | hcp           | 3.056                 | 4.956  | -                                         |       |
| 32.4    | $\beta$        | tetr          | 3.056                 | 4.964  | -                                         |       |
| 42.9    | "              | tetr deformed | 4.384                 | 4.311  | -                                         |       |
| 44.4    | "              | "             | 4.385                 | 4.332  | -                                         |       |
| 44.4    | $\gamma$       | hex           | 2.950                 | 2.772  | -                                         |       |
| 44.5    |                | fcc           | 4.39                  | -      | 4200 psi pressed powder, double sintered. | 18467 |
| 45.0    |                | tetr deformed | 4.387                 | 4.330  | -                                         | 20714 |
| 46.5    |                | fcc           | 4.386                 | -      | Powder sample in pumped N at 1300°C       | "     |
| 47.3    |                | hex           | 2.958                 | 2.779  | -                                         | 20627 |
| 48.4    |                | fcc           | 4.389                 | -      | -                                         | 20714 |
| 48.7    | $\delta$       | hex           | 2.968                 | 5.535  | -                                         | 20627 |
| 50.0    | $\epsilon$     | "             | 2.956                 | 11.275 | -                                         | 20714 |

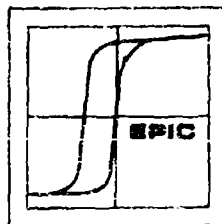
# NIOBIUM-OXYGEN

## GENERAL

The lattice constants for monoclinic  $\alpha\text{-Nb}_2\text{O}_5$  are given:

$$\begin{aligned} a_0 &= 21.34 \text{ Å} \\ b_0 &= 3.816 \text{ Å} \\ c_0 &= 19.47 \text{ Å} \\ \beta &= 120^\circ 2' \end{aligned}$$

[Ref. 17444]



NIOBIUM-NITROGEN

TRANSITION TEMPERATURE

Transition Temperature

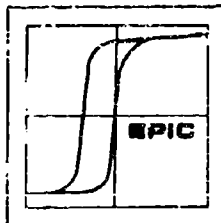
| At. % N | Transition Temperature $T_C$ (°K) |       |          |       | Notes                                     | Ref.   |
|---------|-----------------------------------|-------|----------|-------|-------------------------------------------|--------|
|         | Midpoint                          | Width |          |       |                                           |        |
|         |                                   | Onset | Complete | *     |                                           |        |
| 0       | 8.97                              | 9.4   | 8.5      | -     | -                                         | 9655†  |
| .23     | -                                 | -     | -        | 9.2   | Wire, electron beam melted, heated in N.  | 13366  |
| 16.0    | 5.72                              | 7.2   | -        | -     | -                                         | 9655   |
| 32.4    | -                                 | <1.94 | -        | -     | -                                         | "      |
| 37.5    | 3.8                               | 6.1   | <1.94    | -     | -                                         | 9617** |
| 39.1    | -                                 | -     | -        | 10.8  | -                                         |        |
| 40.1    | -                                 | -     | -        | 10.3  | -                                         |        |
| 42.1    | -                                 | -     | -        | 11.0  | -                                         |        |
| 42.3    | -                                 | -     | -        | 12.7  | -                                         |        |
| 42.8    | 7.2                               | -     | -        | -     | Powder heated in N to 1450°C.             | 9695   |
| 43.2    | -                                 | -     | -        | 13.6  | -                                         | 9617   |
| 44.0    | -                                 | -     | -        | 11.8  | -                                         | "      |
| 44.4    | 7.12                              | 9.7   | 5.2      | -     | -                                         | 9655   |
| 44.6    | -                                 | -     | -        | 12.6  | -                                         | 9617   |
| 45.1    | 8.66                              | 10.6  | 6.4      | -     | -                                         | 9655   |
| 45.4    | 15.0                              | 16.2  | 12.2     | -     | Powder Nb, 16 atm N, 1450°C 5 hours.      | 18726  |
| 46.5    | -                                 | -     | -        | 15.98 | -                                         | 9617   |
| 47.3    | -                                 | 15.25 | 14.7     | -     | Powder 1300°C N stream.                   | 9239   |
| 47.7    | -                                 | -     | -        | 14.13 | -                                         | 9617   |
| 48.4    | <1.94                             | 10.62 | -        | -     | -                                         | 9655   |
| 48.6    | -                                 | -     | -        | 15.59 | -                                         | 9617   |
| 48.7    | -                                 | -     | -        | 14.7  | -                                         |        |
| 48.8    | -                                 | -     | -        | 14.57 | -                                         |        |
| 49.0    | -                                 | -     | -        | 15.63 | -                                         |        |
| 49.4    | 15.2                              | 16.2  | 13.5     | -     | Powder Nb, 1 atm N, 1300°C 3 hours.       | 18726  |
| 49.7    | -                                 | -     | -        | 15.23 | -                                         | 9617   |
| ~50.0   | -                                 | -     | -        | <1.94 | -                                         | 9655   |
|         | 15.940                            | -     | -        | -     | Ammonia 1350-1500°, 20 min.               | 19468  |
|         | -                                 | 15.0  | 14.0     | -     | Stationary N, 1500°C, 1 hour.             |        |
|         | 16.0                              | 16.7  | 14.6     | -     | Nb heated 4-4.5 hours at 1500°C in dry N. | 13390  |

\* Values in this column are not identified by their position in the transition curve.

\*\* Sample specs are found on page 48-49

† Sample specs are found on page 52





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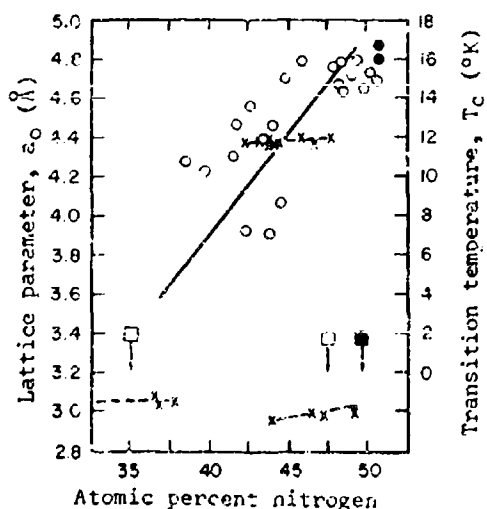
NIOBIUM NITROGEN

TRANSITION TEMPERATURE

Transition Temperature  
(Continued)

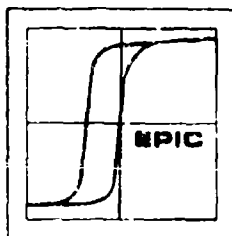
| At. % N | Transition Temperature $T_c$ (°K) |       |          |       | Notes                                                                                                          | Ref.  |
|---------|-----------------------------------|-------|----------|-------|----------------------------------------------------------------------------------------------------------------|-------|
|         | Midpoint                          | Width |          | *     |                                                                                                                |       |
|         |                                   | Onset | Complete |       |                                                                                                                |       |
| ~50.0   | -                                 | 9.0   | 6.0      | -     | Film sputtered. DC argon glow discharge in $\sim 2 \times 10^{-2}$ torr at 2 Å/sec. Polished quartz substrate. | 20528 |
| 50.3    | -                                 | -     | -        | 14.47 |                                                                                                                | 9617  |
| 50.7    | -                                 | -     | -        | 15.30 |                                                                                                                |       |
| 51.2    | -                                 | -     | -        | 14.93 |                                                                                                                |       |

\* Values in this column are not identified by their position in the transition curve.



A plot of data from preceding tables, showing the relationship of lattice constant  $a_0$  and transition temperature to nitrogen content. All curves are least squares approximations.

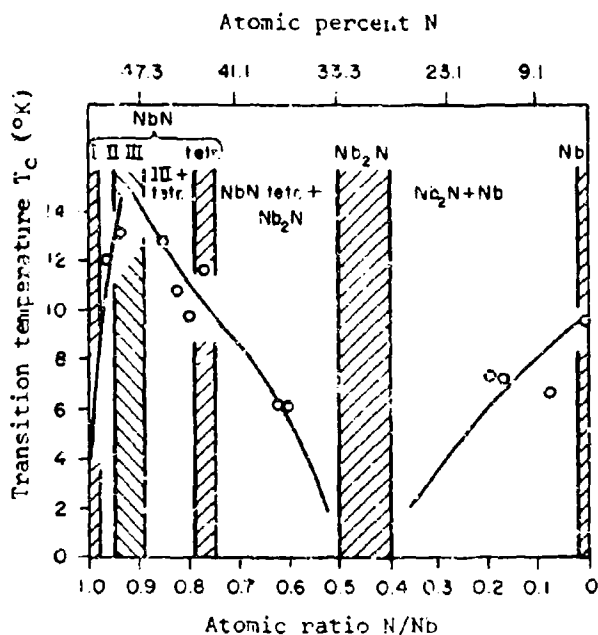
- x - - - - -  $a_0$
- - - - - -  $T_c$
- $T_c < 1.94$
- $T_c$  with the exact N content in doubt



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# NIOBIUM-NITROGEN

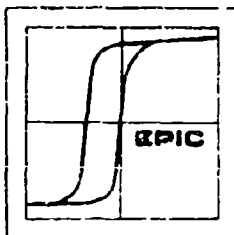
## TRANSITION TEMPERATURE



Temperatures at which the transition region begins at i.e., the onset of superconductivity, for the Nb-N system.

[Ref. 9655]

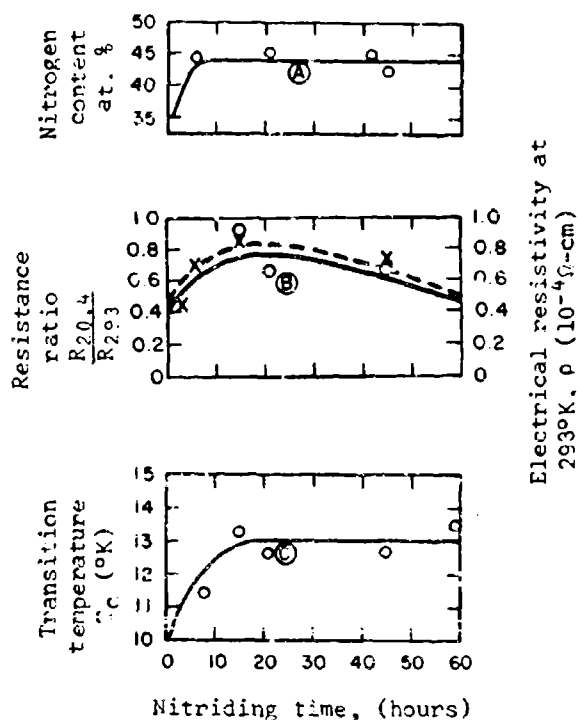
Two conditions during preparation of niobium nitride will affect its properties, first the nitrogen pressure and second the time the sample is left in the nitrogen atmosphere. The two sets of graphs which follow show the effects of these two parameters on the properties of the sample.



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# NIOBIUM-NITROGEN

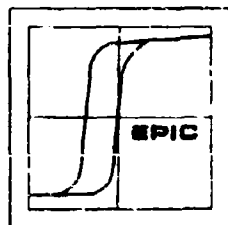
## TRANSITION TEMPERATURE



The effect of time in the nitrogen atmosphere on the properties of niobium-nitrogen systems.

- A) nitrogen content
- B) o ——— o, electrical resistivity  
x - - - x, resistance ratio
- C) transition temperature

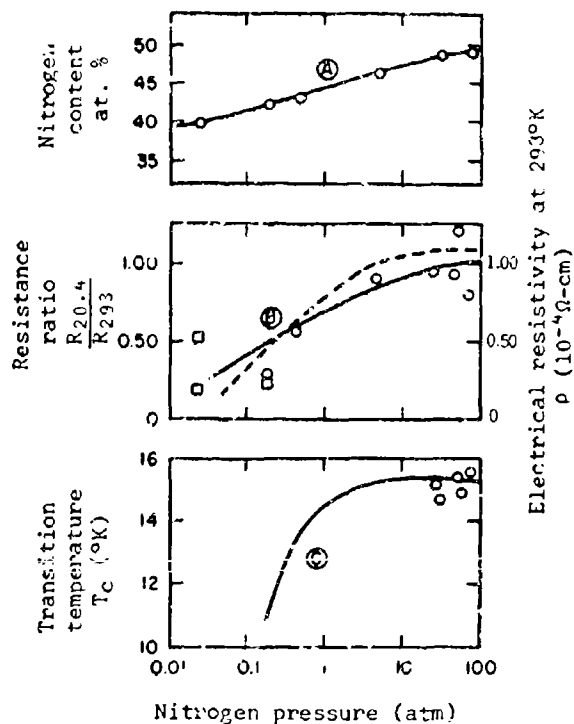
[Ref. 9617]



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# NIOBIUM-NITROGEN

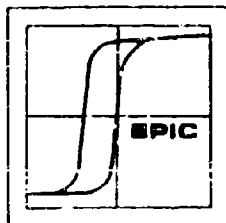
## TRANSITION TEMPERATURE



The effect of nitrogen pressure during preparation,  
on the properties of niobium-nitrogen systems.

- A) nitrogen content
- B)  $\circ$  —  $\circ$ , electrical resistivity  
x - - - x, resistance ratio
- C) transition temperature

[Ref. 9617]

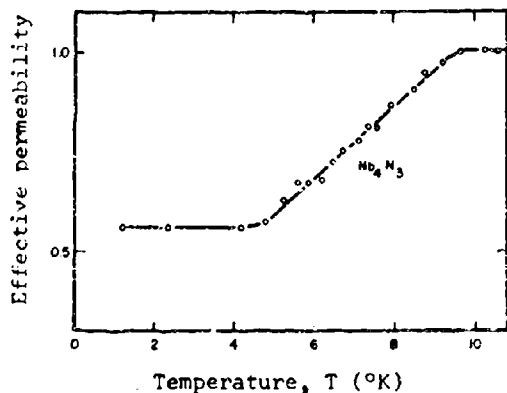
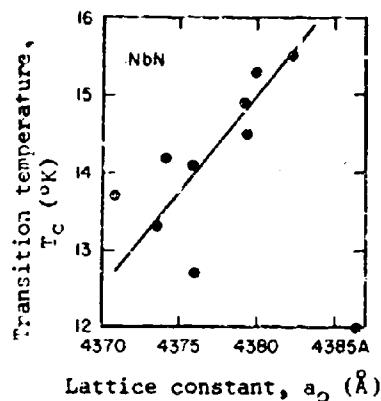


# NIOBIUM-NITROGEN

## TRANSITION TEMPERATURE

Transition temperature as a function of lattice constant for fcc niobium nitride.

[Ref. 9617]



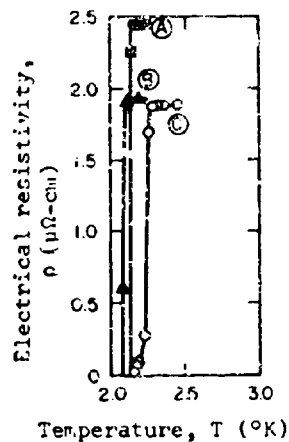
Transition curve for tetragonal  $Nb_4N_3$  in a 26 Oe field.

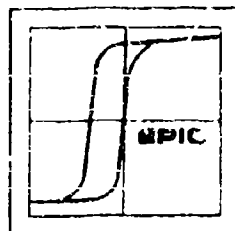
[Ref. 9695]

Electrical resistivity as a function of temperature for:

- A) 0.33 at.% N, He quenched
- B) 0.33 at.% N, vacuum quenched
- C) 1.64 at.% N, vacuum quenched

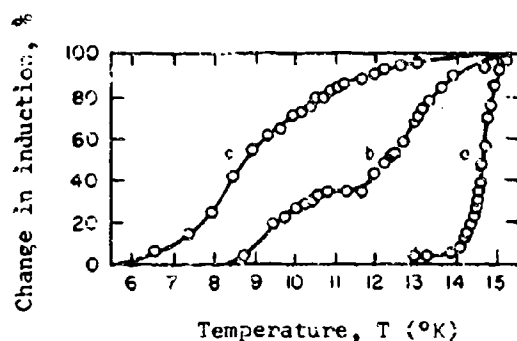
[Ref. 13366]





# NIOBIUM-NITROGEN

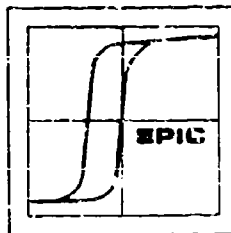
## TRANSITION TEMPERATURE



Transition curves for three niobium nitride samples:

- (a) 47.2 at.% N, prepared in nitrogen stream for not less than 8 hours at 1350°C. Data taken on warming and cooling.
- (b) 44.0 at.% N, prepared in static N for not less than 8 hours at 1200°C. Data taken on warming only.
- (c) 27.2 at.% N, prepared in static N for not less than 8 hours at 1180°C. Data taken on warming only.

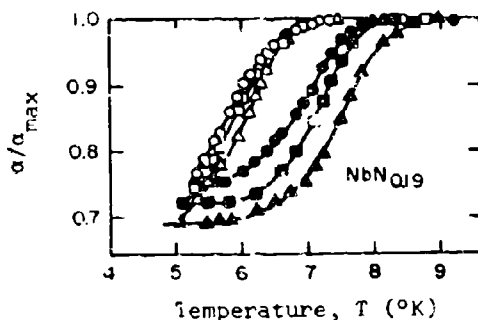
[Ref. 9299]



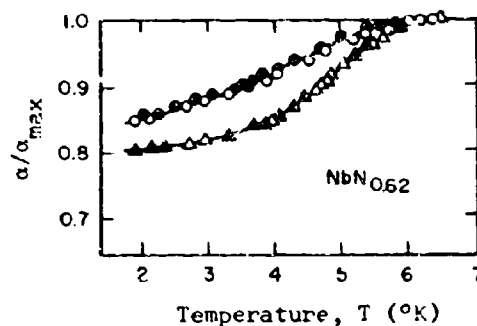
# NIOBIUM-NITROGEN

## TRANSITION TEMPERATURE

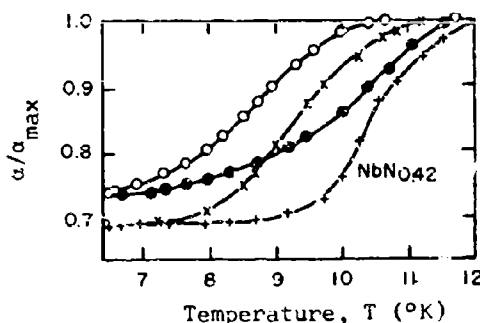
Transition curves for niobium-nitrogen systems.



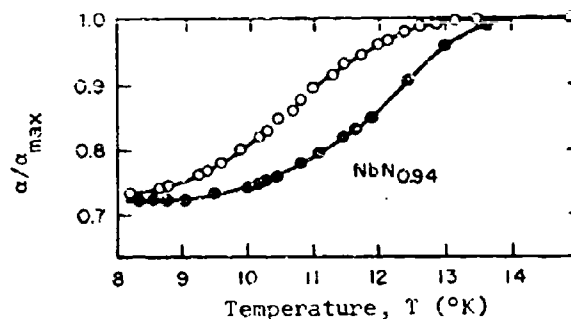
Nb added to NbN and treated 3 hrs. at 1450°C in one atmosphere pressure argon; hcp structure.



Nb added at NbN and treated 3 hrs at 1450°C in one atmosphere pressure argon; tetragonal structure.



Powdered Nb in stationary N at one atmosphere pressure, 4-5 hrs., 1300-1450°C; tetragonal structure.

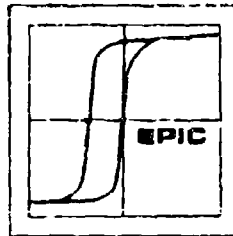


Powdered Nb in stationary N at one atmosphere pressure, 4-5 hrs., 1300-1450°C; fcc structure.

WARMING COOLING FIELD (Oe)

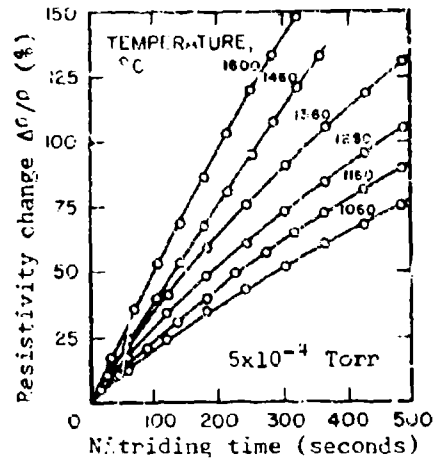
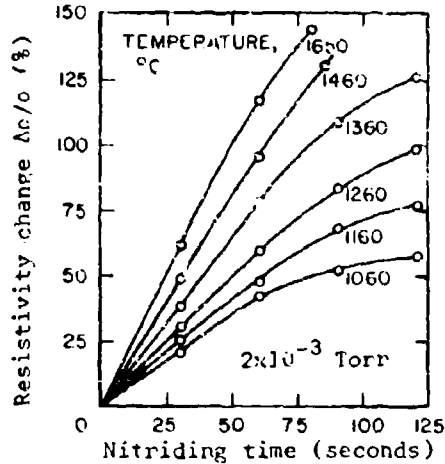
|   |   |      |
|---|---|------|
| ○ | ● | 1450 |
| □ | ■ | 1090 |
| △ | ▲ | 72.5 |
| x | + | 36.2 |

[Ref. 9655]



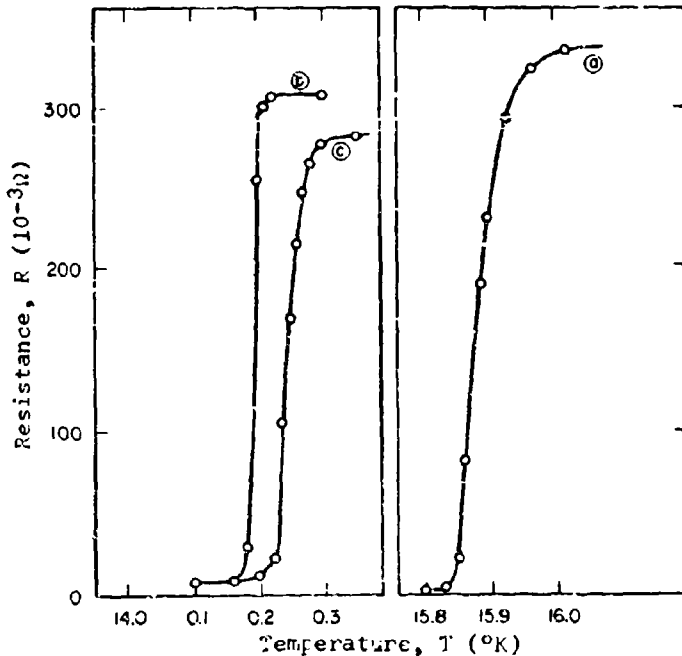
# NIOBIUM-NITROGEN

## TRANSITION TEMPERATURE



Change in resistivity as a function of nitriding time, temperature, and pressure. Data were taken at 10°C,  $\rho_{10^\circ\text{C}} = 13.96 \text{ } (\mu\Omega\text{-cm})$ .

[Ref. 21850]

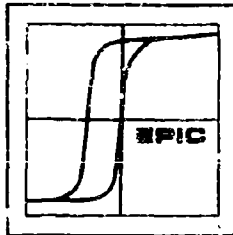


Superconductive transition of three niobium nitride samples:

- a. Prepared in ammonia, 20 minute, at 1350-1500°C.
- b. Prepared in nitrogen, 1 hour at 1500°C.
- c. Prepared in nitrogen, 1 hour at 1500°C.

[Ref. 19468]



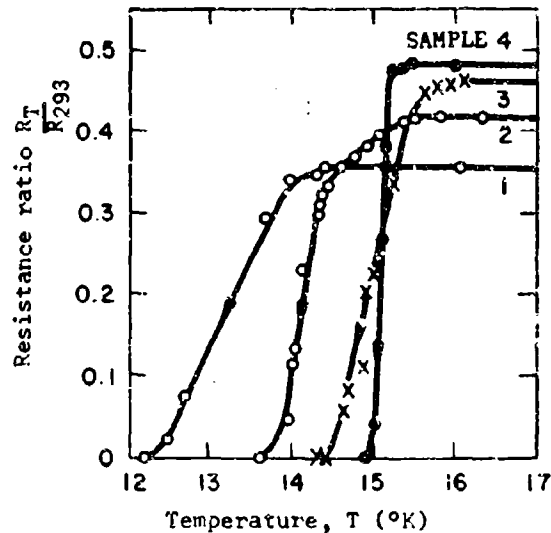


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# NIOBIUM-NITROGEN

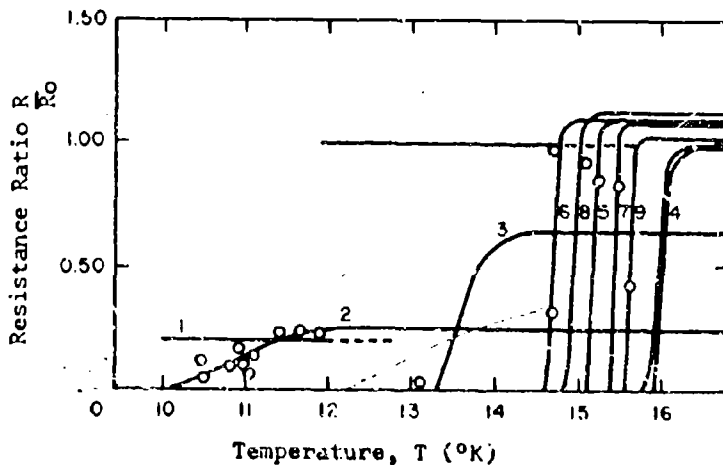
## TRANSITION TEMPERATURE

Resistance ratio curves for  
four niobium nitride samples.  
 $I = 0.017$  Amp.



| Sample | Nitrogen<br>at. % | N-Pressure<br>atm. | Time<br>Hours | Temperature<br>°C |
|--------|-------------------|--------------------|---------------|-------------------|
| 1      | 44.8              | 1.2                | 10            | 1450 - 1500       |
| 2      | 46.2              | 2                  | 30            |                   |
| 3      | 48.3              | 9                  | 50            |                   |
| 4      | 49.7              | 40                 | 45            |                   |

[Ref. 10726]

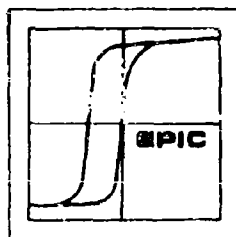


Transition curves for NbN  
formed at 1470°C, under  
different nitriding pressures.

### Nitrogen Pressure (atm)

|          |       |
|----------|-------|
| 1) 0.025 | 6) 32 |
| 2) 0.23  | 7) 52 |
| 3) 0.47  | 8) 55 |
| 4) 5.0   | 9) 80 |
| 5) 28.0  |       |

[Ref. 9017]



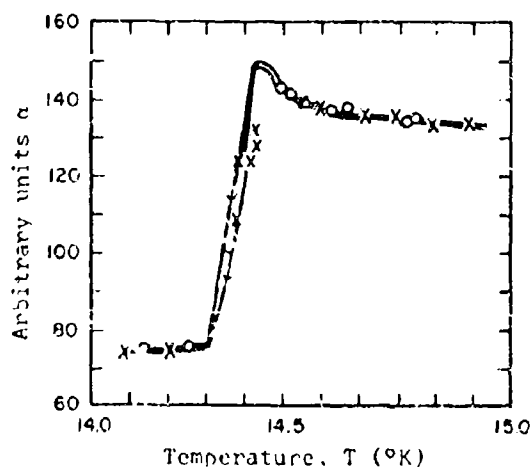
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# NIOBIUM-NITROGEN

## TRANSITION TEMPERATURE

The samples in the following 2 graphs are prepared as follows:

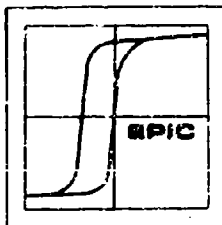
| Sample | Nitrogen<br>at. % | N-Pressure<br>atm. | Time<br>Hours | Temperature<br>°C |
|--------|-------------------|--------------------|---------------|-------------------|
| 1      | 44.8              | 1.2                | 10            | 1450 - 1500       |
| 2      | 46.2              | 2                  | 30            |                   |
| 3      | 48.3              | 9                  | 50            |                   |
| 4      | 49.7              | 40                 | 45            |                   |



Transition curve for a niobium nitride sample. The results of measurement on the sample taken at various field and current conditions are shown in the following graph.

H = 1.9 Oe  
I = 10 Amp

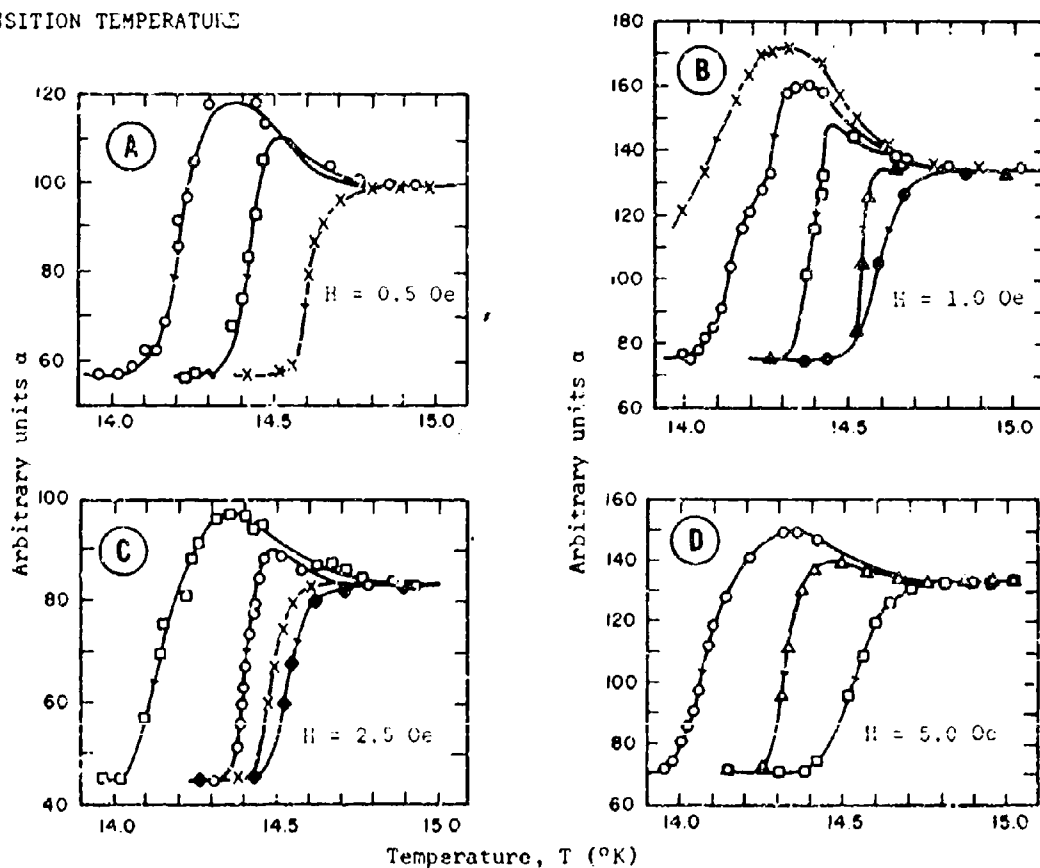
[Ref. 10722]



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# NIOBIUM-NITROGEN

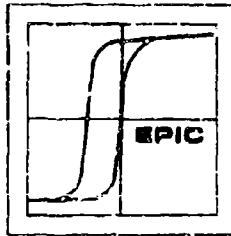
## TRANSITION TEMPERATURE



Transition curves for niobium nitride under various field and current conditions. Sample preparation: 40 atm. pressure N at 1450-1500 for 45 hours. 49.7 at.% present.

| (A)   | (B)   | (C)   | (D)   |
|-------|-------|-------|-------|
| J     | J     | J     | J     |
| (Amp) | (Amp) | (Amp) | (Amp) |
| x 0   | • 0   | ◆ 0   | ◻ 0   |
| ◻ 10  | ▲ 5   | x 5   | Δ 10  |
| ○ 15  | ◻ 10  | ○ 10  | ○ 15  |
|       | ○ 15  | ◻ 15  |       |
|       | x 20  |       |       |

[Ref. 10720]



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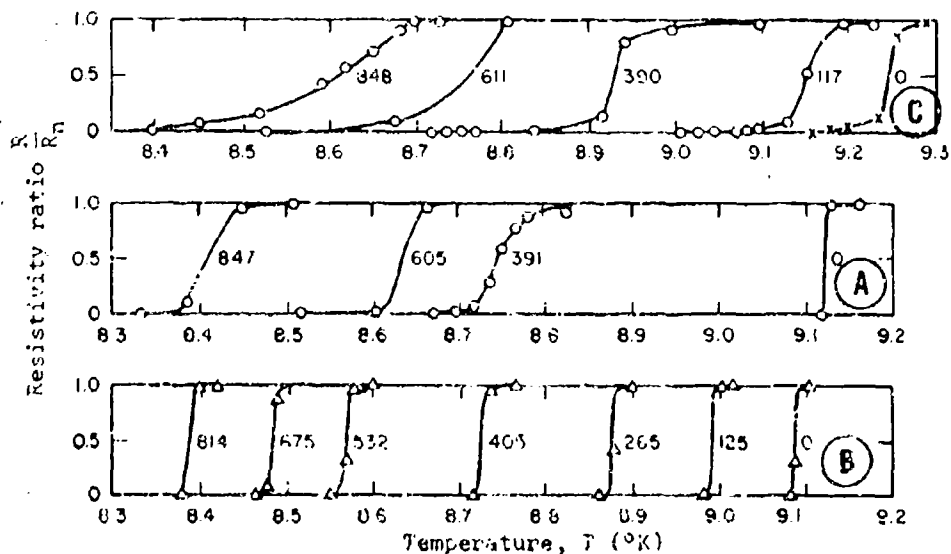
# NIOBIUM-NITROGEN

## TRANSITION TEMPERATURE

The specifications on the samples used in the following graph are given below:

0.029 inch diameter wire

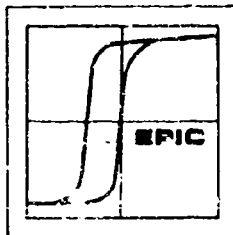
| Property                                   | As<br>Received | Annealed at 1875°C<br>for 2 Hrs. in $3 \times 10^{-6}$ mm Hg | Electron-beam<br>Heated, 5 Passes |
|--------------------------------------------|----------------|--------------------------------------------------------------|-----------------------------------|
| $\frac{R_{293^{\circ}K}}{R_{10^{\circ}K}}$ | ~110           | ~280                                                         | 500                               |
| $T_c$                                      | 9.67           | 9.20                                                         | 9.46                              |



Transition curves for niobium-nitrogen systems at various field strengths. Field strength measured in Oe, is indicated on the curve. The data were taken at  $7.2 \text{ A/cm}^2$ .

- A) .33 at.% N, He quenched
- B) .33 at.% N, vacuum quenched
- C) 1.64 at.% N, vacuum quenched

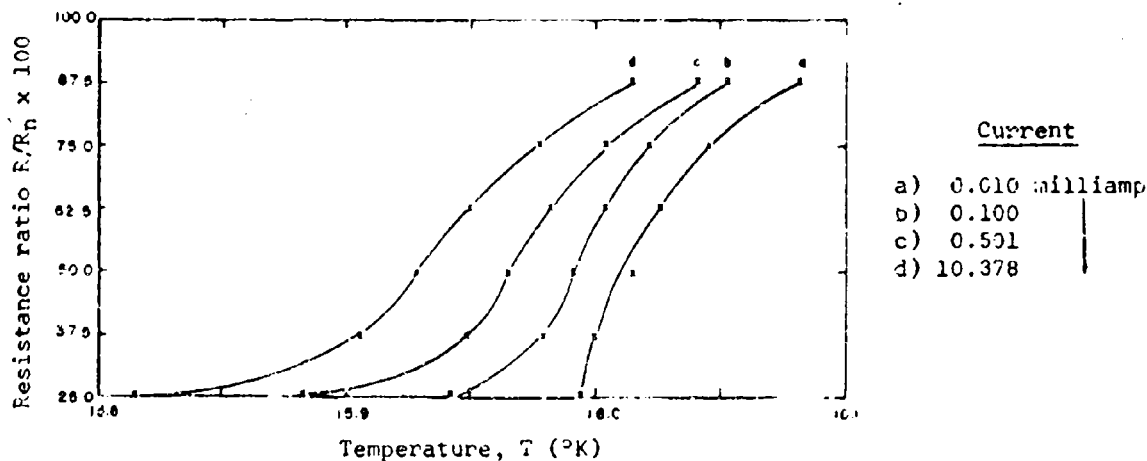
[Ref. 13360]



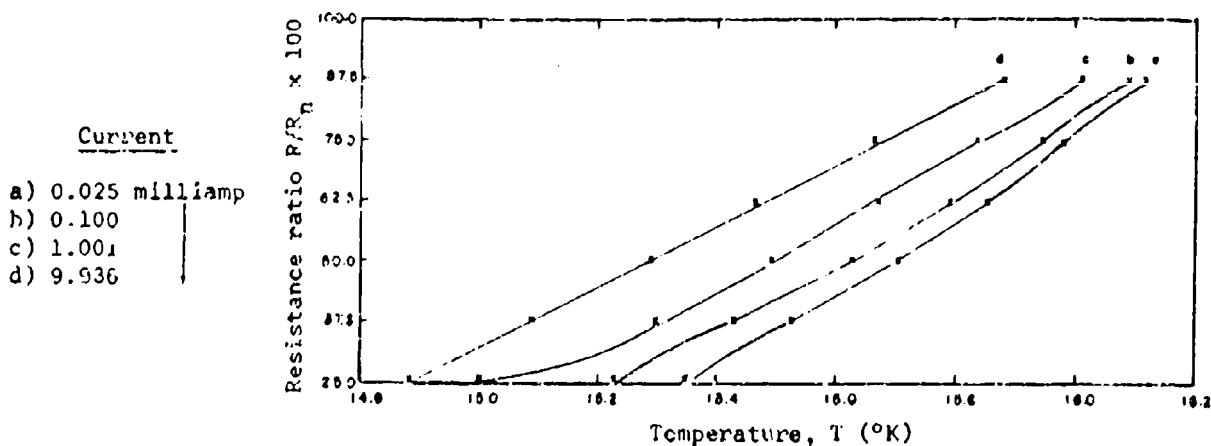
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# NIOBIUM-NITROGEN

## TRANSITION TEMPERATURE



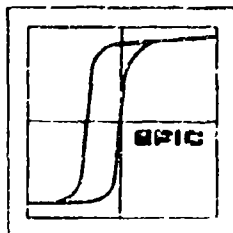
Transition curves for a NbN ribbon cut from a 1 mil sheet.  $R_{300} = 0.19\Omega$ . The Nb was heated in ammonia at  $1550^{\circ}\text{C}$  for 90 minutes.\*



Transition curves for a 5 mil NbN wire  $R_{300} = 0.2$ . The Nb was heated in ammonium at  $1225^{\circ}\text{C}$  for 30 minutes.\*

\* Plotted by EPIC staff

[Ref. 10750]



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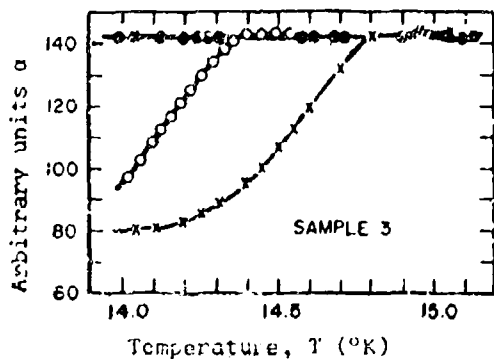
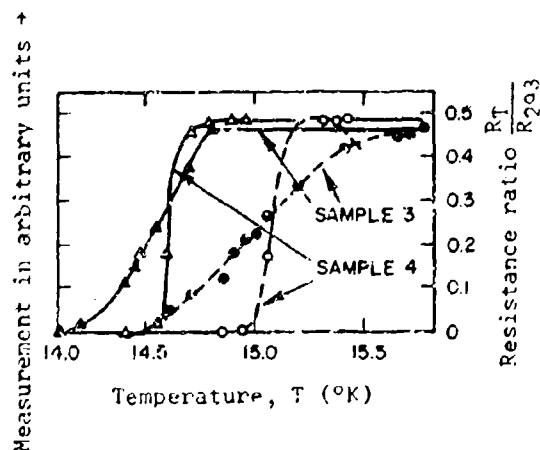
# NIOBIUM-NITROGEN

## TRANSITION TEMPERATURE

Transition curves for niobium nitride samples.

$H = 1 \text{ Oe}$

—  $I = 0.017 \text{ Amp}$   
- - -  $I = \text{zero Amp}$



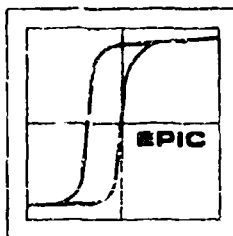
Transition curves for niobium nitride.

$H = 1 \text{ Oe}$

x x x  $I = \text{zero Amp}$   
o o o  $I = 10 \text{ Amp}$   
• • •  $I = 20 \text{ Amp}$

| Sample | Nitrogen<br>At. % | N-Pressure<br>atm | Time<br>Hours | Temperature<br>°C |
|--------|-------------------|-------------------|---------------|-------------------|
| 1      | 44.8              | 1.2               | 10            | 1450 - 1500       |
| 2      | 46.2              | 2                 | 30            |                   |
| 3      | 48.3              | 9                 | 50            |                   |
| 4      | 49.7              | 40                | 45            |                   |

[Ref. 1(728)]



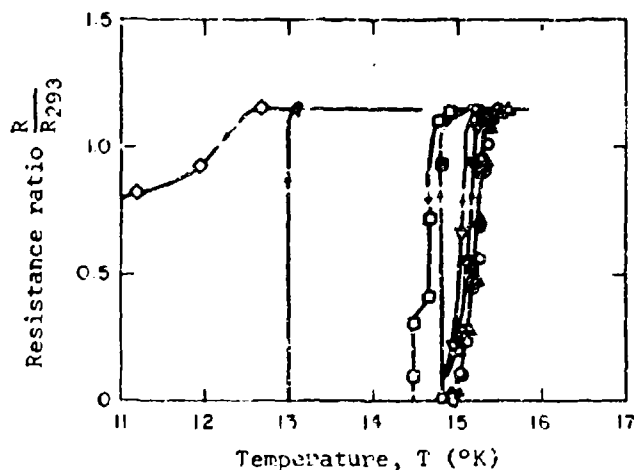
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## NIOBIUM-NITROGEN

### TRANSITION TEMPERATURE

The effect of current on the transition curves of niobium nitride.

| Current I ( $10^{-2}$ Amp) | Rising | Falling |
|----------------------------|--------|---------|
| .17                        | ●      | ○       |
| 1.7                        | ▲      | △       |
| 17.0                       | ▼      | ▽       |
| 4.8                        | ■      | □       |
| 11.0                       | ●      | ◇       |



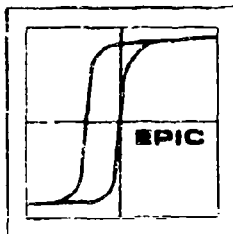
[Ref. 9617]

## NIOBIUM-OXYGEN

### TRANSITION TEMPERATURE

#### Lattice Constant and Transition Temperature

| Wt.% O | At.% O | Lattice Constant ( $\text{\AA}$ )<br>$a_0$ | Transition Temperature<br>$T_c$ ( $^{\circ}\text{K}$ ) | Notes                                                                                                                                | Ref.  |
|--------|--------|--------------------------------------------|--------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|-------|
| 0.101  | -      | $3.3002 \pm 0.0002$                        | -                                                      | Oxygen absorbed for 2 hours at $1000^{\circ}\text{C}$ .                                                                              | 21113 |
| 0.124  | .70    | -                                          | 8.78                                                   | Wires were drawn from electron-beam melted stock, then annealed & outgassed in high vacuum before dissolving oxygen into the sample. | 13366 |
| .26    | 1.4    | -                                          | 5.840                                                  | -                                                                                                                                    | 15227 |
| .27    | 1.52   | -                                          | 8.04                                                   | -                                                                                                                                    | 13366 |
| .32    | 1.80   | -                                          | 7.80                                                   | -                                                                                                                                    | "     |
| .75    | -      | $3.3112 \pm 0.0002$                        | -                                                      | Oxygen absorbed for 37 hours at $1050^{\circ}\text{C}$ .                                                                             | 21113 |
| .86    | 2.6    | -                                          | 7.04                                                   | See note for 13366 above.                                                                                                            | 13366 |



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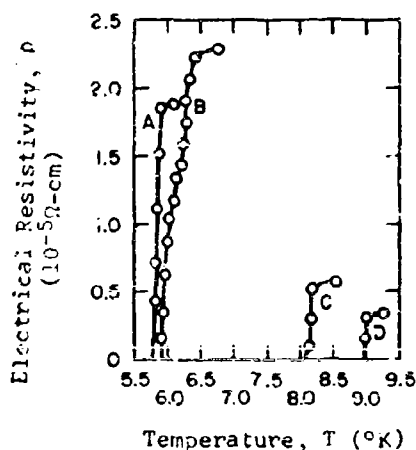
# NIBIUM OXYGEN

## TRANSITION TEMPERATURE

The specifications on the samples used in the following three graphs are given below:

### 0.029 Inch Diameter Wire

| Property           | As Received | Annealed at 1875°C<br>for 2 Hrs. in $3 \times 10^{-6}$ mm Hg | Electron-Beam<br>Melted, 5 Passes |
|--------------------|-------------|--------------------------------------------------------------|-----------------------------------|
| $R_{293^{\circ}K}$ | ~110        | ~280                                                         | 500                               |
| $R_{10^{\circ}K}$  |             |                                                              |                                   |
| $T_c$              | 9.67        | 9.20                                                         | 9.46                              |



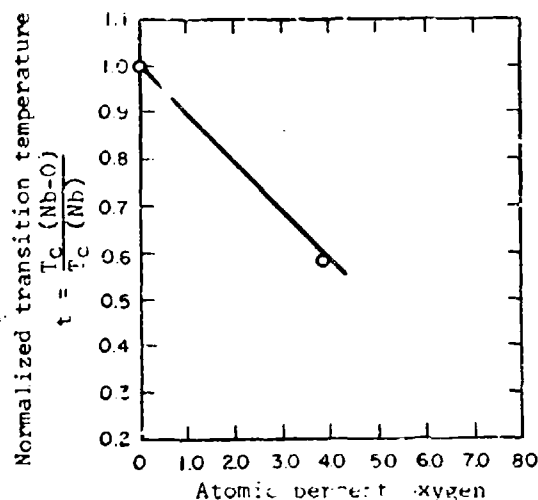
Electrical resistivity for niobium-oxygen systems. Current density  $J = 7.2 \text{ Amp/cm}^2$ .

- A) 3.83 at.% O
- B) 5.18 at.% O
- C) 1.43 at.% O
- D) 6.43 at.% O

o = warming  
x = cooling

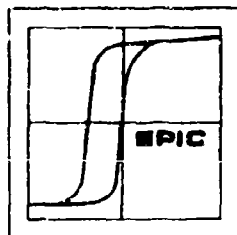
The normalized transition temperature as a function of composition for the Nb-O system.

$$\frac{dT_c}{d(\text{at.\% O})} = -0.93(^{\circ}K/\text{at.\%})$$



[Ref. 13366]

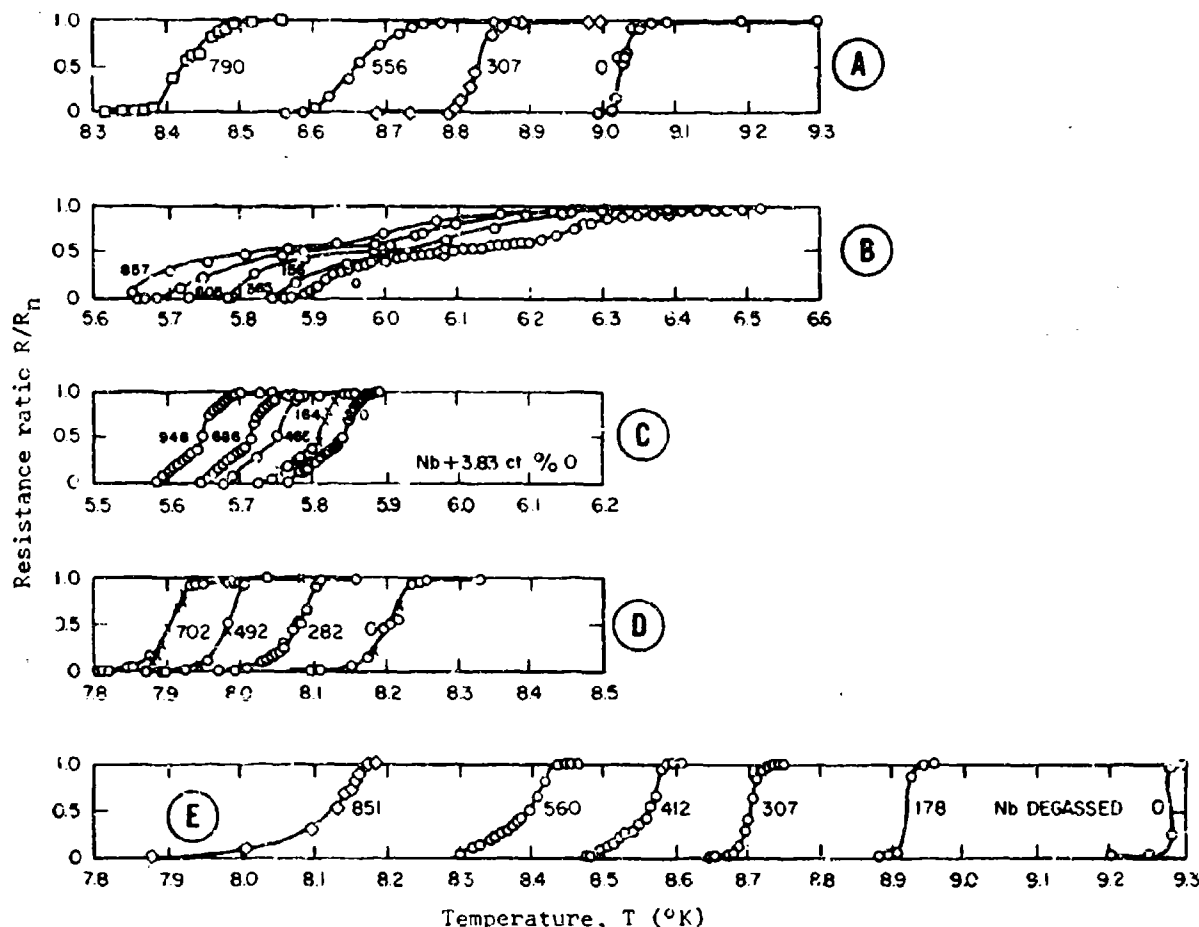




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# NIOBIUM-OXYGEN

## TRANSITION TEMPERATURE



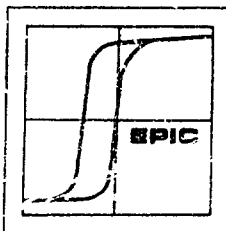
Field effect on the transition curves of niobium-oxygen systems. Field strength measured in Oe, is indicated on the curves.

$J = 7.2 \text{ Amp/cm}^2$

| graph | at. % O |
|-------|---------|
| A)    | 6.43    |
| B)    | 5.18    |
| C)    | 3.83    |
| D)    | 1.43    |
| E)    | 0       |

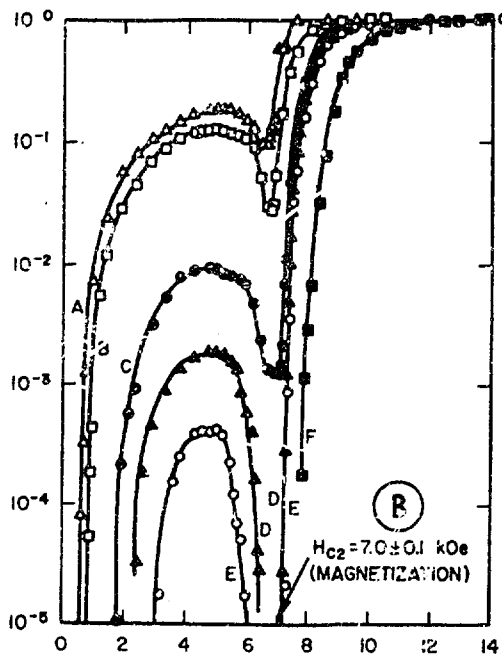
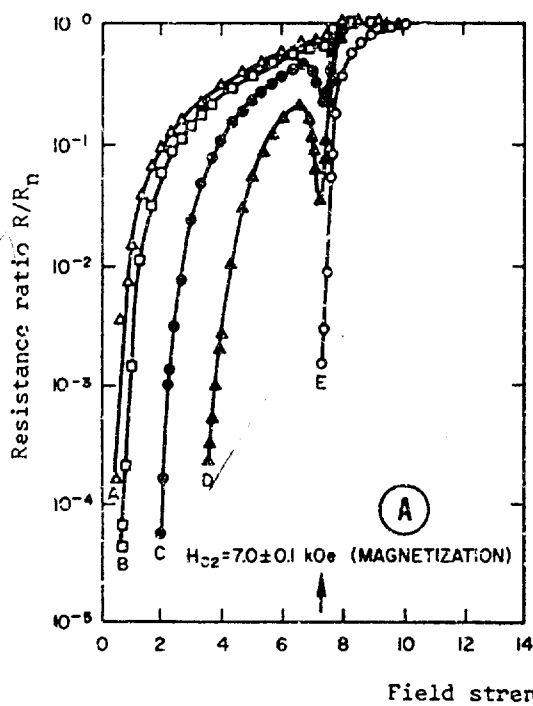
o warming  
x cooling

[Ref. 13366]



NIOBIUM OXYGEN

TRANSITION TEMPERATURE



The transition curves for niobium ribbon with 0.80 at.% oxygen at various current densities.  $H \perp J$  and also perpendicular to the wide side of the ribbon.  $H_{c2} = 7.0 \pm 0.1$  (kOe).

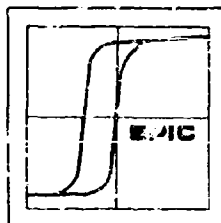
(A) annealed  
I(A) J(A/cm<sup>2</sup>)

|    |       |     |
|----|-------|-----|
| A) | 0.90  | 865 |
| B) | 0.550 | 526 |
| C) | 0.230 | 220 |
| D) | 0.115 | 111 |
| E) | 0.010 | 9.6 |

(B) cold worked  
I(A) J(A/cm<sup>2</sup>)

|    |      |      |
|----|------|------|
| A) | 4.75 | 3287 |
| B) | 2.90 | 2007 |
| C) | 1.25 | 865  |
| D) | 0.95 | 658  |
| E) | 0.16 | 111  |

[Ref. 15459]



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# NIOBIUM-NITROGEN

## CRITICAL FIELD

The specifications on the samples used in the following table are given below:

### 0.029 Inch Diameter Wire

| Property                                   | As Received | Annealed at 1875°C<br>for 2 Hrs. in 3 x 10 <sup>-4</sup> mm Hg | Electron-beam<br>Melted, 5 passes |
|--------------------------------------------|-------------|----------------------------------------------------------------|-----------------------------------|
| $\frac{R_{293^{\circ}K}}{R_{10^{\circ}K}}$ | ~110        | ~280                                                           | 500                               |
| $T_c$                                      | 9.67        | 9.20                                                           | 9.46                              |

### Critical Field

| Material         | $T_c$ (°K) | $\rho$ (μΩ-cm) | $H_{CA}(Oe)$<br>(4.2°K) | $(\frac{\delta H_{CA}}{\delta T})_{T_c}$ | $H_n$ (Oe)<br>(4.2°K) | $H_{fp}$ (Oe)<br>(4.2°K) | Ref.  |
|------------------|------------|----------------|-------------------------|------------------------------------------|-----------------------|--------------------------|-------|
| Nb               | 9.46       | .035           | 1500                    | -403                                     | 2700                  | 1320                     | 13366 |
| Nb + 0.23 at.% N | -          | 1.70           | 1480                    | -403                                     | 3000                  | 780                      | "     |

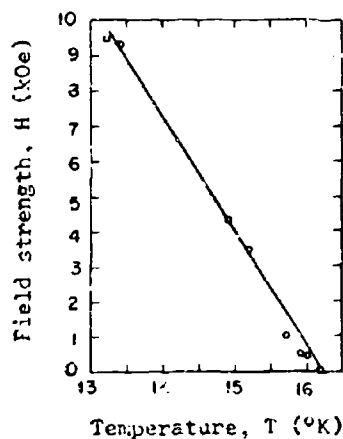
$H_{CA}$  is an approximation of  $H_c$  from the area under the magnetization curve.

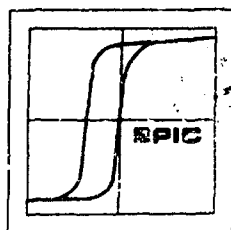
$H_{fp}$  is the field strength at first penetration.

$H_n$  is the field strength when the sample is in the normal state.

Critical field for niobium nitride  
(49.4 at.% N) as a function of  
temperature. Sample preparation:  
Nb powder was nitrided at 1 atm  
pressure of N for 3 hrs. at 1300°C.

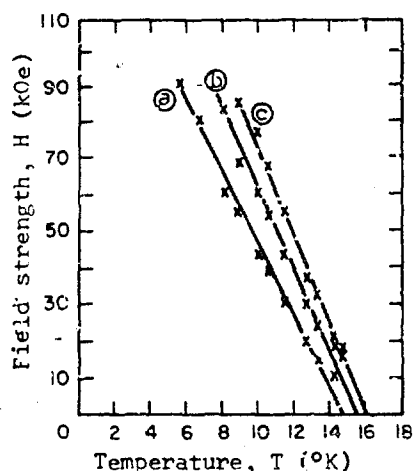
[Ref. 18726]





# NIOBIUM-NITROGEN

## CRITICAL FIELD



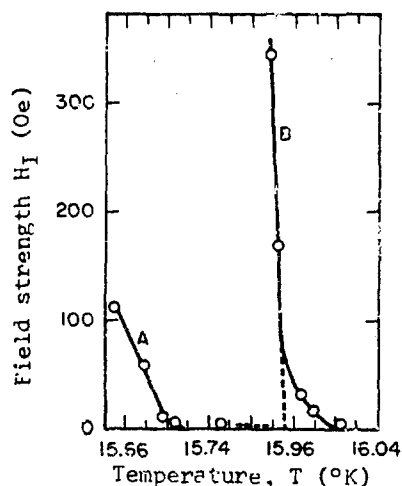
Critical field strength resulting from current densities in two NbN samples:

- a) 1 mil ribbon, heated in ammonia at 1550° for 90 minutes.
- b) 1/4 mil ribbon, heated in ammonia at 1350° for 30 minutes.

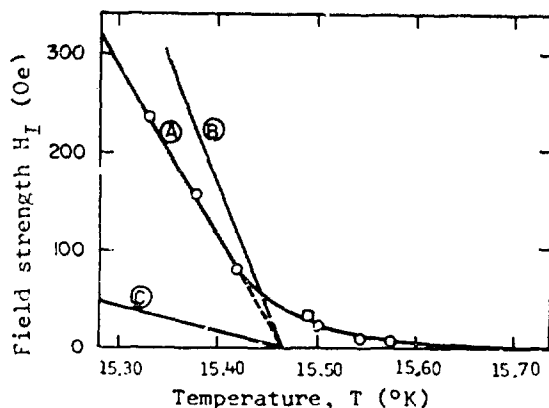
Threshold field for niobium nitride (44.4 at.% N). Powdered Nb was pressed at 43,500 psi and heat-treated in a nitrogen stream for 24 hours at 1300°C and 24 hours at 1450°C.

| Sample | R/R <sub>n</sub> |
|--------|------------------|
| a      | 0.1              |
| b      | 0.5              |
| c      | 0.9              |

[Ref. 18457]

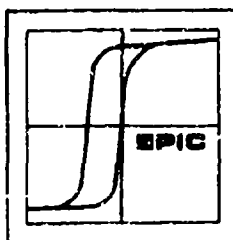


Critical field for 5-mil NbN wire.  
(R<sub>n</sub> = 0.2Ω).



- A) External field corresponding to a field from a current density which raises resistance to 5R<sub>n</sub>.
- B) External field to raise resistance to .5R<sub>n</sub>.
- C) Calculated from (C<sub>s</sub>-C<sub>n</sub>) for a NbN powder. C<sub>s</sub> is the heat capacity in the superconducting state. C<sub>n</sub> is the heat capacity in the normal state.

[Ref. 10754]



# NIOBIUM-OXYGEN

## CRITICAL FIELD

### Threshold Field

| At.% O | Wt.% O | T <sub>c</sub> (°K) | ρ (μΩ-cm) | H <sub>CA</sub> (Oe)<br>(4.20°K) |        | ( $\frac{dH_{CA}}{dT}$ ) <sub>T<sub>c</sub></sub> | H <sub>n</sub> (Oe)<br>(4.20°K) |          | H <sub>fp</sub> (Oe)<br>(4.20°K) |       |
|--------|--------|---------------------|-----------|----------------------------------|--------|---------------------------------------------------|---------------------------------|----------|----------------------------------|-------|
| 0.70   | 0.124  | 8.78                | 3.9       | 1360                             | 1425*  | -403                                              | 7000                            | ~7550*   | 580                              | 590*  |
| 1.52   | 0.27   | 8.04                | 8.2       | 1125                             | 1260†  | -403                                              | ~9670                           | ~11600†  | 350                              | 380†  |
| 1.80   | 0.32   | 7.80                | 9.6       | 1048                             | 1210** | -403                                              | ~10300                          | ~12600** | 290                              | 315** |
| 2.60   | 0.46   | 7.04                | 13.7      | 840                              | 1070†† | -403                                              | ~11500                          | ~15000†† | 170                              | 200†† |

H<sub>CA</sub> is an approximation of H<sub>c</sub> from the area under the magnetization curve.

H<sub>fp</sub> is the field strength at first penetration.

H<sub>n</sub> is the field strength when the sample is in the normal state.

\*3.85°K

†3.57°K

\*\*3.40°K

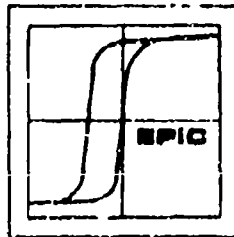
††3.10°K

[Ref. 13366]

### Residual Resistivity and Upper Critical Field

| At.% O | Residual Resistivity<br>(μΩ-cm) | Upper Critical Field<br>H <sub>c2</sub> (kGauss) |
|--------|---------------------------------|--------------------------------------------------|
| 0.20   | 0.82                            | 5.4                                              |
| 0.86   | 3.06                            | 6.6                                              |
| 1.30   | 5.14                            | 8.4                                              |

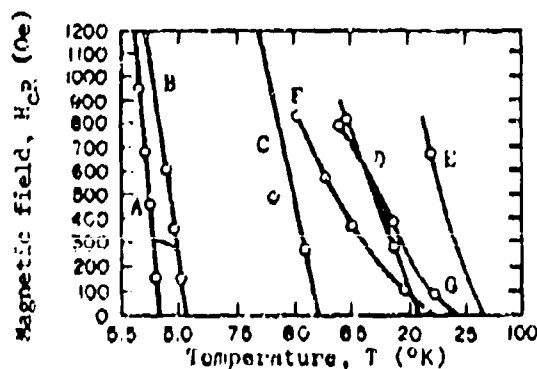
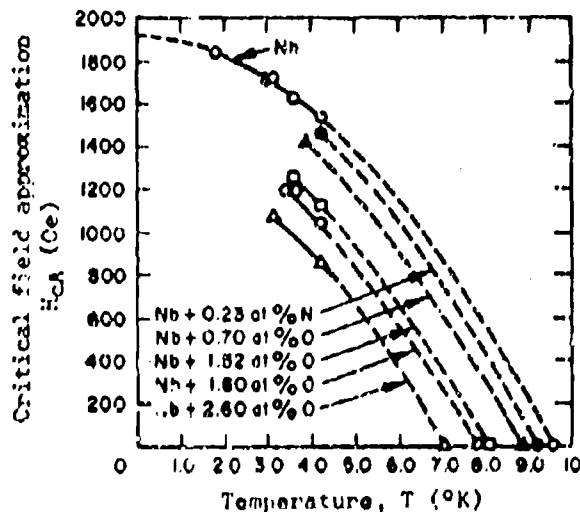
[Ref. 21039]



## NIOBIUM-OXYGEN

### CRITICAL FIELD

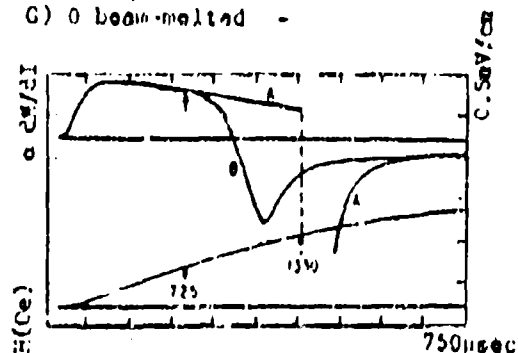
An approximation of the thermodynamic critical field  $H_c$  as a function of temperature.  $H_{cA}$  is approximated from the area under the magnetization curve, and  $H_{cA} = H_0[1-(T/T_c)^2]$ . [Ref. 1336C]

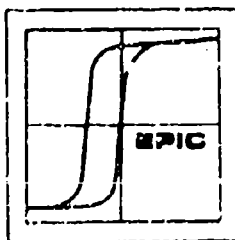


Critical field strength as a function of temperature for niobium-oxygen system.  $J = 7.2 \text{ Amp/cm}^2$ .  $H_{cR}$  is the field at which  $R/R_n = .5$  in the resistance ratio value. [Ref. 1336C]

| At. % O          | $\left(\frac{dH_{cR}}{dT}\right)_{T=T_c} \left(\frac{O\%}{^\circ K}\right)$ |
|------------------|-----------------------------------------------------------------------------|
| A) 3.93          | -5000                                                                       |
| B) 3.18          | -3400                                                                       |
| C) 1.43          | -1200                                                                       |
| D) 0.43          | -1250                                                                       |
| E) 0             | -1140                                                                       |
| F) 0 degraded    | -                                                                           |
| G) 0 beam-melted | -                                                                           |

Oscilloscope traces showing initial penetration of the flux into an electropolished  $\text{Nb}_{0.993}\text{O}_{0.007}$  wire. Trace A is for the sample in an optimum position and bottoms out near -18 mV. Trace B is for the sample moved 1.4 mm upward. Conventional tests show  $H_{c1} = 580 \text{ Oe}$ ,  $H_c = 1360 \text{ Oe}$ , and  $H_{c2} = 7000 \text{ Oe}$ . [Ref. 14582]

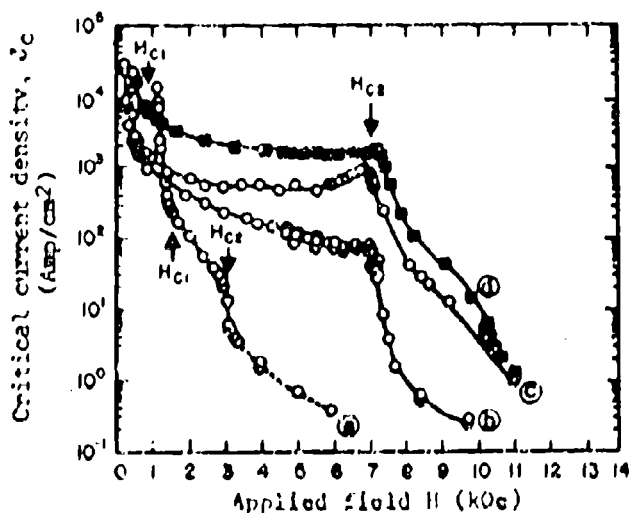




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# NIOBIUM-OXYGEN

## CRITICAL CURRENT DENSITY



Critical current density for a Nb-O system (0.70 at.% O) as a function of applied field.  $H \perp J$ .

Wire (0.30 inches diam.)

a) Outgassed and annealed  $\frac{R_{300^\circ K}}{R_{10^\circ K}} = 500$

b) Annealed

Ribbon (0.035 inches x 0.006 inches)

c) Cold worked  $H \perp$  w.s. (wide side)

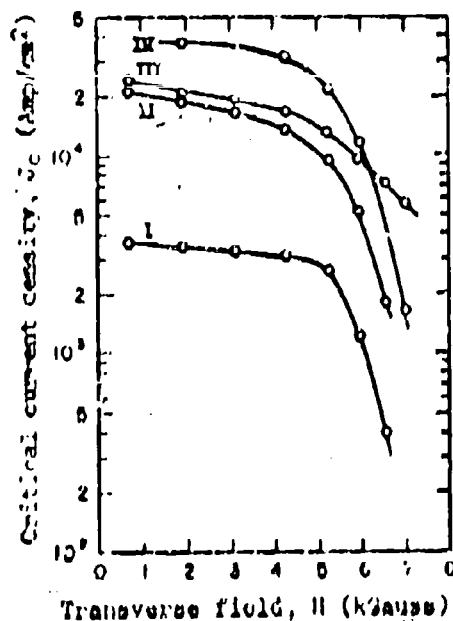
d) Cold worked  $H \parallel$  w.s.

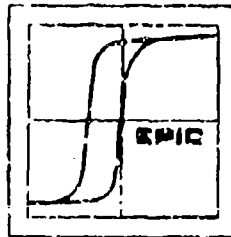
[Ref. 15459]

Critical current density for niobium with 0.86 at.% oxygen.

- I. 0.8 mm diam. wire, soft annealed with oxygen atoms in random solution.
- II. 0.3 mm diam. wire cold worked with oxygen atoms precipitated at dislocations.
- III. 0.3 mm diam. wire cold worked with oxygen atoms in random solution.
- IV. 0.8 mm diam. wire soft annealed with partly ordered oxygen atoms.

[Ref. 21039]

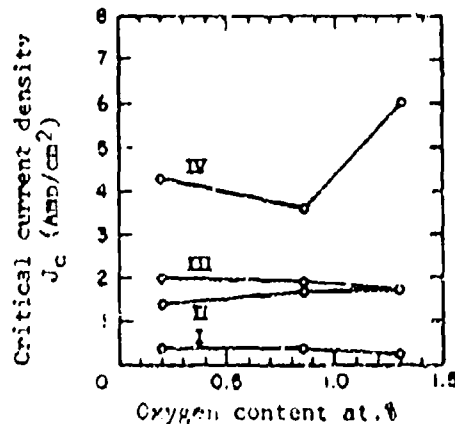




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# NIOBIUM-OXYGEN

## CRITICAL CURRENT DENSITY

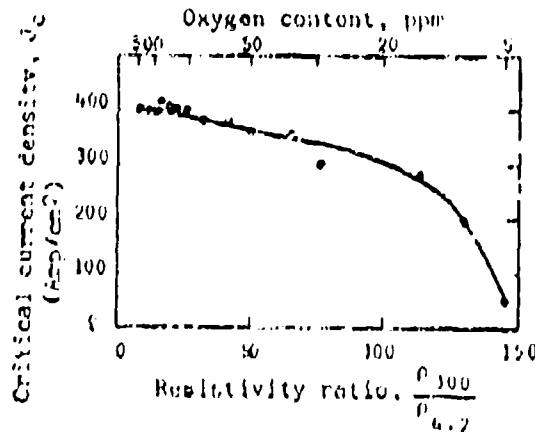


Critical current density for Nb-O as a function of oxygen content. Data taken at 3(kGauss).

- I. 0.8 mm diam. wire, soft annealed with oxygen atoms in random solution.
- II. 0.3 mm diam. wire cold worked with oxygen atoms precipitated at dislocations.
- III. 0.3 mm diam. wire cold worked with oxygen atoms in random solution.
- IV. 0.8 mm diam. wire soft annealed with partly ordered oxygen atoms.

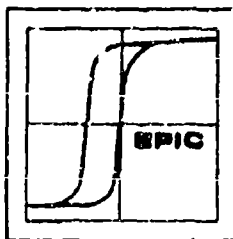
[Ref. 21629]

Effect of oxygen content on critical current density in single crystal niobium. The data were taken at 4.2°K and at the upper critical field  $H_{c2}$ .



[Ref. 19627]

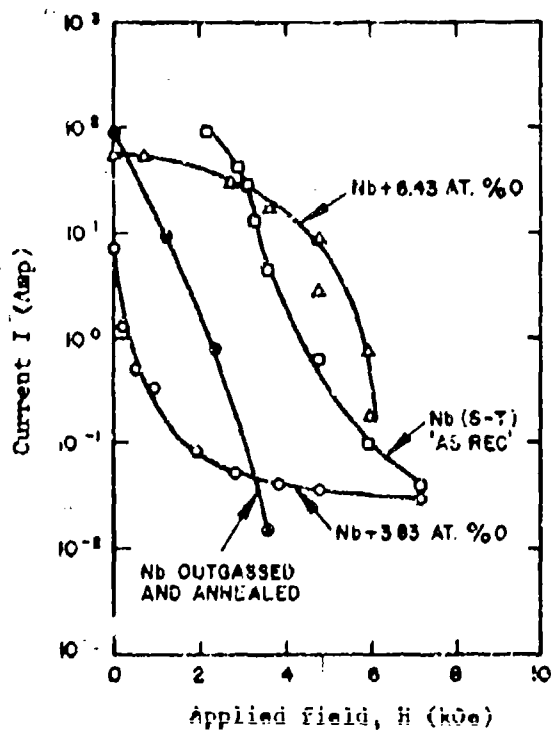




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NIOBIUM-OXYGEN

CRITICAL CURRENT DENSITY

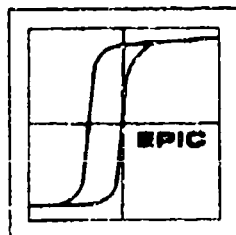


Critical current as a function of transverse applied field. Data taken at 4.2°K.

0.029 Inch Diameter Wire

| Property                                   | As<br>Received | Annealed at 1875°C<br>for 2 hrs. in $3 \times 10^{-6}$ mm Hg | Electron-Beam<br>Melted, 5 passes |
|--------------------------------------------|----------------|--------------------------------------------------------------|-----------------------------------|
| $\frac{R_{293^{\circ}K}}{R_{10^{\circ}K}}$ | ~110           | ~200                                                         | 600                               |
| $T_c$                                      | 9.67           | 9.20                                                         | 9.45                              |

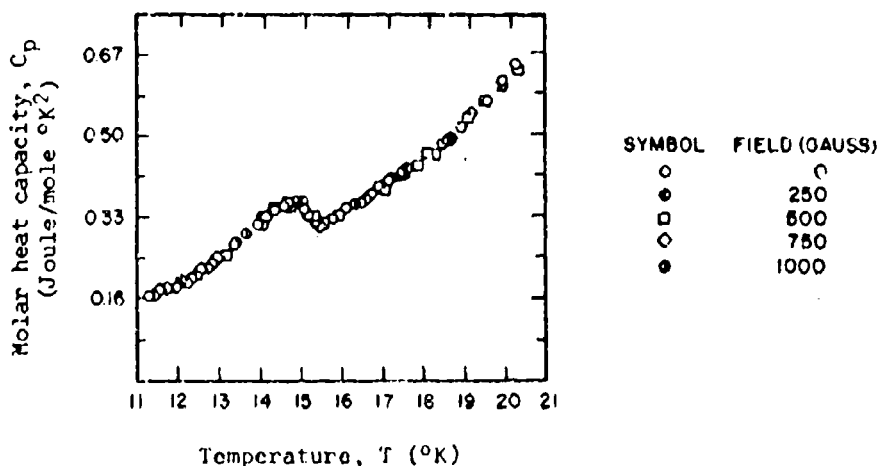
[Ref. 10366]



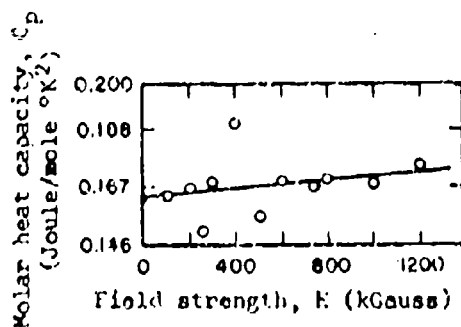
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# NIOBIUM-NITROGEN

## SPECIFIC HEAT

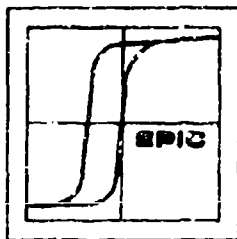


Heat capacity as a function of temperature for NbN. The sample was prepared from powdered Nb heated in a nitrogen atmosphere for 12 hours at 1300°C.



Heat capacity as a function of field strength at 11°K. A powdered Nb sample was heated in nitrogen for 12 hours at 1300°C.

[Ref. 20629]



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# NIOBIUM-OXYGEN

## SPECIFIC HEAT

### Coefficient of Electronic Specific Heat

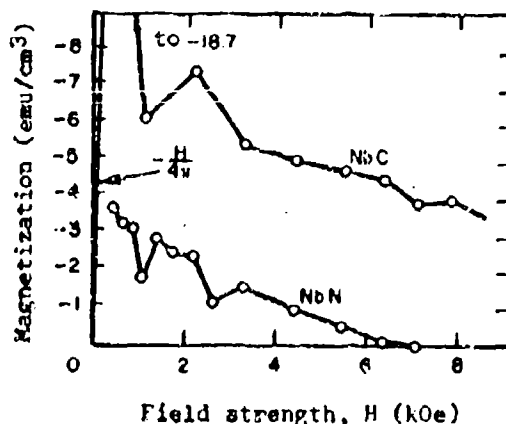
| At. % O | $\gamma$ ( $10^{-4}$ cal/mole $^{\circ}\text{K}^2$ )                   |                                           |
|---------|------------------------------------------------------------------------|-------------------------------------------|
|         | $\frac{V}{8\pi} \left( \frac{\delta H_{ca}}{\delta T} \right)_{T_c}^2$ | $0.17 \left( \frac{H_p^2}{T_c^2} \right)$ |
| 0.70    | 16.7                                                                   | 17.6                                      |
| 1.52    | 16.8                                                                   | 16.4                                      |
| 1.80    | 16.9                                                                   | 16.4                                      |
| 2.60    | 17.0                                                                   | 16.0                                      |

Data taken at 4.20°K

[Ref. 13366]

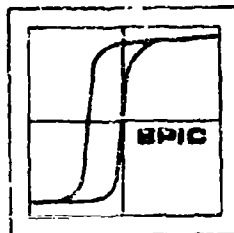
# NIOBIUM-NITROGEN

## MAGNETIC HYSTERESIS



Magnetization for NbN as a function of applied field. Data taken at 4.2°K.  
NDC curve is shown for comparison.

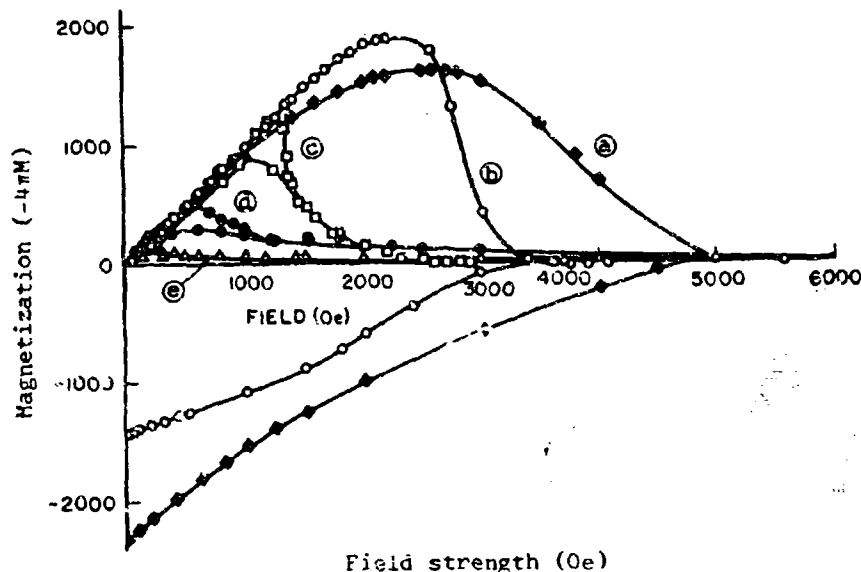
[Ref. 21847]



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# NIOBIUM-OXYGEN

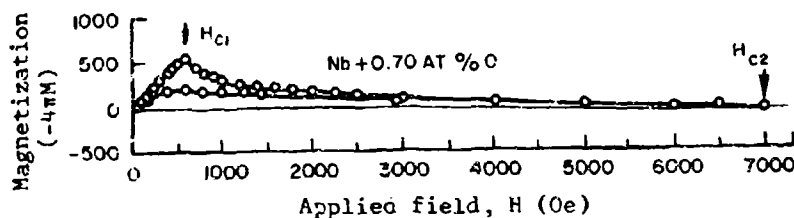
## MAGNETIC HYSTERESIS



Magnetization as a function of field strength for the Nb-O system and Nb at 4.2°K.

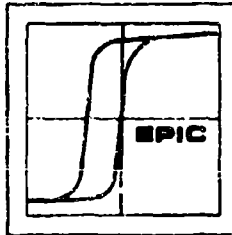
- a) Nb + 6.43 at.% O.
- b) 0.020 inch diam wire,  $\frac{R_{298^\circ K}}{R_{10^\circ K}} = 68$ .
- c) Sample referred to in table as annealed & outgassed.
- d) Nb + 0.70 at.% O.
- e) Nb + 1.75 at.% O.

[Ref. 13366]



Magnetization as a function of field strength for a Nb-O sample (0.70 at.% O) showing the upper and lower critical fields. Data taken at 4.2°K.

[Ref. 15459]

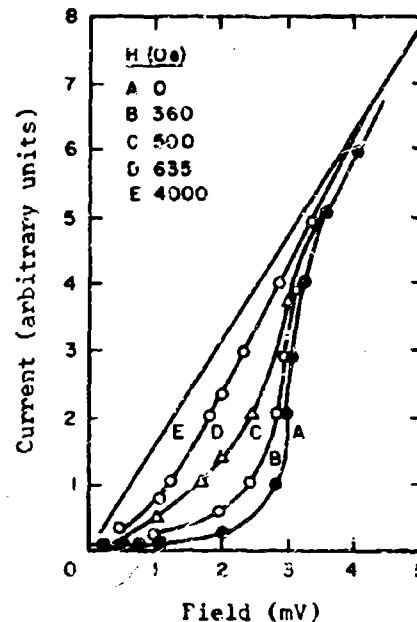


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## NIORIUM-OXYGEN

### DEVICE

Tunnel current through a Nb-NbO-Pb sandwich at 4.18°K, at different magnetic fields. Zone refined Nb was outgassed at 2000°C and 20Å thick NbO films were formed by heating the Nb to 40°C in pure oxygen for 2 hours. Lead was deposited to 1000Å thickness. [Ref. 21733]



## NIORIUM-NITROGEN

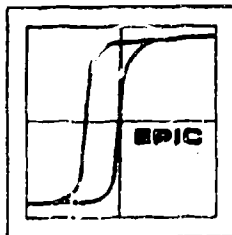
### SEMICONDUCTING PROPERTIES

| Electrical<br>Resistivity<br>$\rho$ ( $\mu\Omega$ -cm) | Thermal<br>Conductivity<br>K (W/cm°K) | Seebeck Coefficient<br>S ( $\mu$ V/°C) | Hall Coefficient<br>R ( $10^{-4}$ cm <sup>3</sup> /coul) | Notes      | Ref.  |
|--------------------------------------------------------|---------------------------------------|----------------------------------------|----------------------------------------------------------|------------|-------|
| 60                                                     | 0.010                                 | -                                      | -0.13*                                                   | -          | 3803  |
| 200                                                    | -                                     | -2.0                                   | -                                                        | -          | 11599 |
| -                                                      | -                                     | -1.6                                   | -                                                        | Arc melted | 14991 |
| -                                                      | -                                     | +2.8                                   | -                                                        | Annealed   | "     |
| 200                                                    | 0.033                                 | -                                      | -                                                        | -          | 13723 |
| 450                                                    | -                                     | -                                      | -                                                        | 2050°C     | 18179 |

\*  $\delta = +0.22 \times 10^{-23}$  (cm/V<sup>2</sup>sec<sup>2</sup>)

$$\delta = \frac{R}{e\rho^2} = n_s \mu_s^2 - n_a \mu_a^2$$

n is the carrier concentrations,  $\mu$  is the mobility.

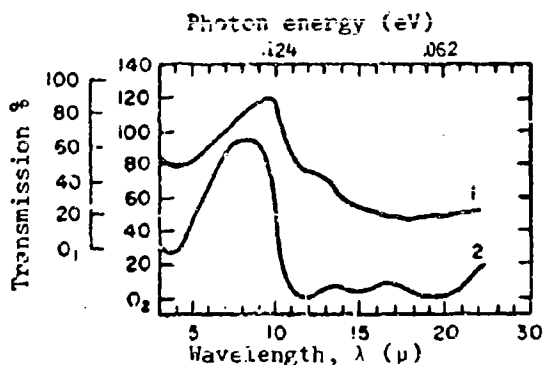


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# NIOBIUM-OXYGEN

## ABSORPTION

- 1) Niobium was oxidized in a water solution of boric acid and borax, then the metallic niobium substrate was dissolved in hydrofluoric acid.
- 2) Monoclinic  $Nb_2O_5$ .



Absorption spectra for niobium oxide as a function of wavelength.

[Ref. 17133]

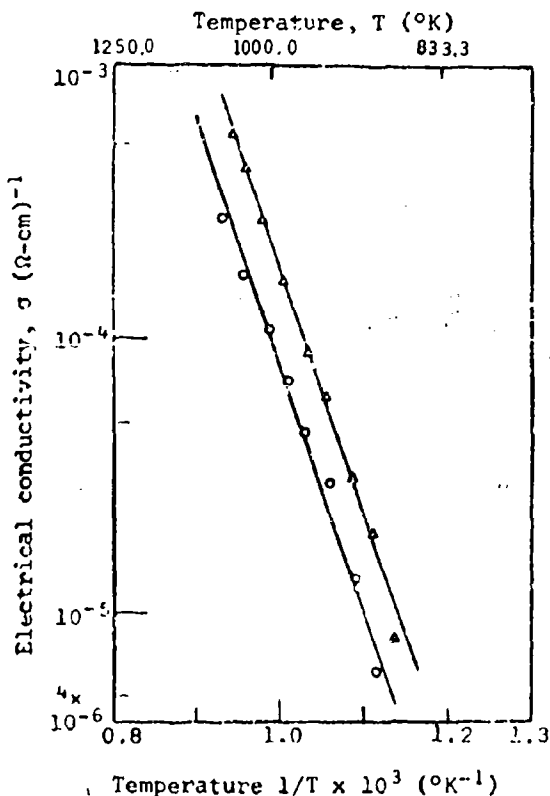
# NIOBIUM-OXYGEN

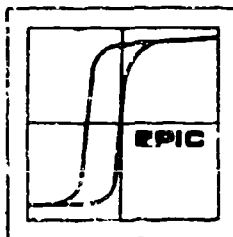
## ELECTRICAL CONDUCTIVITY

Electrical conductivity for  $\alpha-Nb_2O_5$ . Oxide powders were pressed at 40,000 psi and sintered 1300-1350°C for two hours. Measured in oxygen at:

- △ 0.12 atmospheres
- 0.9 atmospheres.

[Ref. 3274]





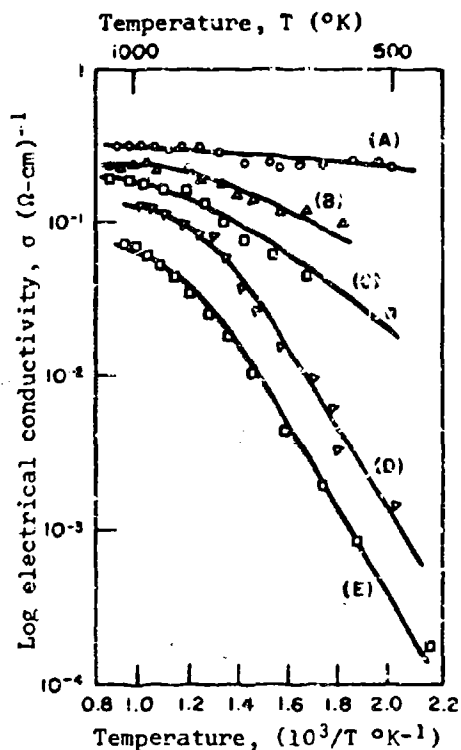
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# NIOBIUM-OXYGEN

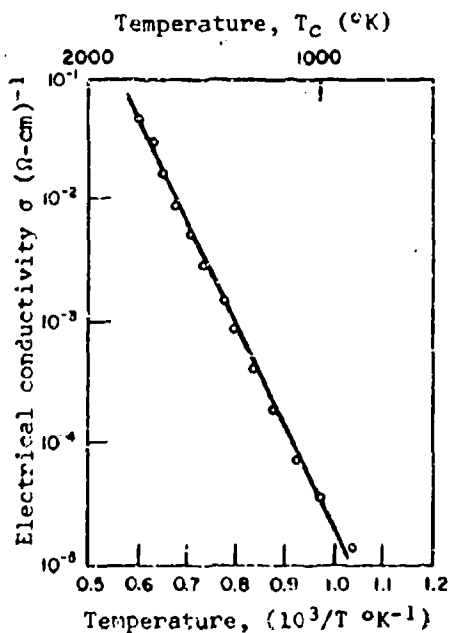
## ELECTRICAL CONDUCTIVITY

Electrical conductivity of sintered  $\alpha$ -Nb<sub>2</sub>O<sub>5</sub> at 10<sup>-6</sup> atm. pressure of air after reduction at the same pressure:

- A) 8 hours at 875°C
- B) 8 hours at 810°C
- C) 1/2 hour at 860°C
- D) 8 hours at 750°C
- E) 1/2 hour at 800°C

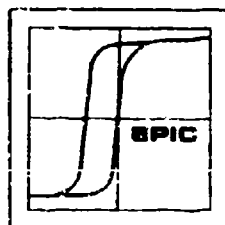


[Ref. 5936]



Electrical conductivity for near-stoichiometric  $\alpha$ -Nb<sub>2</sub>O<sub>5</sub> at 1 atm pressure oxygen. Powdered  $\alpha$ -Nb<sub>2</sub>O<sub>5</sub> was pressed at 15,000 psi and sintered at 1380°C.

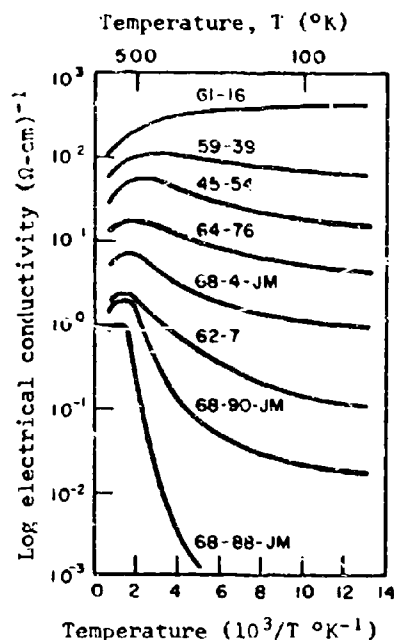
[Ref. 7840]



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# NIOBIUM-OXYGEN

## ELECTRICAL CONDUCTIVITY

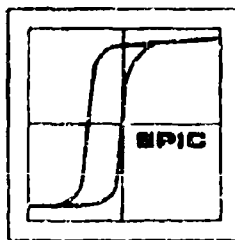


Electrical conductivity for non-stoichiometric  $\alpha$ - $\text{Nb}_2\text{O}_5$ .  $\text{Nb}_2\text{O}_5$  powder was pressed to 20,000 psi and sintered in air at 1390°C for 3 hours, oxygen content and electron mobility at 1000°C are given below:

| Sample designation | $\text{Nb}_2\text{O}_5$<br>( $\bar{x}$ ) | Electron mobility, $\mu$<br>( $\text{cm}^2/\text{V sec}$ ) |
|--------------------|------------------------------------------|------------------------------------------------------------|
| 61-16              | 4.8632                                   | 0.211                                                      |
| 59-39              | 4.9326                                   | 0.254                                                      |
| 45-54              | 4.9558                                   | 0.194                                                      |
| 64-76              | 4.9784                                   | 0.192                                                      |
| 68-4-JM            | 4.9934                                   | 0.228                                                      |
| 62-7               | 4.9980                                   | 0.284                                                      |
| 68-90-JM           | 4.9980                                   | 0.221                                                      |
| 68-88-JM           | 4.9988                                   | 0.231                                                      |

[Ref. 4168]





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# NIOBIUM-OXYGEN

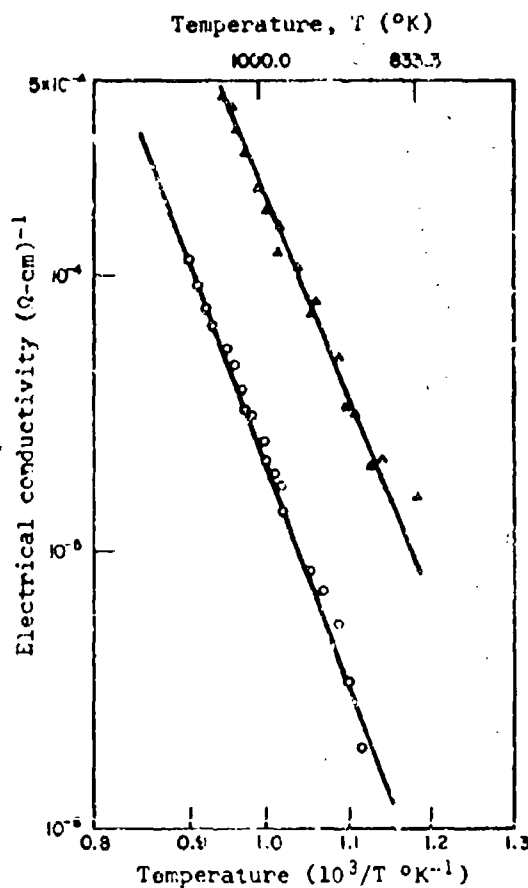
## ELECTRICAL CONDUCTIVITY

Electrical conductivity for niobium oxide.

Δ  $\alpha$ - $\text{Nb}_2\text{O}_5$  powder, pressed at 40,000 psi and sintered at 1300-1350°C for two hrs.

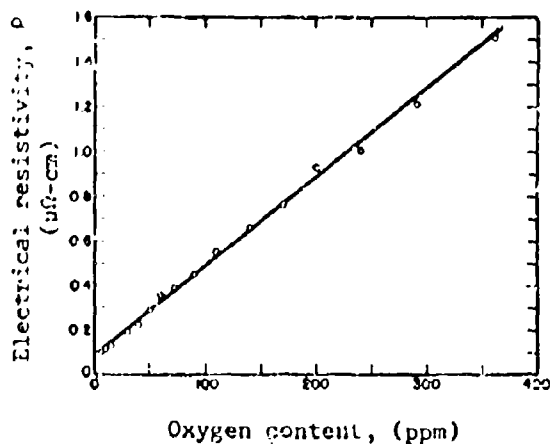
○  $\text{Nb}_2\text{O}_5$  single crystal.

[Ref. 3274]



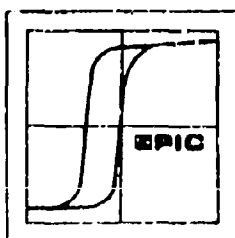
# NIOBIUM-OXYGEN

## ELECTRICAL RESISTIVITY



The effect of oxygen content on residual resistivity of niobium. Data taken at 4.2°K on single crystal niobium. After treatment, 5 ppm oxygen remained and the content shown in the graph was added.

[Ref. 19627]



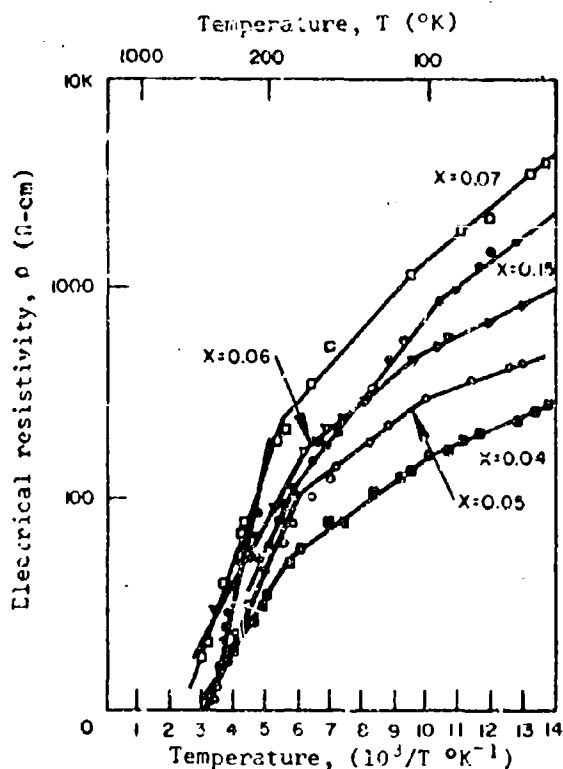
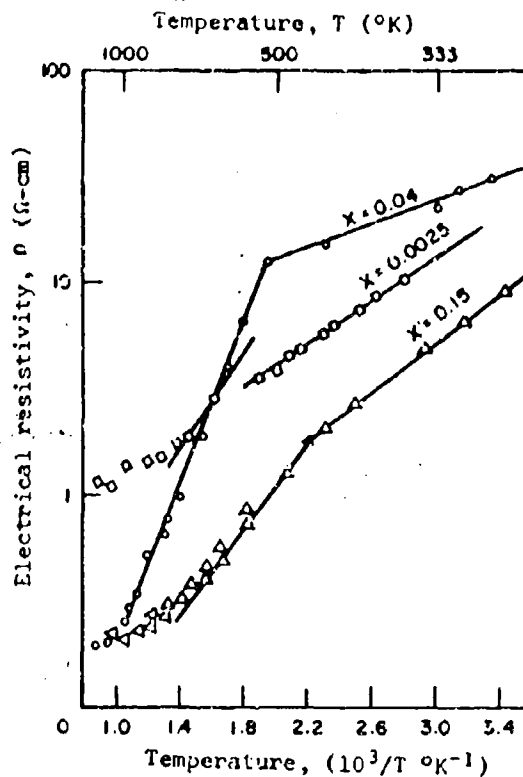
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# NIOBIUM-OXYGEN

## ELECTRICAL RESISTIVITY

Electrical resistivity of sintered polycrystalline niobium oxide with varied tungsten content,  $(\text{Nb}_{1-x}\text{W}_x)_2\text{O}_5$ .

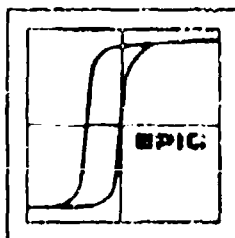
- $(\text{Nb}_{0.96}\text{W}_{0.04})_2\text{O}_5$ .
- $(\text{Nb}_{0.9975}\text{W}_{0.0025})_2\text{O}_5$ .
- △  $(\text{Nb}_{0.85}\text{W}_{0.15})_2\text{O}_5$ .



Electrical resistivity of sintered polycrystalline niobium oxide with varied tungsten content,  $(\text{Nb}_{1-x}\text{W}_x)_2\text{O}_5$ .

- $(\text{Nb}_{0.93}\text{W}_{0.07})_2\text{O}_5$ .
- $(\text{Nb}_{0.85}\text{W}_{0.15})_2\text{O}_5$ .
- ▽  $(\text{Nb}_{0.94}\text{W}_{0.06})_2\text{O}_5$ .
- $(\text{Nb}_{0.95}\text{W}_{0.05})_2\text{O}_5$ .
- $(\text{Nb}_{0.96}\text{W}_{0.04})_2\text{O}_5$ .

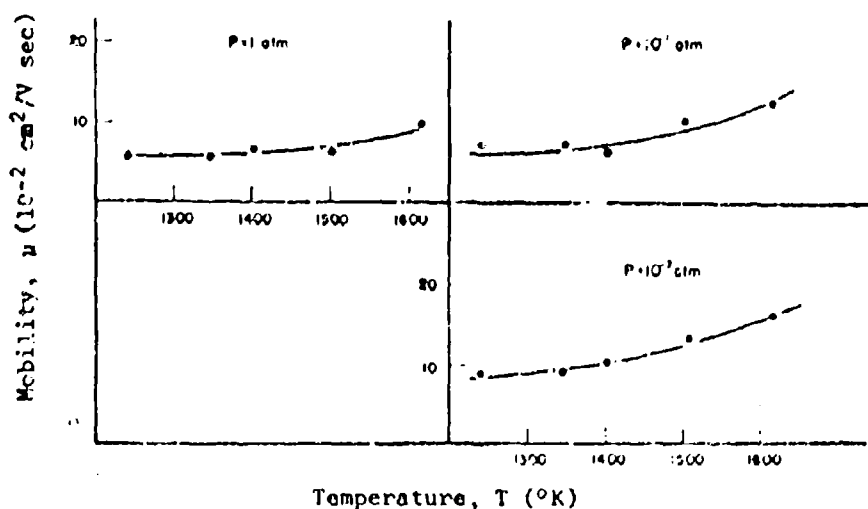
[Ref. 5956]



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# NIOBIUM-OXYGEN

## MOBILITY



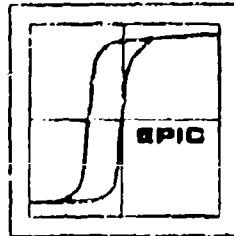
Electron mobility as a function of temperature for  $\alpha\text{-Nb}_2\text{O}_5$  at different oxygen vapor pressures.

[Ref. 16662]

## Electron Mobility

| Electron Mobility,<br>( $\text{cm}^2/\text{V sec}$ ) | Sample                                              | Temperature<br>( $^{\circ}\text{K}$ ) | Ref.  |
|------------------------------------------------------|-----------------------------------------------------|---------------------------------------|-------|
| ~.07                                                 | $\alpha\text{-Nb}_2\text{O}_5$                      | 1000                                  | 19883 |
| 0.218*                                               | nonstoichiometric<br>$\alpha\text{-Nb}_2\text{O}_5$ | 1273                                  | 14168 |

\* This is an average of 24 values ranging from 0.09 to 0.40 as  $x$  ( $\text{Nb}_2\text{O}_{5-x}$ ), increased from 4.8568 to 4.9992.



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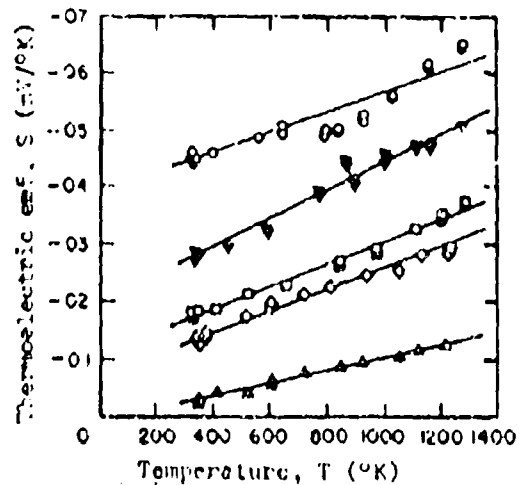
# NIOBIUM OXYGEN

## THERMOELECTRIC PROPERTIES

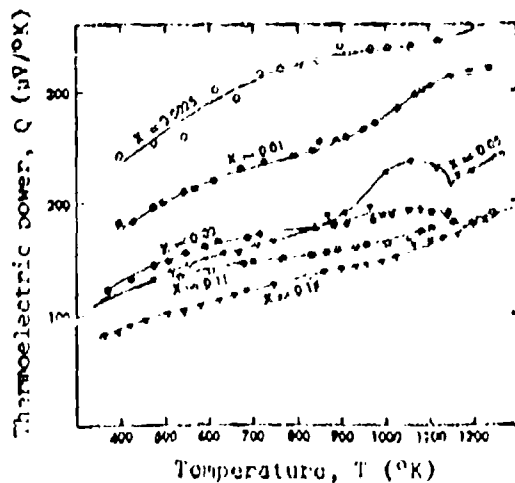
Temperature dependence of the Seebeck coefficient for nonstoichiometric  $\alpha\text{-Nb}_2\text{O}_5$ . High purity oxide powder was pressed to 20,000 psi and sintered for 3 hours at 1390°C. Departures from stoichiometry were produced by isopiestic reduction and followed by homogenization at 1100°C for several days.

Oxygen Content  
X

|   |        |
|---|--------|
| o | 4.9988 |
| v | 4.9977 |
| □ | 4.9908 |
| ◇ | 4.9814 |
| Δ | 4.8850 |



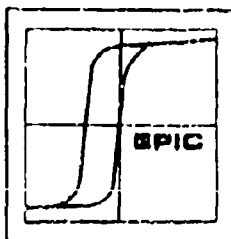
[Ref. 21734]



Thermoelectric power of sintered polycrystalline niobium oxide with varied tungsten content,  $(\text{Nb}_{1-x}\text{W}_x)_2\text{O}_5$ .

|   |                                                     |
|---|-----------------------------------------------------|
| o | $(\text{Nb}_{0.9975}\text{W}_{0.0025})_2\text{O}_5$ |
| ■ | $(\text{Nb}_{0.99}\text{W}_{0.01})_2\text{O}_5$     |
| ● | $(\text{Nb}_{0.97}\text{W}_{0.03})_2\text{O}_5$     |
| □ | $(\text{Nb}_{0.95}\text{W}_{0.05})_2\text{O}_5$     |
| ▼ | $(\text{Nb}_{0.93}\text{W}_{0.07})_2\text{O}_5$     |
| v | $(\text{Nb}_{0.91}\text{W}_{0.09})_2\text{O}_5$     |

[Ref. 5956]

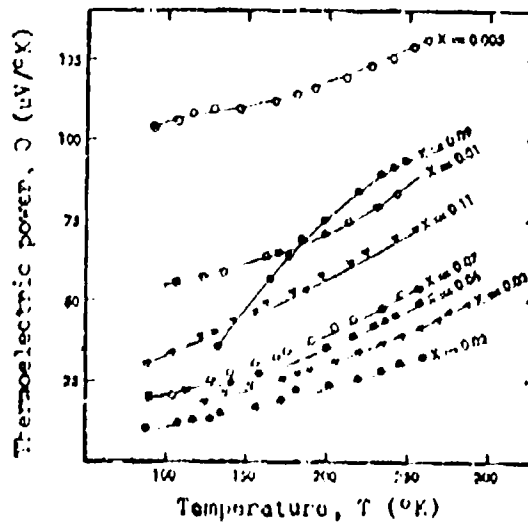


## NIOBIUM-OXYGEN

### THERMOELECTRIC PROPERTIES

Thermoelectric power of sintered polycrystalline niobium oxide with varied tungsten content,  $(\text{Nb}_{1-x}\text{W}_x)_2\text{O}_5$ .

- $(\text{Nb}_{.995}\text{W}_{.005})_2\text{O}_5$ .
- $(\text{Nb}_{.91}\text{W}_{.09})_2\text{O}_5$ .
- $(\text{Nb}_{.99}\text{W}_{.01})_2\text{O}_5$ .
- ▼  $(\text{Nb}_{.89}\text{W}_{.11})_2\text{O}_5$ .
- $(\text{Nb}_{.93}\text{W}_{.07})_2\text{O}_5$ .
- $(\text{Nb}_{.94}\text{W}_{.06})_2\text{O}_5$ .
- ▽  $(\text{Nb}_{.97}\text{W}_{.03})_2\text{O}_5$ .
- $(\text{Nb}_{.98}\text{W}_{.02})_2\text{O}_5$ .



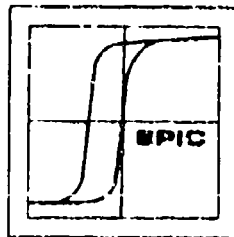
[Ref. 5956]

## NIOBIUM-OXYGEN

### DIELECTRIC PROPERTIES

The  $\text{Nb}_2\text{O}_5$  samples in the two following graphs have the following impurities:

| Sample # | Wt. %          |                |                         |                        |               |                         |
|----------|----------------|----------------|-------------------------|------------------------|---------------|-------------------------|
|          | $\text{SiO}_2$ | $\text{TiO}_2$ | $\text{Fe}_2\text{O}_3$ | $\text{P}_2\text{O}_5$ | $\text{SO}_3$ | $\text{Ta}_2\text{O}_5$ |
| 1        | 0.01           | 0.17           | 0.04                    | -                      | -             | -                       |
| 2        | 0.02           | 0.24           | 0.01                    | <0.01                  | 0.02          | 0.25                    |
| 3        | 0.31           | 1.51           | 0.1                     | "                      | 0.2           | 20                      |
| 4        | 0.06           | 0.3            | 1.96                    | "                      | "             | 0.29                    |
| 5        | 0.23           | 0.47           | 0.13                    | 0.08                   | 0.45          | -                       |
| 6        | 6.04           | 1.7            | 0.85                    | <0.01                  | 0.02          | 0.6                     |

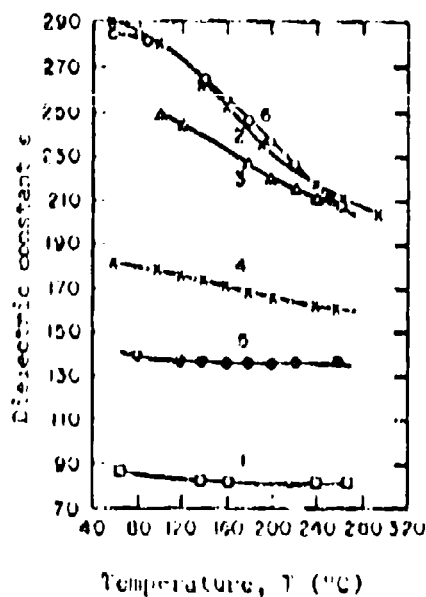
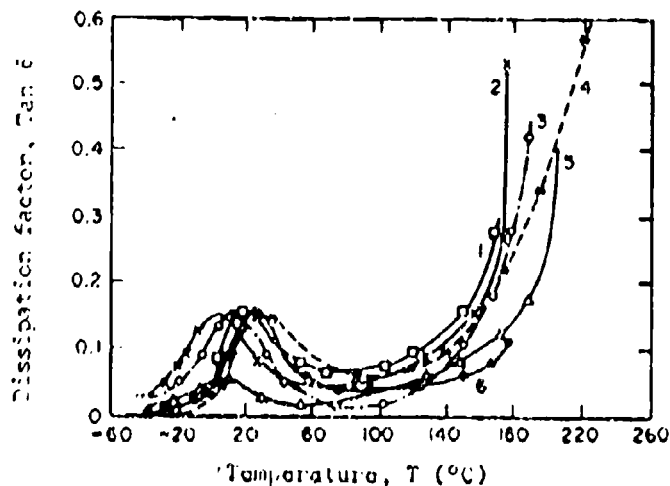


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# NIOBIUM-OXYGEN

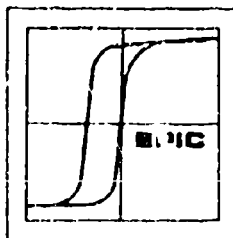
## DIELECTRIC PROPERTIES

Temperature dependence of  $\tan \delta$  of  $Nb_2O_5$ . Sample preparation: Pressed powders were fired at 1350-1450°C. Measurements taken at 1 kc.



Temperature dependence of dielectric constant of  $Nb_2O_5$ . Sample preparation: Pressed powders were fired 1350-1450°C. Measurements taken at 1 Mc.

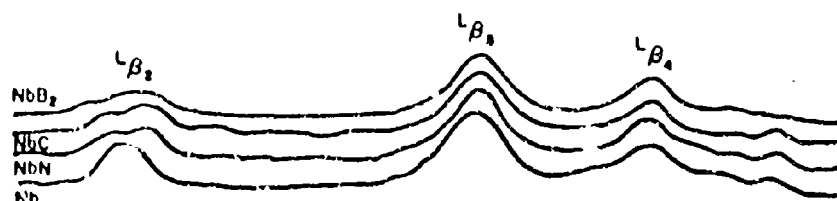
[Ref. 19117]



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# NIOBIUM-NITROGEN

## PHOTON EMISSION PROPERTIES



The L series spectra for NbN. Curves are given for NbB<sub>2</sub>, NbC and Nb for comparison.

[Ref. 16346]

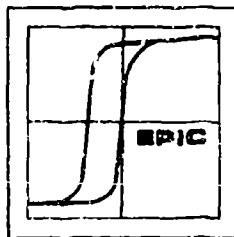
L line intensities for Nb compounds:

| Line                            | Nb   | NbN  | NbC  | NbB <sub>2</sub> |
|---------------------------------|------|------|------|------------------|
| L <sub>α1</sub>                 | 100  | 100  | 100  | 100              |
| L <sub>α2</sub>                 | 11   | 11   | 11   | 11               |
| L <sub>β1</sub>                 | 60.0 | 60.5 | 61.0 | 62.0             |
| L <sub>β3</sub>                 | 9.9  | 9.5  | 9.9  | 10.2             |
| L <sub>β2</sub>                 | 5.3  | 4.0  | 4.0  | 3.5              |
| L <sub>γ1</sub>                 | 2.0  | 1.47 | 1.48 | 1.40             |
| N <sub>IV</sub>                 | 0.56 | 0.39 | 0.39 | 0.36             |
| N <sub>V</sub>                  | 1.27 | 0.91 | 0.90 | 0.77             |
| N <sub>IV</sub> +N <sub>V</sub> | 1.83 | 1.30 | 1.29 | 1.13             |

Relative values of the variation of the L<sub>β2</sub> and L<sub>γ1</sub> lines for equal L<sub>β1</sub> intensities.

| Line            | Nb  | NbN  | NbC  | NbB <sub>2</sub> |
|-----------------|-----|------|------|------------------|
| L <sub>β2</sub> | 100 | 71.5 | 72.9 | 68.5             |
| L <sub>γ1</sub> | 37  | 26.3 | 27   | 27.6             |

[Ref. 15346]



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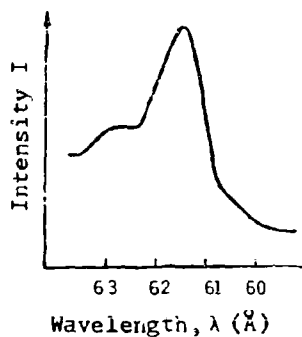
## NIOBIUM-NITROGEN

### PHOTON EMISSION PROPERTIES

Integral intensity of  $L_{82}$  bands for niobium nitrogen system, taking  $L_{82}$  line for Nb as unity.

| At. % N | Integral Intensity |
|---------|--------------------|
| 6.32    | 0.68               |
| 6.8     | 0.79               |
| 8.1     | 1.05               |
| 10.2    | 1.10               |
| 11.9    | 1.10               |
| 12.6    | 0.74               |

[Ref. 16347]



M emission band for Nb-N with 12.44% nitrogen.

[Ref. 19820]

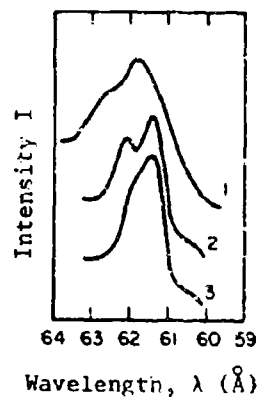
## NIOBIUM-OXYGEN

### PHOTON EMISSION PROPERTIES

M emission bands for:

- 1)  $Nb_2O_5$
- 2) Nb (cold emitter)
- 3) Nb (above 100°C)

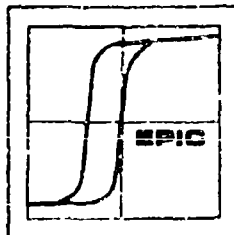
[Ref. 19820]





SECTION 2  
NIOBIUM-NITROGEN-  
OXYGEN SYSTEMS

AIR FORCE MATERIALS LABORATORY  
RESEARCH AND TECHNOLOGY DIVISION  
AIR FORCE SYSTEMS COMMAND



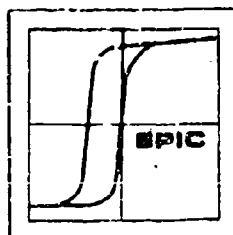
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# NIOBIUM-NITROGEN-OXYGEN

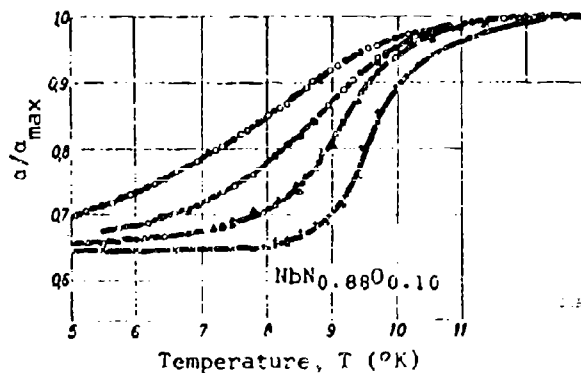
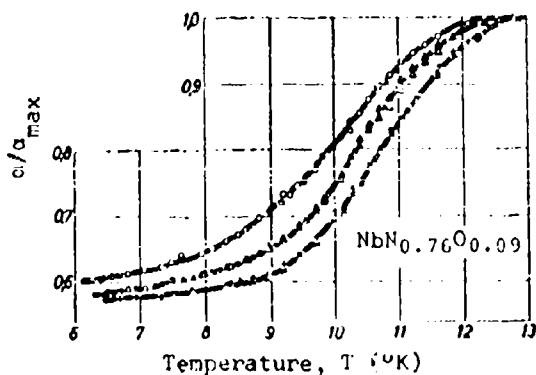
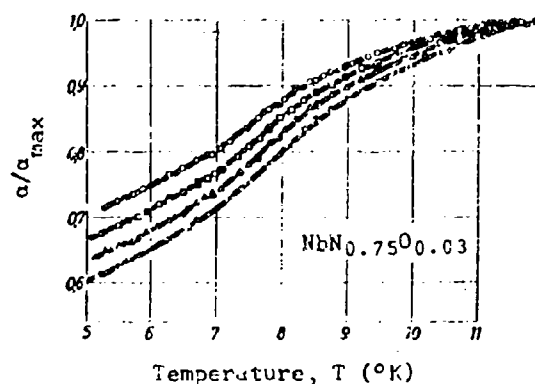
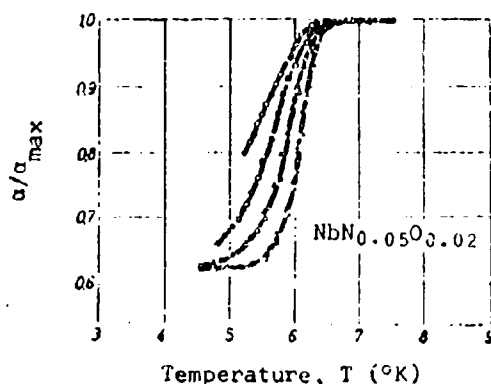
## LATTICE CONSTANT AND TRANSITION TEMPERATURE

| At.% N | Atomic Ratio |      | Symmetry | Lattice Constant (Å) |                | Transition Temp. °K |       |          | Ref.  |       |
|--------|--------------|------|----------|----------------------|----------------|---------------------|-------|----------|-------|-------|
|        | N/Nb         | O/Nb |          | a <sub>0</sub>       | c <sub>0</sub> | Midpoint            | Onset | Complete |       |       |
| 4.7    | .05          | .02  | α        | bcc                  | 3.311          | -                   | -     | -        | 20714 |       |
| "      | "            | "    | "        | "                    | -              | -                   | 5.28  | 6.5      | 9655  |       |
| 12.2   | .14          | .01  | α+β      | hcp                  | 3.050          | 4.958               | -     | -        | 20714 |       |
| "      | "            | .03  |          | "                    | -              | -                   | 6.02  | 7.1      | 9655  |       |
| 27.5   | .38          | .07  |          | hex                  | -              | -                   | -     | < 1.94   | -     | "     |
| 35.7   | .58          | .02  |          | hcp                  | 3.050          | 4.989               | -     | -        | -     | 20714 |
| "      | "            | "    |          | retr                 | -              | -                   | -     | 6.0      | -     | 9655  |
| 39.3   | .65          | .05  | β        |                      | 4.386          | 4.367               | -     | -        | 20714 |       |
| 39.7   | .66          | .10  | -        |                      | -              | 6.80                | 11.6  | -        | 9655  |       |
| 43.5   | .77          | .07  | -        |                      | -              | 4.386               | 4.329 | -        | -     | 20714 |
| "      | "            | "    | -        |                      | -              | -                   | -     | 9.92     | 12.7  | 9655  |
| 46.8   | .88          | .10  | γ        | fcc                  | 4.388          | -                   | -     | -        | 20714 |       |
| "      | "            | .08  | "        | "                    | -              | -                   | 7.66  | 12.1     | 9655  |       |



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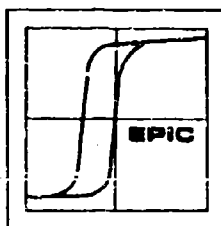
NIOBIUM-NITROGEN-OXYGEN  
TRANSITION TEMPERATURE



Transition curves for niobium nitride with residual oxygen.

| Field (Oe) | Warming | Cooling |
|------------|---------|---------|
| 145        | ●       | ○       |
| 109        | ■       | □       |
| 72.5       | ▲       | △       |
| 36.2       | +       | x       |

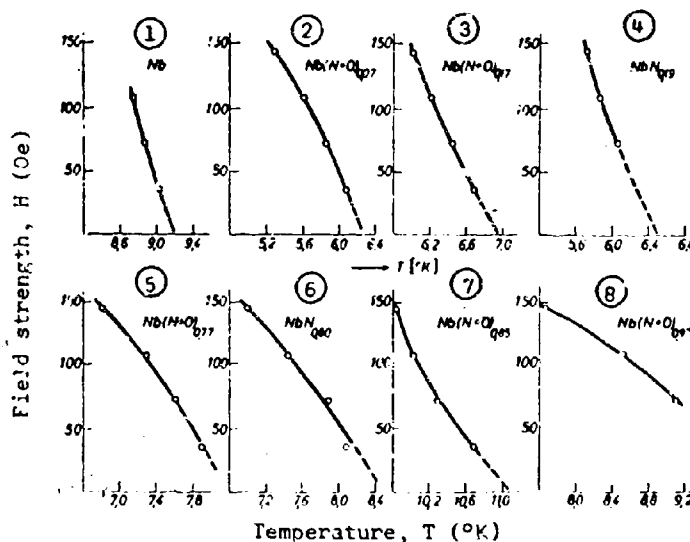
[Ref. 9655]



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# NIOBIUM-NITROGEN-OXYGEN

## CRITICAL FIELD

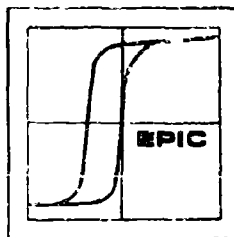


Critical field for niobium-nitrogen system with residual oxygen. Schröder's data on niobium nitrogen systems was supplemented by these data with residual oxygen. Some of the procedures used in the preparation of the NbN samples were eliminated and oxygen remained in the following amounts:

- 1) Nb
- 2) NbN<sub>0.05</sub>O<sub>0.02</sub>
- 3) NbN<sub>0.14</sub>O<sub>0.03</sub>
- 4) NbN<sub>0.19</sub>
- 5) NbN<sub>0.66</sub>O<sub>0.10</sub>
- 6) NbN<sub>0.80</sub>
- 7) NbN<sub>0.77</sub>O<sub>0.07</sub>
- 8) NbN<sub>0.88</sub>O<sub>0.08</sub>

[Ref. 9655]

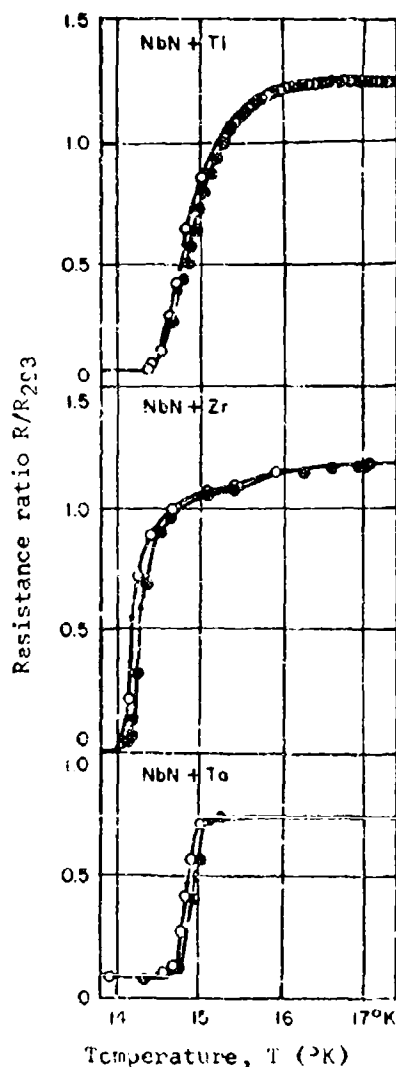
SECTION 2  
NIOBIUM-NITROGEN-M



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# NIOBIUM-NITROGEN-M

## TRANSITION TEMPERATURE

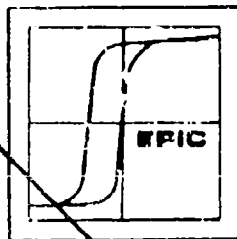


Transition curves for niobium-nitrogen system with additional metals. Strips of niobium 2mm x 0.06mm were alternated with 1-1.5mm x 0.35mm strips of the additional metal. These samples were rolled and heated 1 - 2 hours at 1700°C in vacuum. Then the diffused metal specimens were heated in nitrogen at 30-40 atmosphere of pressure for seven hours.

- 1) NbN + Ti
- 2) NbN + Zr
- 3) NbN + Ta

[Ref. 9617]

SECTION 3  
NIOBIUM-MAGNESIUM &  
NIOBIUM-ALUMINUM SYSTEMS



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## NIOBIUM ALLOYS AND COMPOUNDS

### NIOBIUM-MAGNESIUM AND NIOBIUM-ALUMINUM SYSTEMS

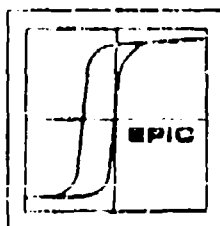
#### GENERAL

Nb-Al Three distinct compounds are formed in the niobium-aluminum binary system;  $Nb_3Al$  in the  $\beta$ -Wolfram phase,  $Nb_2Al$  in the  $\sigma$ -tetragonal and  $NbAl_3$  in the tetragonal. The data available for these compounds include transition temperature, critical field, magnetic hysteresis, and magnetic susceptibility.

Lattice constants and transition temperatures are given for four ternary compounds;  $Nb_3Al_{0.5}Ge_{0.5}$ ,  $NbAl_xSb_{1-x}$ , and  $Nb_3Al_xSn_{1-x}$ , with  $\beta$ -Wolfram structure and  $Nb_3Al_2C$  in the  $\beta$ -manganese. The nature of this latter structure is not fully understood and the lattice constants given for this material are those for the hexagonal subcell of the H phase. Johnston, et al, [Ref. 17803] claim that the  $\beta$ -manganese structure is favorable for the occurrence of superconductivity, however, in the niobium-aluminum system the  $\beta$ -tungsten structure gives better results.

Irradiation with fast neutrons  $1.5 \times 10^{18} \text{ n/cm}^2$ , increases the critical current density, [Ref. 15568]. Primary flux 0.1-4.0 MeV.  $\Delta J/nvt \left( \frac{10^5 \text{ A/cm}^2}{10^{18} \text{ n/cm}^2} \right) = 1.75$ .

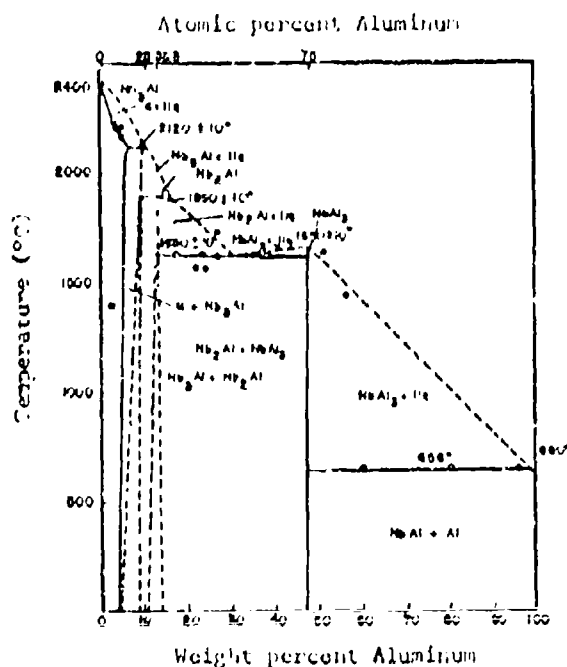




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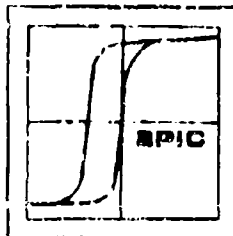
# NIOBIUM-ALUMINUM

## GENERAL



Phase diagram for niobium-aluminum alloys. Powder samples, are melted in He, 400-500 mm Hg pressure.

[Ref. 14280]



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## NIOBIUM-MAGNESIUM SYSTEM

### TRANSITION TEMPERATURE

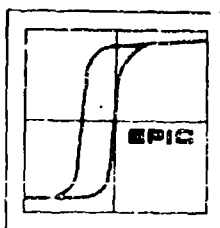
Nb-Mg The transition temperature for a niobium-magnesium sample, NbMg<sub>2</sub>, is given as 5.6°K [Ref. 10724].

## NIOBIUM-ALUMINUM

### TRANSITION TEMPERATURE

#### Lattice Constant and Transition Temperature

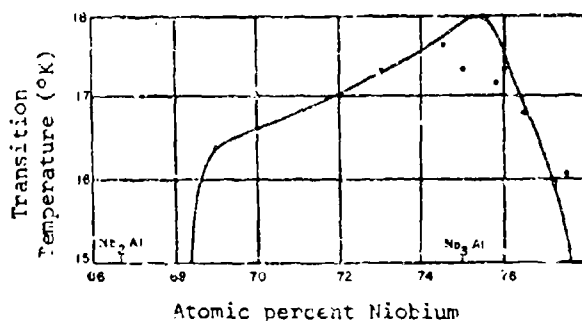
| At. % Al | Crystallography                  | Lattice Constant (Å) |                | Nb-Al<br>Transition<br>Temperature<br>T <sub>c</sub> (°K) | Notes                                                                                      | Ref.   |
|----------|----------------------------------|----------------------|----------------|-----------------------------------------------------------|--------------------------------------------------------------------------------------------|--------|
|          |                                  | a <sub>0</sub>       | c <sub>0</sub> |                                                           |                                                                                            |        |
| 25       | Nb <sub>3</sub> Al, β-tungsten   | 5.1871.002           |                |                                                           | Pressed pellets<br>fired in He<br>vac furnace                                              | 14387  |
|          |                                  | --                   | --             | 16.8-18.0                                                 | --                                                                                         | 9290   |
|          |                                  | --                   | --             | 17.0                                                      | --                                                                                         | 13020  |
|          |                                  | --                   | --             | 17.1                                                      | Fired at<br>1500°C.                                                                        | 13155  |
|          |                                  | --                   | --             | 17.5                                                      | Fired at<br>1500°C.                                                                        | "      |
|          |                                  | --                   | --             | 17.6                                                      | Melted granu-<br>lar compacts.                                                             | 19482  |
|          |                                  | --                   | --             | 17.7                                                      | Arc-cast, be-<br>fore irradiation                                                          | 15568  |
|          |                                  | --                   | --             | 17.40                                                     | Irradiated w/fast<br>neutrons,<br>1.5 x 10 <sup>18</sup> n/cm <sup>2</sup> ,<br>0.1-4 MeV. | "      |
|          |                                  | 5.183                | --             | 15.7                                                      | --                                                                                         | 19550  |
| 33       | Nb <sub>2</sub> Al, α-tetragonal | 9.957                | 5.167          | --                                                        | --                                                                                         | 14380  |
| "        | "                                | --                   | --             | 7-12                                                      | --                                                                                         | 9290   |
| 75       | NbAl <sub>3</sub> , tetragonal   | 5.438                | 8.601          | --                                                        | --                                                                                         | Hansen |



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## NIOBIUM-ALUMINUM

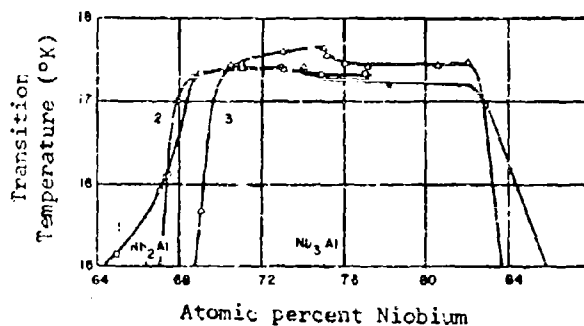
### TRANSITION TEMPERATURE



Transition temperature for a pressed, sintered, niobium-aluminum alloy as a function of niobium content.

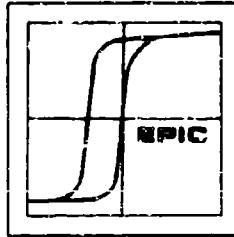
[Ref. 19482]

- 1 - pressed powder, presintered  
(1 hr. at 1000°C in vacuum)
- 2 - pressed powder, without  
presintering
- 3 - compact granules, without  
presintering



Transition temperature for niobium-aluminum alloys as a function of atomic percent niobium. Raetz and Saur claim a higher purity for the samples prepared from granules than those prepared from powders. Their sample preparations show a lower absorption of gases by the granules.

[Ref. 19482]

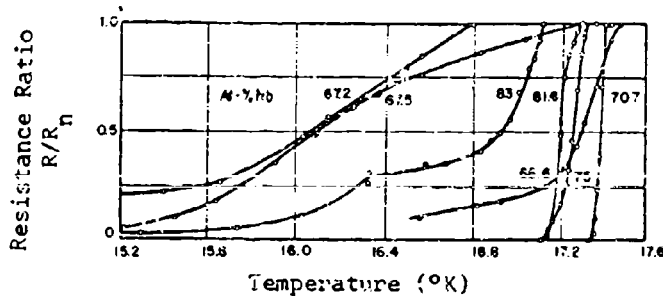
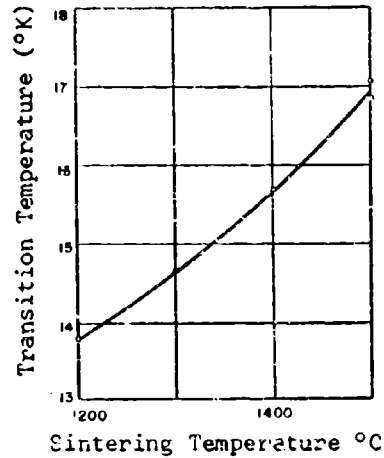


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## NIOBIUM-ALUMINUM

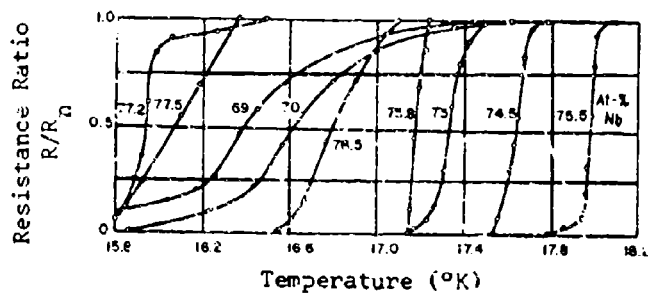
### TRANSITION TEMPERATURE

Transition temperature as a function of sintering temperature for a pressed, sintered niobium-aluminum ( $\text{Nb}_3\text{Al}$ ) powder. [Ref. 19482]

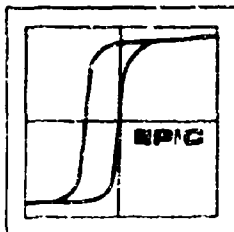


Transition curves for niobium-aluminum alloys. The niobium content (at.%) present in the alloy is indicated on the curve. Samples are arc-melted from a pressed powder without presintering.

Transition curves for niobium-aluminum alloys. The niobium content (at.%) in the alloy is indicated on the curve. Samples are sintered from a pressed powder.



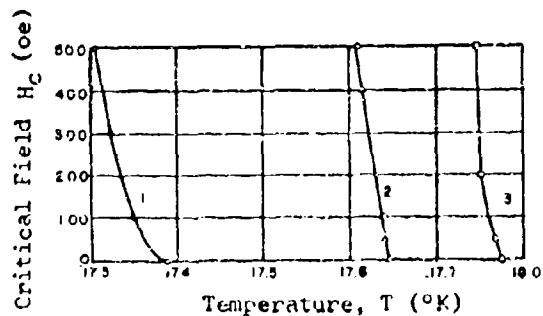
[Ref. 19482]



## NIOBIUM-ALUMINUM

### CRITICAL FIELD

- 1 - pressed powder without presintering  
(70.7 at.% Nb)
- 2 - compact granules without presintering  
(75 at.% Nb, Nb<sub>3</sub>Al)
- 3 - pressed powder presintered 1 hr. at  
1000°C in vacuum (75.5 at.% Nb, Nb<sub>3</sub>Al)  
For this sample  $\frac{\delta H_C}{\delta T} = -40 \text{ KOe/}^\circ\text{K}$



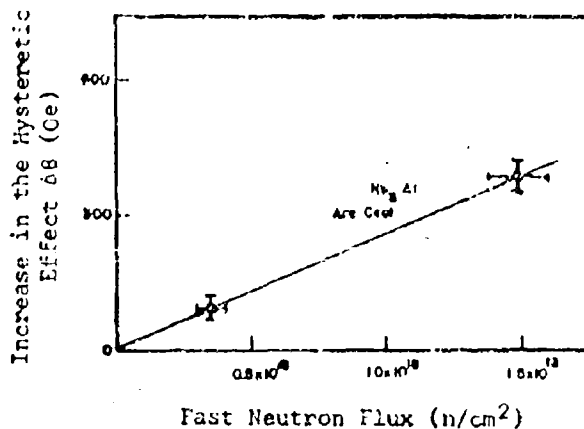
Critical field as a function of temperature for niobium-aluminum alloys. Samples were arc-melted.

[Ref. 19482]

### MAGNETIC HYSTERESIS

The change in magnetic hysteresis  $\delta$  as a result of fast neutron irradiation of a niobium-aluminum alloy. The sample was arc-cast from powder. Before irradiation, the magnetic hysteresis  $\delta$  of the sample, was equal to 60 Oe in a 4000 Oe field. Primary flux, 0.1-4 MeV.

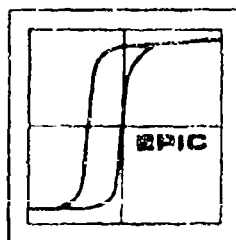
[Ref. 15569]



| neutron<br>irradiation<br>flux (n/cm <sup>2</sup> ) | Applied Field (oe) |      |      |
|-----------------------------------------------------|--------------------|------|------|
|                                                     | 2000               | 3000 | 4000 |
| $5 \times 10^{16}$                                  | 187                | 123  | 59   |
| $3.5 \times 10^{17}$                                | 311                | 205  | 147  |

Magnetic hysteresis for arc-cast Nb<sub>3</sub>Al.  
Primary flux 0.1-4 MeV.

[Ref. 17820]



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# NIOBIUM-ALUMINUM-M

## TRANSITION TEMPERATURE

### Lattice Constant and Transition Temperature

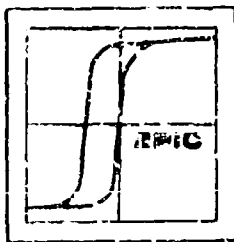
| Formula                   | Crystallography                          | Lattice Constant (Å) |       | Transition Temperature (°K) | Notes                                                     | Ref.  |
|---------------------------|------------------------------------------|----------------------|-------|-----------------------------|-----------------------------------------------------------|-------|
|                           |                                          | $a_0$                | $c_0$ |                             |                                                           |       |
| $Nb_3Al_2C$               | $\beta$ -manganese, H phase, hex subcell | 2.67                 | 8.02  | < 4.2                       | Sintered and annealed at 1000°C in vacuum furnace, cooled | 17803 |
| $Nb_3Al_{.5}Ge_{.5}$      | $\beta$ -tungsten                        | 5.175                | --    | 12.6                        | Powder pressed & sintered 3 hours at 1500°C.              | 13155 |
| $Nb_3Al_{.3}Sb_{.7}$      | --                                       | --                   | --    | 7.7                         | --                                                        | 19550 |
| $Nb_3Al_{<.3>.7}Sb_{>.7}$ | --                                       | --                   | --    | < 4.2                       | --                                                        | "     |

|                    |    |    |    |    |    |       |
|--------------------|----|----|----|----|----|-------|
| $Nb_3Al_xSn_{2-x}$ | -- | -- | -- | -- | -- | 13155 |
|--------------------|----|----|----|----|----|-------|

| Aluminum Content<br>$x$ | 16 hours, 950°C |       |              | 16 hours, 1200°C |       |              | 3 hours, 1500°C |       |              |
|-------------------------|-----------------|-------|--------------|------------------|-------|--------------|-----------------|-------|--------------|
|                         | $a_0$           | $T_c$ | $\Delta T_c$ | $a_0$            | $T_c$ | $\Delta T_c$ | $a_0$           | $T_c$ | $\Delta T_c$ |
| 0                       | --              | 17.9  | 0.5          | 5.292            | 18.1  | 0.2          | --              | --    | --           |
| .02                     | --              | 17.8  | 0.4          | --               | 17.9  | 0.4          | --              | --    | --           |
| .04                     | --              | 19.0  | 0.2          | --               | 18.0  | 0.2          | --              | --    | --           |
| .06                     | --              | 17.8  | 0.2          | --               | 18.0  | 0.2          | --              | --    | --           |
| .08                     | --              | --    | --           | --               | 17.9  | 0.2          | --              | --    | --           |
| .10                     | --              | --    | --           | 15.290           | 18.4  | 0.06         | 15.286          | 18.3  | 0.3          |
| .12                     | --              | 17.8  | 0.3          | --               | 19.4  | 0.3          | 15.281          | 18.2  | 1.3          |
| .20                     | --              | --    | --           | 15.290           | 16.9  | 0.7          | 5.272           | 13.1  | 2.9          |
| .40                     | --              | --    | --           | 15.276           | 15.4  | 0.4          | 5.257           | 15.1  | 0.9          |
| .60                     | --              | --    | --           | 15.270           | 15.2  | 0.6          | 5.231           | 14.5  | 2.8          |
| .80                     | --              | --    | --           | 15.262           | 14.6  | 0.4          | 5.217           | 15.0  | 1.0          |
| .99                     | --              | --    | --           | --               | --    | --           | 15.200          | 16.1  | 1.0          |
| 1.00                    | --              | --    | --           | --               | --    | --           | 5.186           | 17.1  | 0.8          |

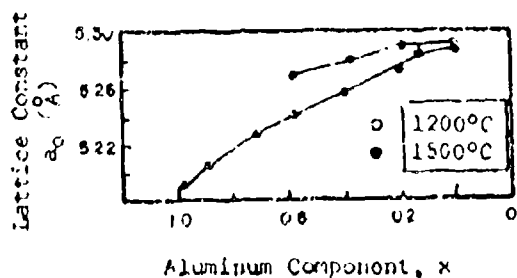
\* $\Delta T_c$  is the width of the transition region. All powdered samples pressed and sintered except as follows: † not pressed before sintering, \*\* sintered sample was re-fired.

†† a sample with  $x = .10$ , fired for 3 hours at 1800°C without pressing had the following values:  $a_0 = 5.276\text{Å}$ ,  $T_c = 7.3^\circ\text{K}$ ,  $\Delta T_c = 2.6$



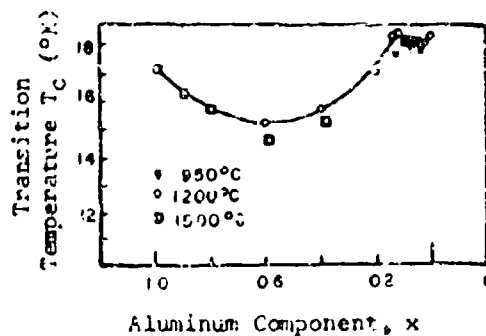
# NIOBIUM-ALUMINUM-X

## TRANSITION TEMPERATURE



Lattice constants as a function of composition for  $Nb_3Al_xSn_{1-x}$ .

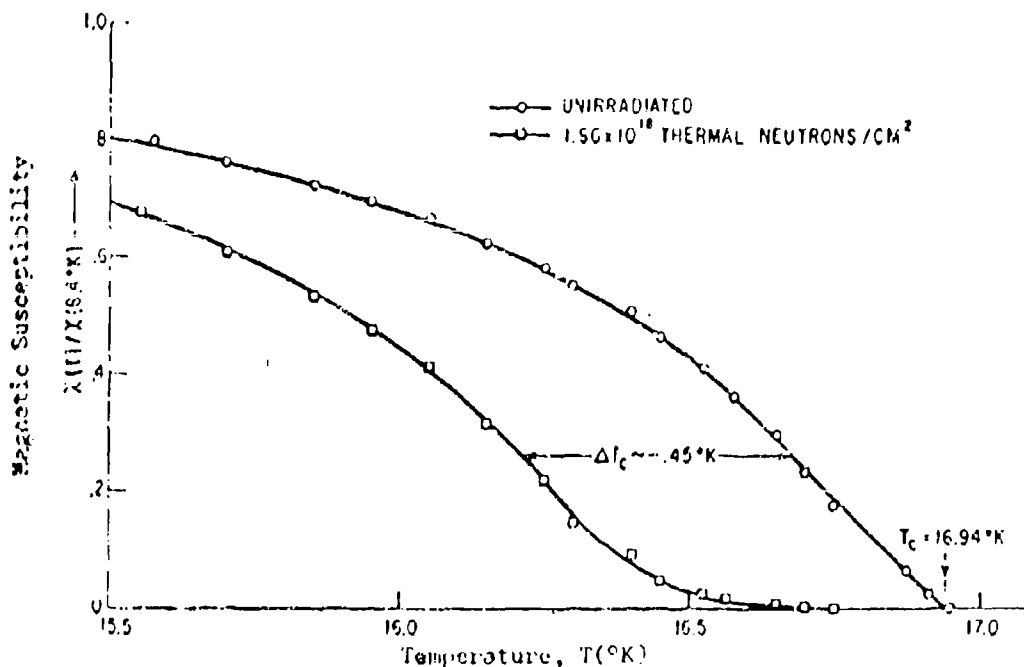
Samples were pressed and sintered at temperatures indicated.



Transition temperature of a niobium-aluminum-tin alloy as a function of  $x$  in  $Nb_3Al_xSn_{1-x}$ .

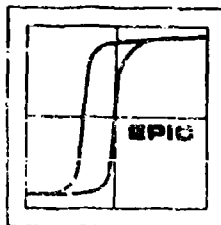
## MAGNETIC SUSCEPTIBILITY

[Ref. 13155]



Normalized susceptibility for  $Nb_3Al$  with .321 at.% U. The powdered samples were ground from an arc-cast rod.

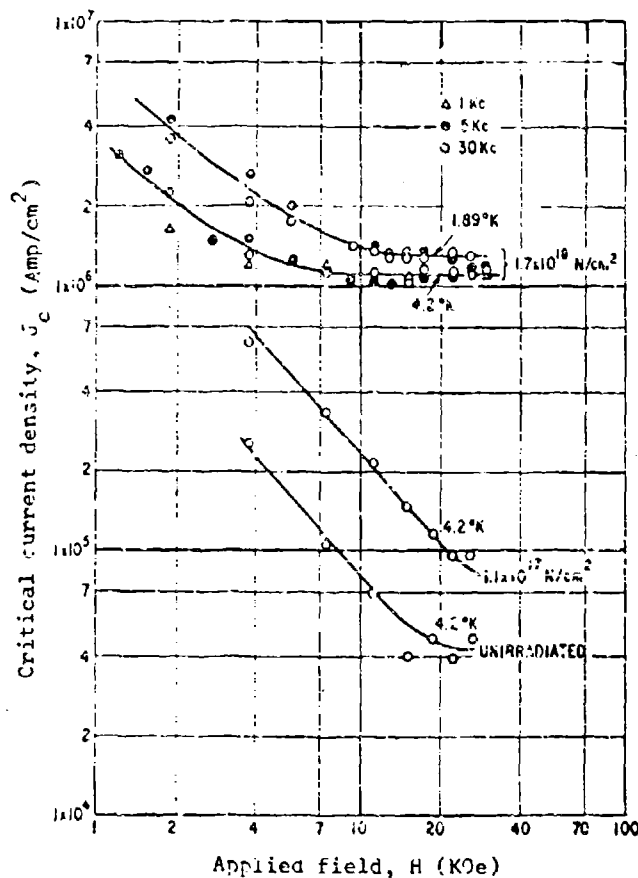
[Ref. 21907]



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# NIOBIUM-ALUMINUM-M

## CURRENT DENSITY

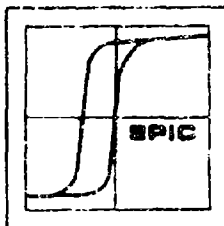


Current density of  $\text{Nb}_3\text{Al}$  as a function of applied field. The powdered samples, (70 $\mu$  particles) were ground from arc cast ingots and irradiated by thermal neutrons. The samples contained .321 at.% U.

[Ref. 21908]



SECTION 3  
NIOBIUM-SILICON &  
NIOBIUM-PHOSPHOROUS SYSTEMS



## NIOBIUM ALLOYS AND COMPOUNDS

### NIOBIUM-SILICON AND NIOBIUM-PHOSPHOROUS SYSTEMS

#### GENERAL

**Nb-Si** Until recently none of the niobium silicides showed a transition temperature above  $1.20\text{K}^\dagger$ . The 1963 paper of Galasso and Pyle [Ref. 21256] reports a  $\text{Nb}_3\text{Si}$  compound, with an ordered  $\text{Cu}_3\text{Au}$  structure, to have a  $T_c$  of  $1.5^\circ\text{K}$ .

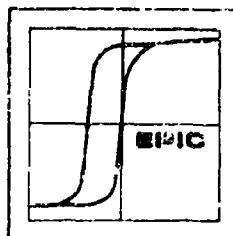
In a 1964 paper, Gold presented an empirical method of predicting the transition temperature of superconducting alloys and compounds. He claims that if  $\text{Nb}_3\text{Si}$  were to assume a  $\beta$ -tungsten structure, it would have a transition temperature between  $22.6$  and  $30.9^\circ\text{K}^*$ .

One attempt to form niobium and silicon into the  $\beta$ -tungsten structure was made by Holleck, et al. They began with  $\beta$ -tungsten  $\text{Nb}_3\text{Sn}$  and added niobium and silicon in a 3:1 ratio. The samples were hot pressed and sintered for 50 hours at  $1600^\circ\text{C}$ . For compositions to 50 mole percent  $\text{Nb(3)Si}$ , the  $\text{Nb}_3\text{Sn-Nb(3)Si}$  system was homogeneous. The lattice constant at the 50 percent point was  $5.25 \text{ \AA}$ . Projected to a possible  $\beta$ -tungsten structure, Holleck et al. claim the lattice constant for  $\text{Nb}_3\text{Si}$  to be  $5.19 \text{ \AA}$ . There is further doubt about the existence of this phase since the  $\text{Nb}_5\text{Si}_3$  phase will suppress the  $\beta$ -tungsten structure [Ref. 21457].

**Nb-P** No transition temperatures are reported for the niobium-phosphorous system. However, electrical resistivity data are given.

<sup>†</sup> The  $1.20^\circ\text{K}$  values come from [Refs. 9695 and 9793]. [Ref. 12216] gives the lowest temperature measured:  $T_c = 1.02^\circ\text{K}$ .

\* Gold, L., PHYS. STAT. SOL., v.4, p. 261 (1964).



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# NIOBIUM-SILICON

## GENERAL

### Lattice Constant

| At. % Si | Formula                           | Crystallography                           | Lattice Constant (Å) |                 | Ref.  |
|----------|-----------------------------------|-------------------------------------------|----------------------|-----------------|-------|
|          |                                   |                                           | $a_c$                | $c_o$           |       |
| 25       | Nb <sub>3</sub> Si                | cubic: Cu <sub>3</sub> Au                 | 4.211†               | --              | 21256 |
| 37.5     | Nb <sub>5</sub> Si <sub>3</sub>   | D8 <sub>8</sub>                           | 7.536                | 5.248           | *     |
| "        | α-Nb <sub>5</sub> Si <sub>3</sub> | tetr: Cr <sub>5</sub> B <sub>3</sub> type | 6.570                | 11.884          | 21416 |
| "        | β-Nb <sub>5</sub> Si <sub>3</sub> | tetr: Ni <sub>3</sub> P type              | 10.018               | 5.077           | "     |
| 67       | NbSi <sub>2</sub>                 | C40                                       | 4.785 ±<br>.005      | 6.576 ±<br>.005 | "     |

\* Schachner, H., et al. MM. CHEM., v. 85, no. 1, p. 245 (1954).

†  $a_0 = 4.207$  HCl transport method of preparation [Ref. 21843].

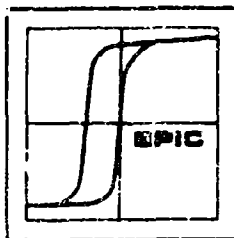
# NIOBIUM-PHOSPHOROUS

## GENERAL

### Lattice Constant

| Compound         | Lattice Constants (Å) |       |        |           | Symmetry   | Ref.  |
|------------------|-----------------------|-------|--------|-----------|------------|-------|
|                  | $a_o$                 | $b_o$ | $c_o$  | $\beta$   |            |       |
| NbP              | 3.334                 | -     | 11.378 | -         | tetr.      | *     |
| NbF <sub>2</sub> | 8.878                 | 3.266 | 7.529  | 119°8'±5' | monoclinic | 20108 |

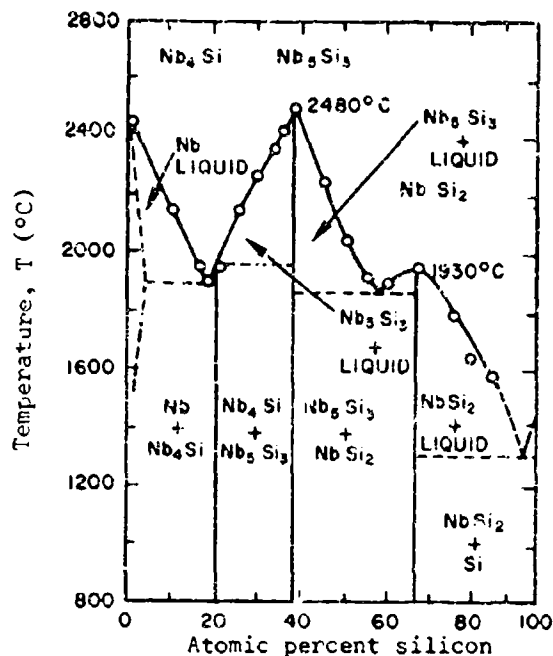
\* Boller, H. and E. Partne. ACTA.CRYST., v. 16, p. 1095, (1963).



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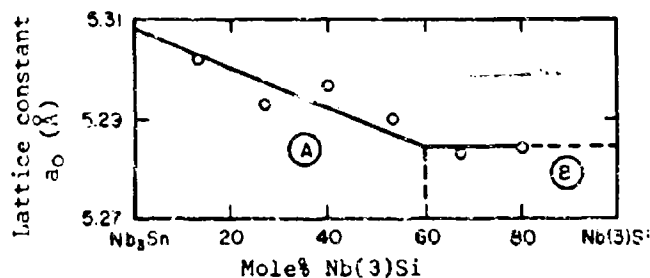
# NIOBIUM-SILICON

## GENERAL



Phase diagram for the niobium-silicon system. ○ observed melting points.

[Ref. 21421]

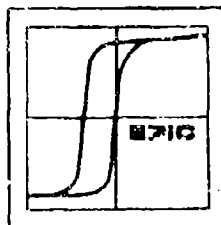


A - single phase region

B - two phase region

Lattice constant for the Nb<sub>3</sub>Sn-Nb(3)Si system. At 50% Nb(3)Si  $a_0 = 5.25$  Å and the probable lattice constant for a  $\beta$ -tungsten Nb<sub>3</sub>Si is given as 5.19 Å.

[Ref. 21457]



# NIOBIUM-SILICON

## SEMICONDUCTING PROPERTIES

### Semiconducting Properties

| Electrical<br>Resistivity<br>$\rho$ ( $\mu\Omega$ -cm) | Thermoelectric EMF<br>$\mu V/^{\circ}C$ | Hall coefficient<br>$R_H \times 10^{-4}$ ( $cm^3$ /coul) | Notes                              | Ref.  |
|--------------------------------------------------------|-----------------------------------------|----------------------------------------------------------|------------------------------------|-------|
| 6.3                                                    | --                                      | --                                                       | NbSi <sub>2</sub>                  | 18179 |
| 24.5                                                   | --                                      | --                                                       | "                                  | 13723 |
| 50.4                                                   | ( $\alpha$ ) + 14.4                     | -.77*                                                    | "                                  | 16993 |
| --                                                     | (S) 13.6                                | --                                                       | NbSi <sub>2</sub><br>arc-melted    | 14991 |
| --                                                     | 13.7                                    | --                                                       | NbSi <sub>2</sub><br>annealed      |       |
| --                                                     | 8.74                                    | --                                                       | NbSi <sub>1.95</sub><br>arc-melted |       |
| --                                                     | 10.35                                   | --                                                       | NbSi <sub>1.95</sub><br>annealed   |       |
| --                                                     | 12.4                                    | --                                                       | NbSi <sub>2.05</sub><br>arc-melted |       |
| --                                                     | 11.57                                   | --                                                       | NbSi <sub>2.05</sub><br>annealed   |       |

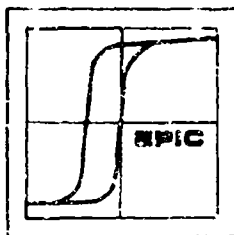
\* Hall mobility:  $\mu_H = 1.5$  ( $cm^2/V$  sec)

## NIOBIUM-PHOSPHOROUS

### ELECTRICAL RESISTIVITY

Ripley [Ref. 11072] reports the formation of  $\beta$ -NbP with the following percentages:  
Nb-74.4% and P-24.9%. The electrical resistivity is reported in the table below.

| $\rho$ ( $\Omega$ -cm) |                      |
|------------------------|----------------------|
| 20 $^{\circ}C$         | -197 $^{\circ}C$     |
| $1.7 \times 10^{-3}$   | $0.4 \times 10^{-3}$ |



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NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-SILICON

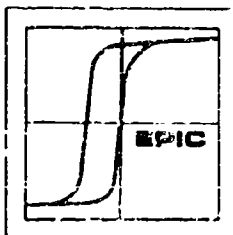
PHOTON EMISSION

Integral intensity of  $L_{\beta_2}$  bands for niobium-silicon compounds, taking  $L_{\beta_2}$  line for Nb as unity.

| <u>Compound</u>         | <u>Intensity</u> |
|-------------------------|------------------|
| $Nb_5Si_3$              | 0.60             |
| $NbSi_2$ (w/impurities) | 0.99             |

[Ref. 16347]

SECTION 4  
NIOBIUM-SCANDIUM, NIOBIUM-  
TITANIUM & NIOBIUM-VANADIUM SYSTEMS



## NIOBIUM ALLOYS AND COMPOUNDS

### NIOBIUM-SCANDIUM, NIOBIUM-TITANIUM AND NIOBIUM-VANADIUM SYSTEMS

#### GENERAL

**Nb-Sc** The transition temperature given by Hake, et al [Ref. 10713] for Nb-15Sc is greater than 4.2°K. This alloy was formed by melting the components in an arc-furnace on a water cooled copper hearth, inverted and melted at least six times. Rapid quenching resulted after the arc was broken.

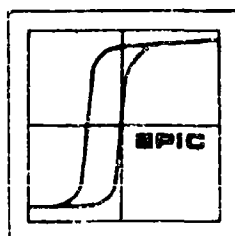
The critical current density measurements were taken on a cold rolled alloy reduced 85%.  $J_c$  is determined by increasing  $I$  until a slight voltage is noticed,  $\sim 0.25$   $\mu V$ .

**Nb-Ti** The niobium-titanium system assumes a cubic structure except in the titanium rich region, 75-80 at.% titanium. The transition temperature shows the change of phase near 83% titanium and extrapolates to  $T_c = 0.5^\circ K$  for non-alloyed titanium.

The difference between  $H_{c2}$ , the measured upper critical field, and  $H_{c2}^*$ , the upper critical field from the GLAG theory, is discussed by Shapira and Neuringer [Ref. 21646].

**Nb-V** The niobium-vanadium system assumes an alpha phase solid solution throughout the entire range of vanadium compositions, and the lattice constants for this system decrease linearly from  $a_0 \approx 3.32$  for niobium to  $a_0 \approx 3.03$  for vanadium. The transition temperatures have a value of  $T_c \approx 9^\circ K$  for niobium, reach a minimum of  $T_c \approx 4^\circ K$  and then rise to  $T_c \approx 5^\circ$  for vanadium.

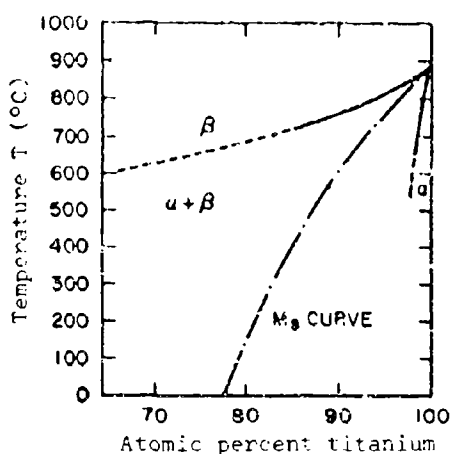




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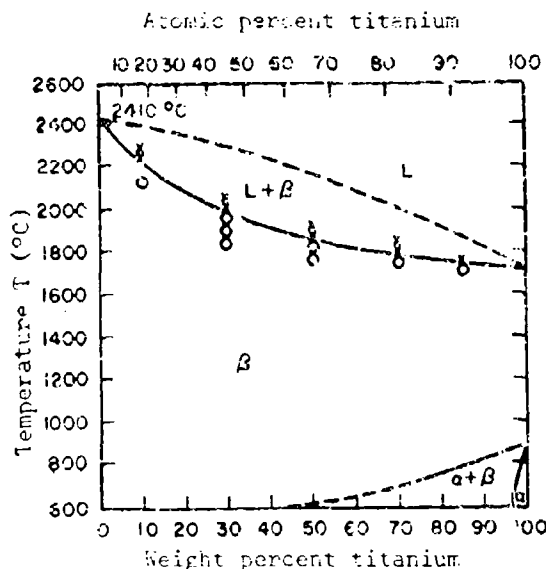
# NIOBIUM-TITANIUM

## GENERAL



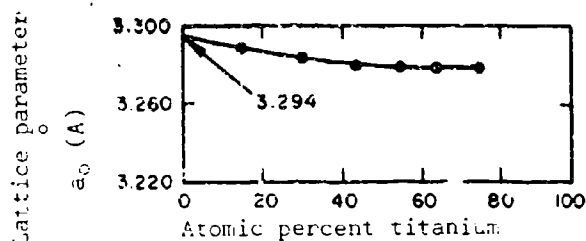
The high titanium region of the niobium-titanium phasediagram, showing the martensite curve.

[Ref. 12583]



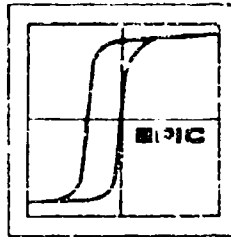
Phase diagram for the niobium-titanium system. The phase changes from  $\beta$  (cubic) to mixed  $\alpha$  (hcp) and  $\beta$  phases in the titanium-rich region.

[Ref. 21471]



[Ref. 21471]

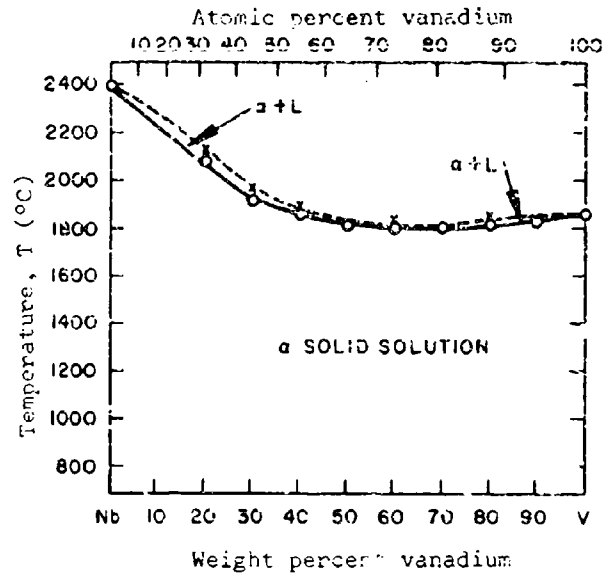
Lattice parameter of the niobium-titanium system as a function of titanium content.



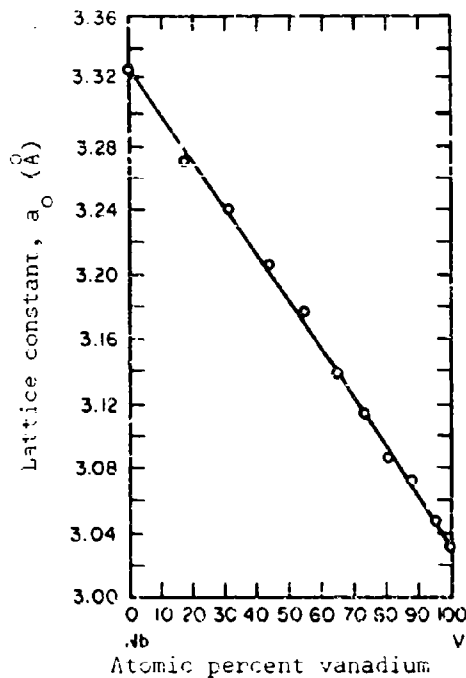
# NIOBIUM-VANADIUM

## GENERAL

Phase diagram for niobium-vanadium system.

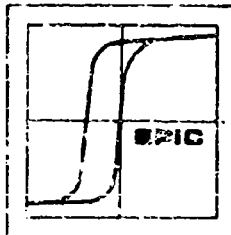


[Ref. 21466]



Lattice constants for the niobium-vanadium system. Niobium in sheet or pellet form powder, was melted with sheet vanadium in an arc furnace. The alloys were remelted three or four times to increase homogeneity. Data taken above 550°C.

[Ref. 21466]



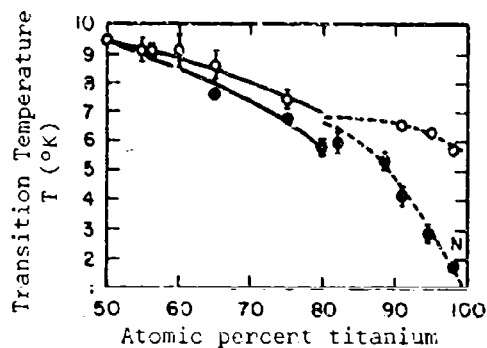
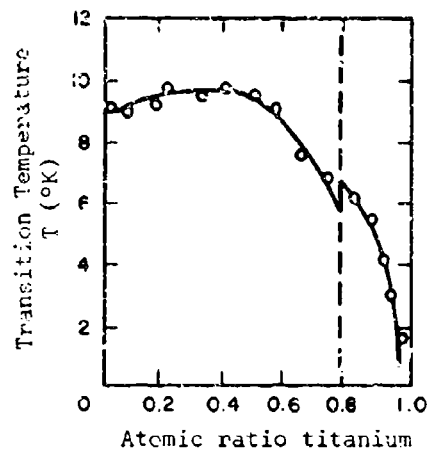
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# NIOBIUM-TITANIUM

## TRANSITION TEMPERATURE

Transition temperatures for the niobium-titanium system, showing the phase change.

[Ref. 12583]



Transition temperatures for the niobium-titanium system in the titanium-rich zone. On extrapolation,  $T_c = 0.5^\circ\text{K}$  for titanium.

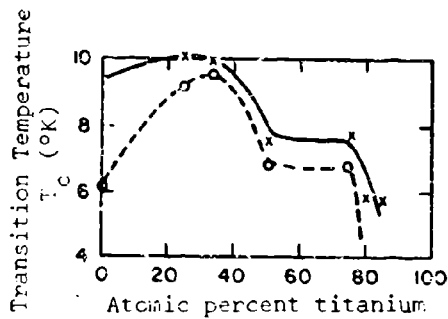
- slow cooled
- water quenched

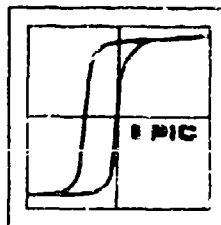
[Ref. 12583]

Transition temperature for the niobium-titanium system.

- $H = 5$  (KOe)
- x  $H = 0$

[Ref. 21849]





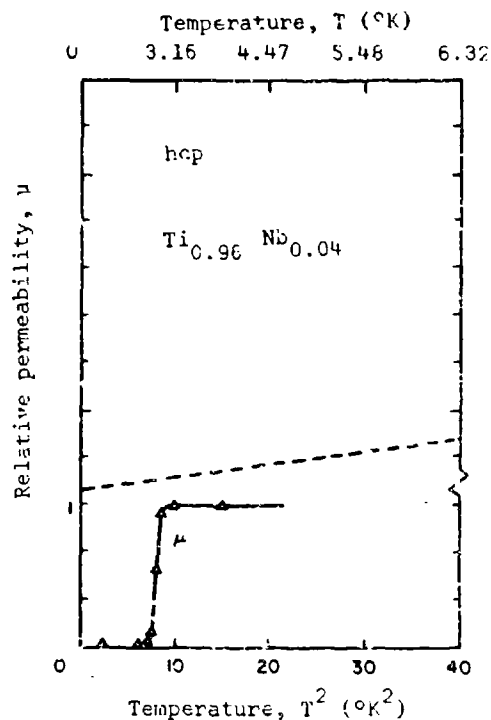
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NIOBIUM-TITANIUM

TRANSITION TEMPERATURE

Transition curve for single phase hcp  
 $\text{Ti}_{0.96}\text{Nb}_{0.04}$  from permeability  
measurements

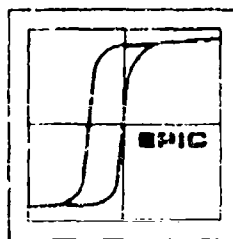
[Ref. 15532]



Lattice Constant and Transition Temperature

| At. % Ti | Symmetry | Lattice Constant (Å) |       | Transition Temperature<br>$T_c$ (°K) | Notes                                            | Ref.  |
|----------|----------|----------------------|-------|--------------------------------------|--------------------------------------------------|-------|
|          |          | $a_o$                | $c_o$ |                                      |                                                  |       |
| ~80      | hex      | 2.93                 | 4.57  | 7.9                                  | at the $\beta$ -( $\alpha$ + $\beta$ ) boundary  | 11542 |
| 97.5     | hcp      | --                   | --    | 1.5                                  | arc-melted, cold rolled, annealed 650°C, 2 hours | 17310 |

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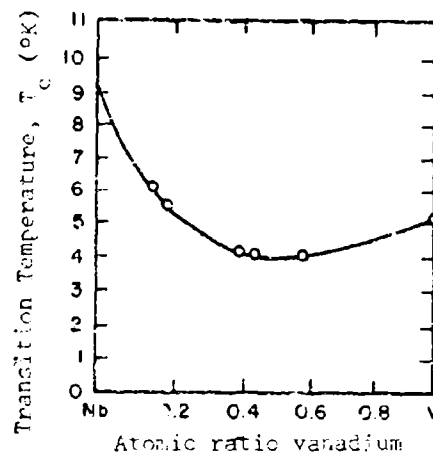
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# NIOBIUM-VANADIUM

## TRANSITION TEMPERATURE

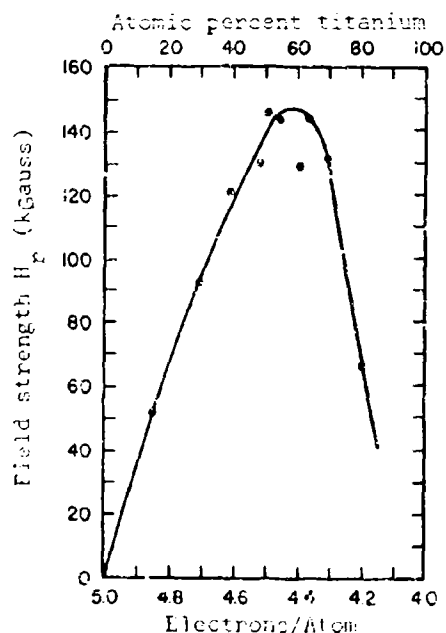
Transition temperature for niobium-vanadium system.

[Ref. 12583]



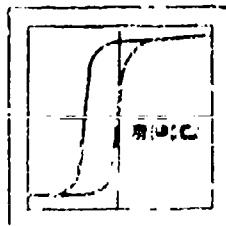
# NIOBIUM-TITANIUM

## CRITICAL FIELD



Field strength necessary to restore resistivity to titanium-niobium samples. The data are taken at  $J = 10 \text{ amp/cm}^2$  and  $T = 1.2^\circ\text{K}$ .

[Ref. 15326]



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# NIOBIUM-TITANIUM

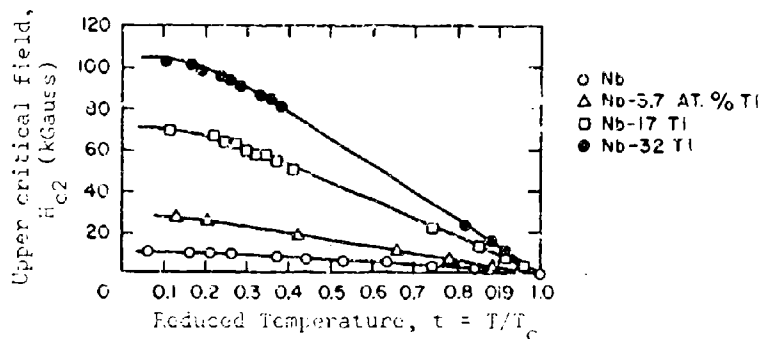
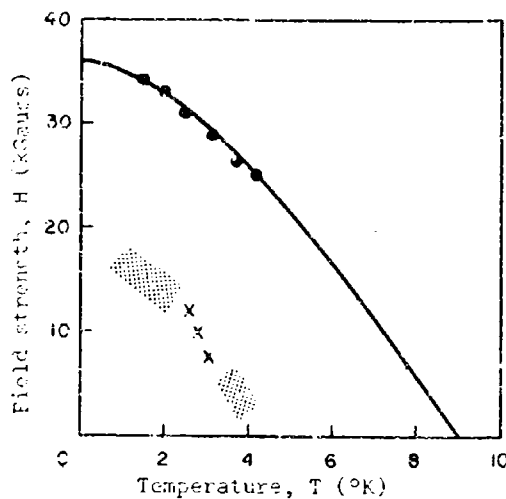
## CRITICAL FIELD

Upper critical field and resistance minima  
for  $Nb_{0.9}Ti_{0.1}$ , highly annealed with a  
small amount of defects.

X - resistance minima  
(these will probably extend into the shaded area)

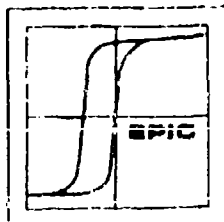
• -  $H_{c2}(T)$

[Ref. 21841]



The upper critical field for niobium and three niobium-titanium alloys.

[Ref. 15479]



# NIOBIUM-TITANIUM

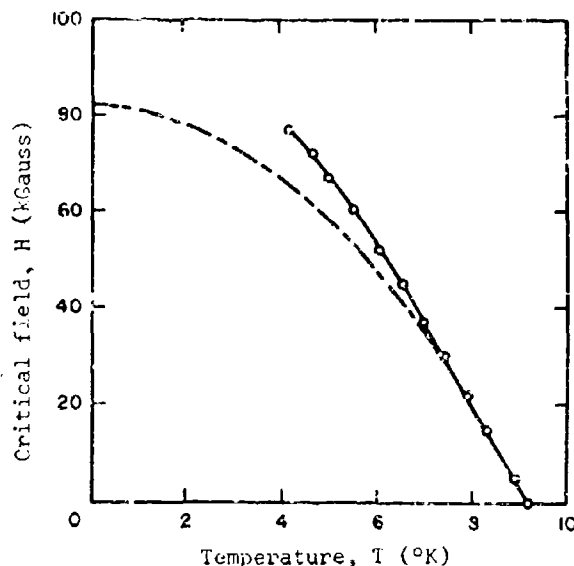
## CRITICAL FIELD

Critical field for 2Nb-Ti. Data taken  
at  $J = 1$  to  $10 \text{ Amp/cm}^2$ .

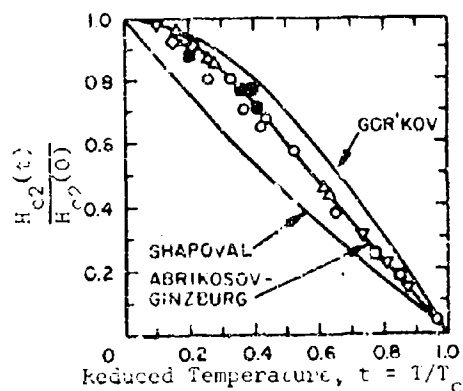
$$H_c = 82 \text{ kGauss}$$

$$--- H = H_c \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right]$$

[Ref. 11689]



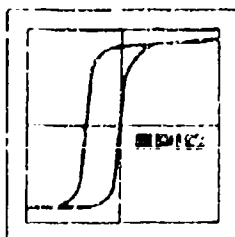
Upper transition field ratio



- Nb COLD WORKED
- Nb ANNEALED
- △ Nb 3.8 AT. % Ti COLD WORKED
- ◇ Nb 17 AT. % Ti COLD WORKED
- ▽ Nb 34 AT. % Ti COLD WORKED
- Nb 56 AT. % Ti COLD WORKED

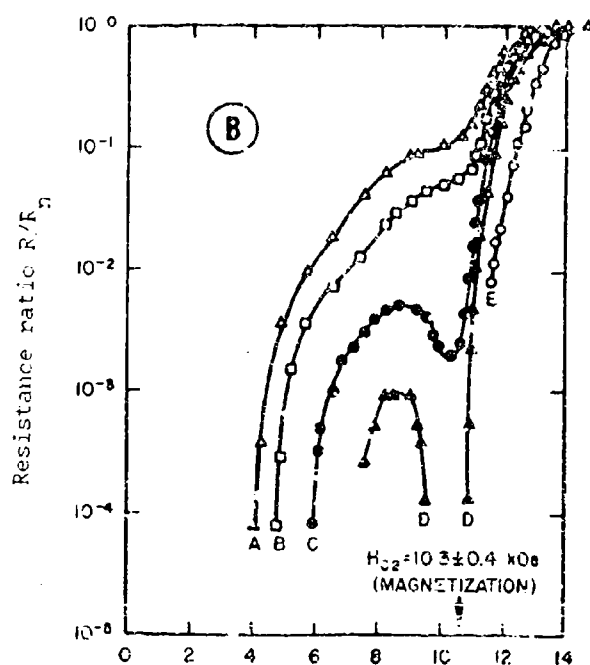
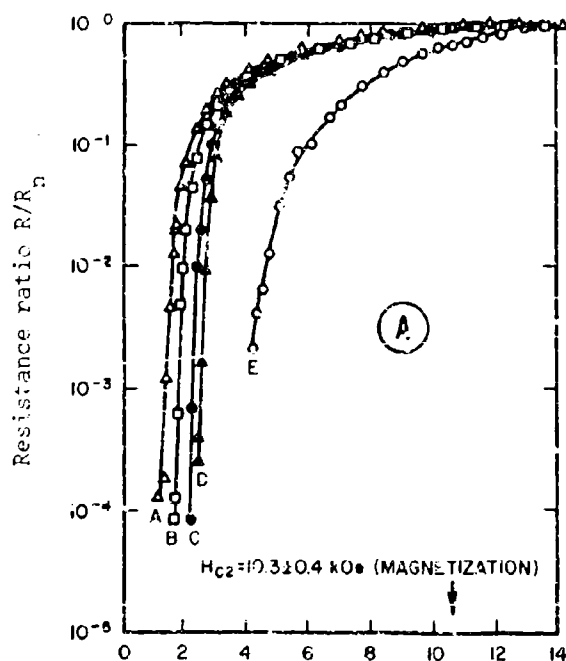
The upper critical field ratio for niobium-titanium.

[Ref. 15470]



NIOBIUM-TITANIUM

CRITICAL FIELD



Transition curves for niobium + 3.0 at.% titanium, ribbon samples.

(A)

annealed

|   | I (A)  | J (A/cm <sup>2</sup> ) |
|---|--------|------------------------|
| A | 1.62   | 797                    |
| B | 0.975  | 480                    |
| C | 0.457  | 240                    |
| D | 0.321  | 158                    |
| E | 0.0195 | 9.6                    |

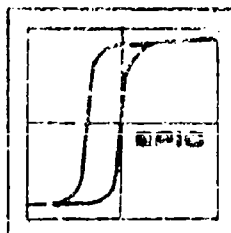
(B)

cold worked

|   | I (A) | J (A/cm <sup>2</sup> ) |
|---|-------|------------------------|
| A | 1.06  | 797                    |
| B | 1.00  | 480                    |
| C | 0.56  | 240                    |
| D | 0.33  | 158                    |
| E | 0.020 | 9.6                    |

[Ref. 15459]





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NIOBIUM-TITANIUM

CRITICAL FIELD

Electrical Resistivity and Critical Field

Rolled Sample

| <u>At.% Ti</u> | <u><math>\rho_n</math><br/>(<math>\mu\Omega</math>-cm.)</u> | <u><math>H_{c*}</math><br/>(kGauss)</u> |       |
|----------------|-------------------------------------------------------------|-----------------------------------------|-------|
| 5              | 6.8                                                         | 33.2                                    | 39.9  |
| 10†            | 12.0                                                        | 51.3                                    | 58.7  |
| 15             | 19.0                                                        | 58.0                                    | 64.0  |
| 30             | 30.6                                                        | 104.4                                   | 112.0 |
| 40             | 42.2                                                        | 123.0                                   | 129.0 |
| 59.5           | 58.7                                                        | 144.0                                   | 146.0 |
| 70.0           | 79.4                                                        | 137.0                                   | 140.0 |
| 75.0           | 98.5                                                        | 112.5                                   | 116.3 |
| 80.0           | 97.2                                                        | 98.0                                    | 108.0 |
| 90.0           | 63.8                                                        | 38.0                                    | 44.8  |

Wire Sample

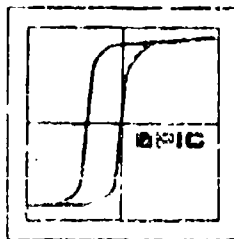
|      |      |       |    |
|------|------|-------|----|
| 48   | 49.3 | 125.0 | -- |
| 57.3 | 55.8 | 137.5 | -- |
| 62.3 | 63.0 | 145.0 | -- |
| 66.9 | 78.3 | "     | -- |
| 70.0 | 95.7 | 136.2 | -- |

[Ref. 11924]

\*  $H_c$  data taken at  $J = 10 \text{ Amp/cm}^2$ ,  $T = 1.2^\circ\text{K}$

† 10 at.% titanium alloy:  $\rho = 13.6 \mu\Omega$ -cm,  $H_c = 28.1 \text{ kGauss}$

[Ref. 16589]



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# NIOBIUM-SCANDIUM

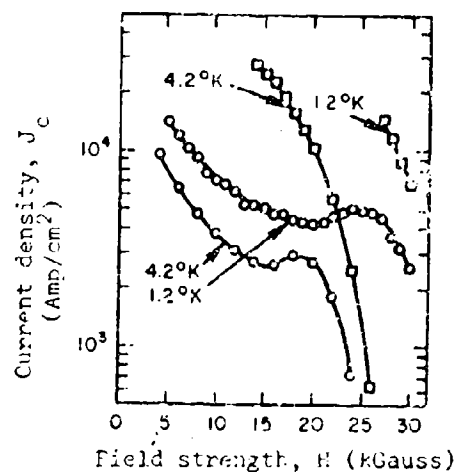
## CURRENT DENSITY

Critical current density for a niobium-scandium alloy (15 at.% Sc).

○ H ⊥ rolling plane

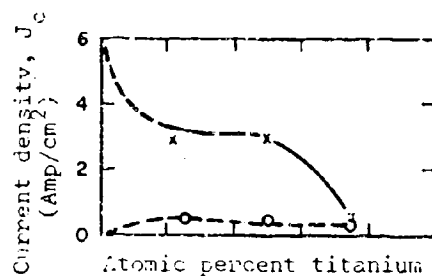
□ H || rolling plane

[Ref. 19713]



# NIOBIUM-TITANIUM

## CURRENT DENSITY

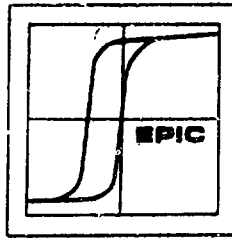


x H = 0

o H = 5 (KOe)

Critical current density for the niobium-titanium system. Data taken at 5°K.

[Ref. 21849]



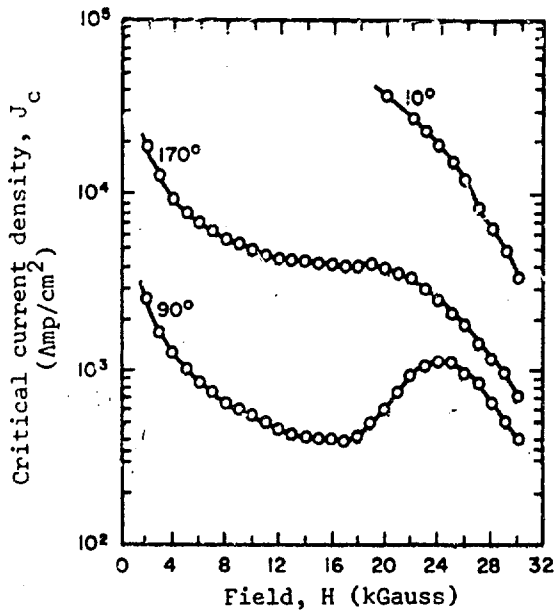
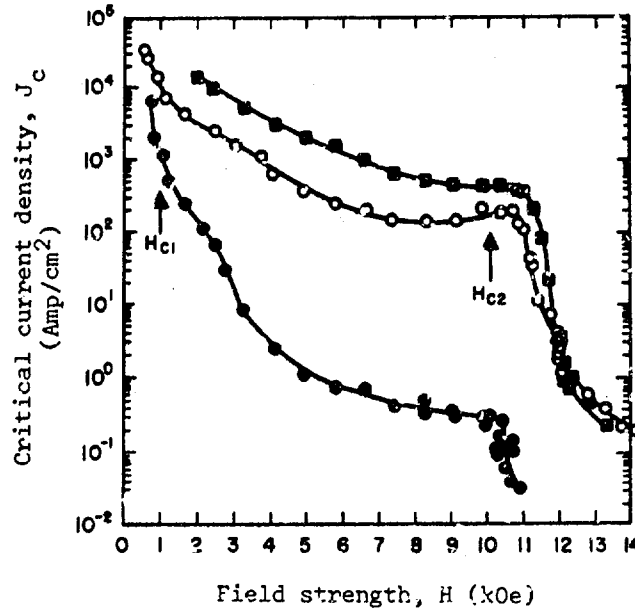
# NIOBIUM-TITANIUM

## CURRENT DENSITY

Critical current density for niobium + 3.0 at.% titanium for different field orientations. The field,  $H$  is perpendicular to the current.

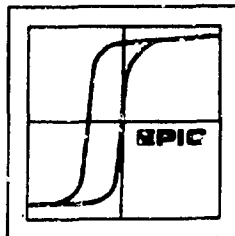
- cold worked ribbon  $H \perp$  wide side
- cold worked ribbon  $H \parallel$  wide side
- annealed wire

[Ref. 15459]



Critical current density as a function of field strength for a Nb-10 at.% Ti alloy reduced 62:1. The data were taken at 4.2°K ( $\theta$  is the angle between the field and the rolling plane).

[Ref. 15344]



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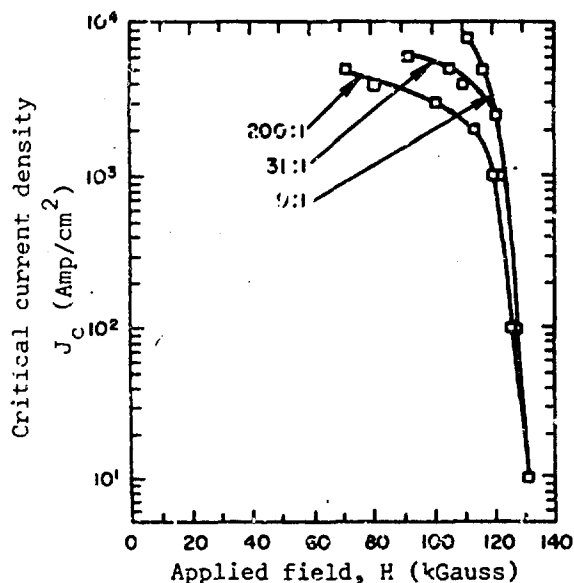
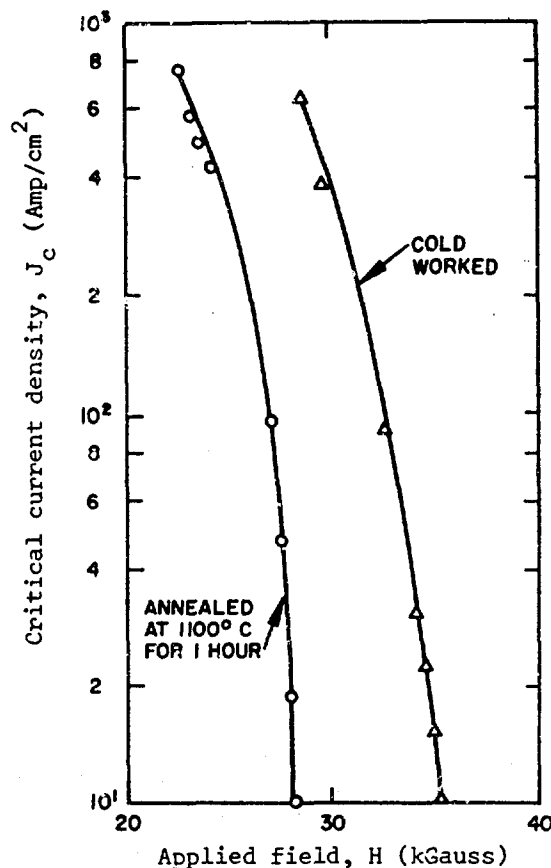
# NIOBIUM-TITANIUM

## CURRENT DENSITY

Critical current density as a function of transverse applied field for Nb 10 at.% Ti.

Data were taken at 4.2°K.

[Ref. 16589]

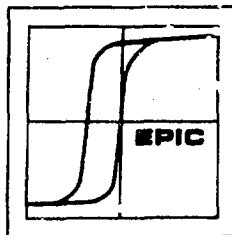


Critical current density for 35 Nb-65 Ti alloy.

The data were taken at 1.2°K with H parallel to the rolling plane and perpendicular to J.

The samples were cold rolled; the thickness reduction ratios are indicated on the curves.

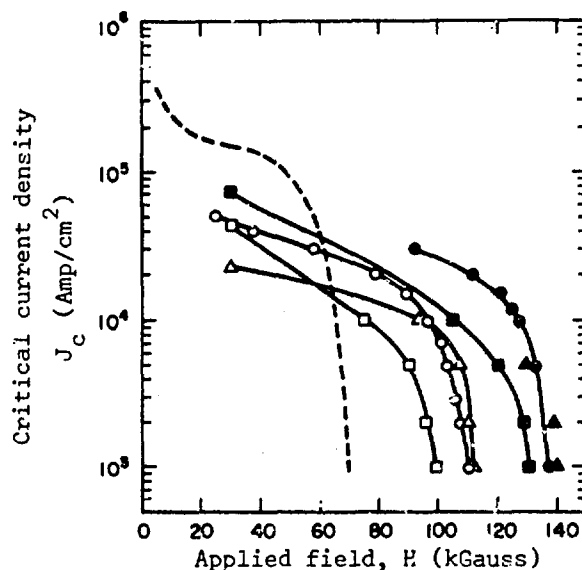
[Ref. 15320]



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NIOBIUM-TITANIUM

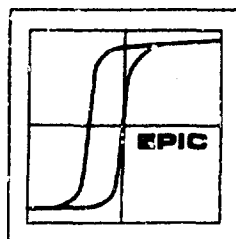
CURRENT DENSITY



Critical current density as a function of transverse applied field.

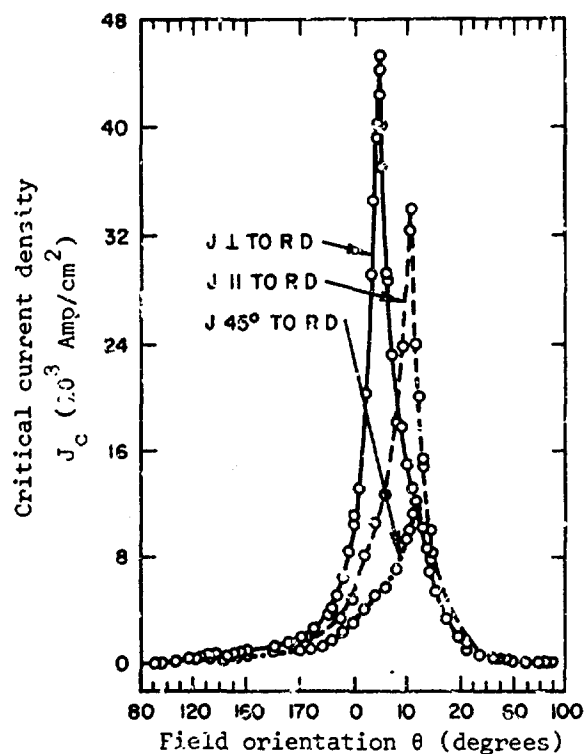
| 1.2°K | 4.2°K |                                                                                                            |
|-------|-------|------------------------------------------------------------------------------------------------------------|
| ■     | □     | Nb <sub>.30</sub> Ti <sub>.70</sub> 0.010 in. diam. wire                                                   |
| ▲     | △     | Nb <sub>.39</sub> Ti <sub>.61</sub> 0.0051 in. diam. wire                                                  |
| ●     | ○     | Nb <sub>.50</sub> Ti <sub>.50</sub> 0.0016 thick strip reduced 275:1<br>by cold rolling, H   rolling plane |
| ----- |       | Nb <sub>.75</sub> Zr <sub>.25</sub> for comparison                                                         |

[Ref. 15320]



NIOBIUM-TITANIUM

CURRENT DENSITY



Critical current density for three Nb-40 at.% Ti alloys as a function of the angle between applied field and rolling plane.

$H = 30$  kGauss

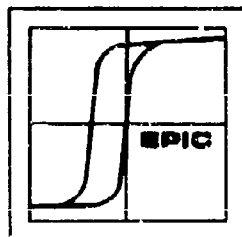
$T = 4.2^\circ\text{K}$

$J \parallel$  R.P.

$H \perp J$

240 : 1 reduction

[Ref. 15344]



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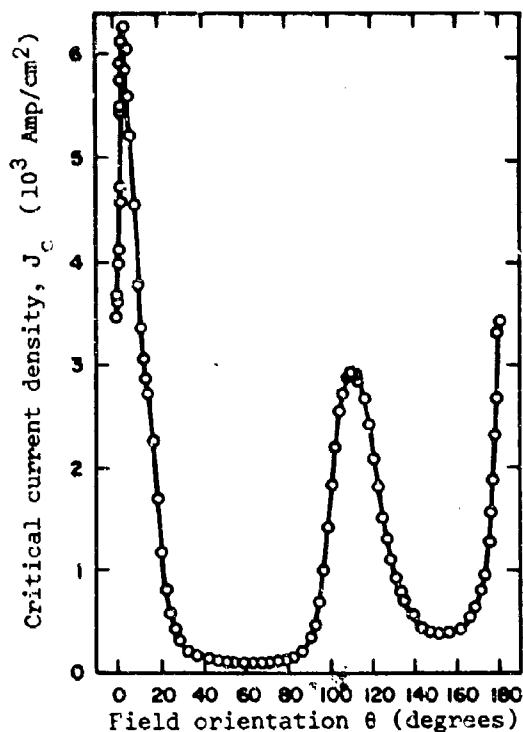
# NIOBIUM-TITANIUM

## CURRENT DENSITY

Critical current density for a Nb-40 at.% Ti alloy as a function of the orientation of H with the rolling plane of the sample.

H  $\perp$  rolling direction  
J  $\parallel$  rolling direction  
H = 30 kGauss  
T = 4.2°K  
24 : 1 reduction

[Ref. 15344]

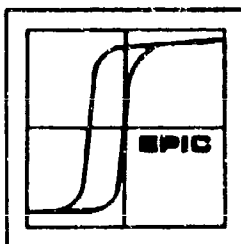


## Critical Current Density

$J_c$  ( $10^3$  Amp/cm $^2$ )

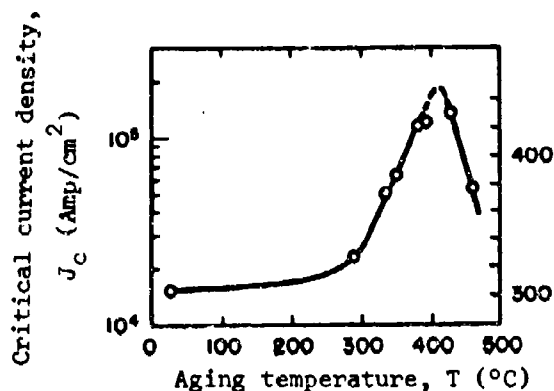
| Ti  | Rolling Plane |           | Unrolled | Reduction | T°K | Notes                                 |
|-----|---------------|-----------|----------|-----------|-----|---------------------------------------|
|     | H $\parallel$ | H $\perp$ |          |           |     |                                       |
| 80% | 4.8           | 4.4       | --       | 99%       | 1.2 | 30 kGauss standard sample preparation |
| 65  | 4.6           | 0.38      | 0.10     | 90        | 4.2 |                                       |
| 50  | 1.4           | 0.12      | 0.16     | 92        | "   |                                       |
| 28  | 3.5           | 0.10      | 0.12     | 90        | "   |                                       |

[Ref. 10713]



# NIOBIUM-TITANIUM

## CURRENT DENSITY



A niobium-titanium alloy (79.3 at.% Ti) was machined, slightly rolled and recrystallized at 800°C. Further rolling (80%) and aging at temperatures, shown on the above graph, markedly affect the critical current density and upper critical field.

$H_{c2}$  before annealing 110kG (1.2°K)

$H_{c2}$  after annealing 128kG (1.2°K)

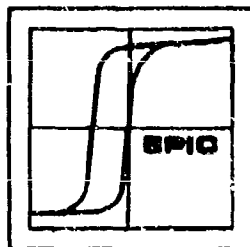
### Data Taken

H = 30 kGauss

T = 4.2 °K

[Ref. 19868]

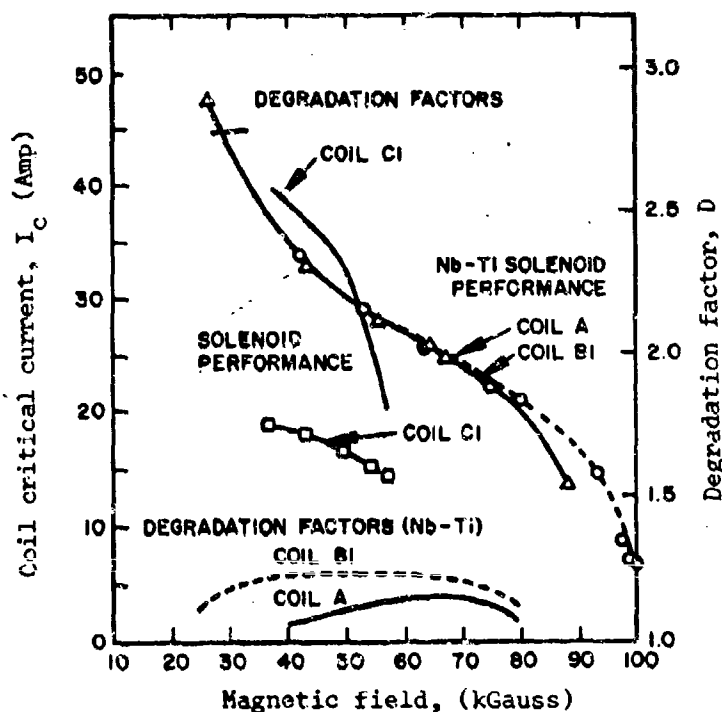




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# NIOBIUM-TITANIUM

## CURRENT DENSITY

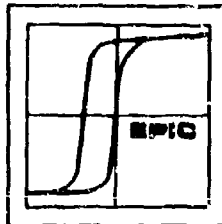


Characteristics of niobium-titanium wires wound into solenoids 4.250 in long.

| Coil             | <u>o.d.</u> | <u>i.d.</u> | <u>Turns</u> | <u>Wire</u> |
|------------------|-------------|-------------|--------------|-------------|
| A                | 0.986 in.   | 0.194 in.   | 10878        | Nb-56% Ti   |
| B1               | 2.637       | 1.105       | 17768        | Nb-61% Ti   |
| C1               | 5.261       | 3.729       | 21076        | Nb-25% Zr   |
| (for comparison) |             |             |              |             |

$$D = \frac{I_c \text{ (short wire)}}{I_c \text{ (coil)}}$$

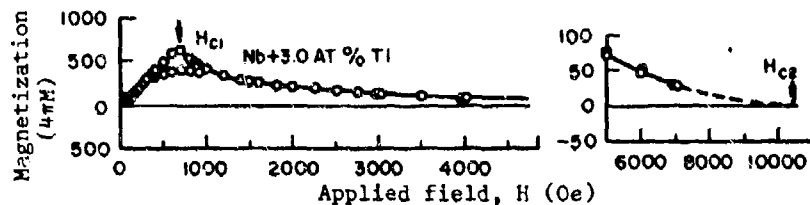
[Ref. 19479]



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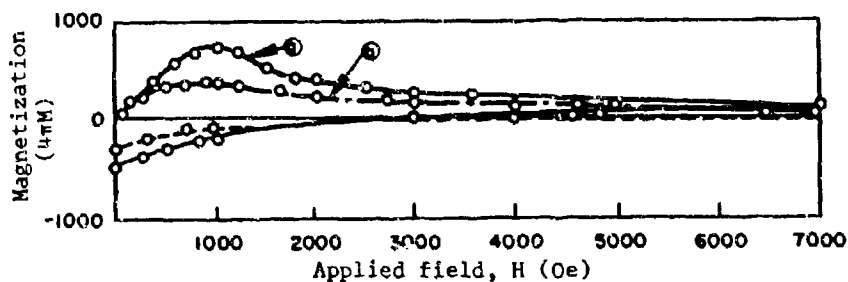
# NIOBIUM-TITANIUM

## MAGNETIC HYSTERESIS



Magnetization for niobium + 3.0 at.% titanium wires. Homogenized by passing large currents through the samples at  $<10^{-6}$  mm Hg vacuum for 4 hours at 1700°C.

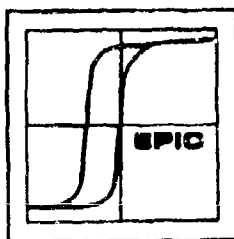
[Ref. 15459]



Magnetization as a function of applied field for a niobium-10 at.% titanium alloy. Data taken at 3.56°K.

- a) Rods, 1.2 cm long, 0.6 cm diameter
- b) Powder, 45-60  $\mu$  particle size

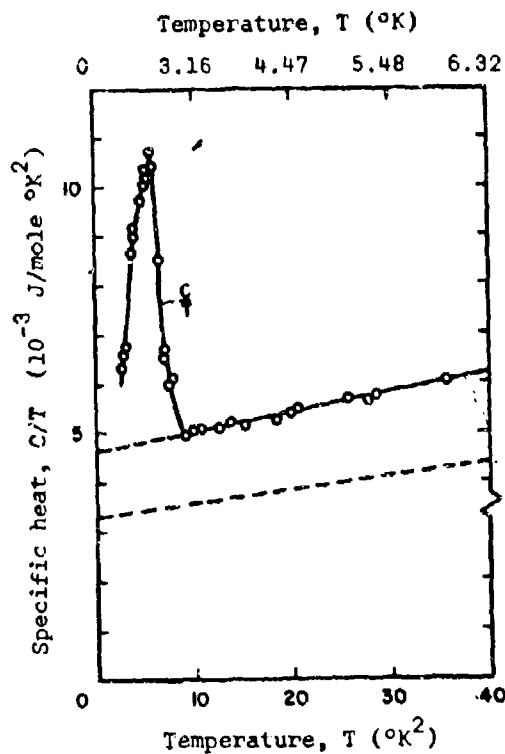
[Ref. 10778]



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NIOBIUM-TITANIUM

SPECIFIC HEAT



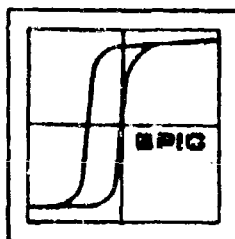
Specific heat for single phase, hcp,  $\text{Ti}_{0.96}\text{Nb}_{0.04}$  as a function of temperature.

[Ref. 15532]

Magnetic and Thermal Data

| At. % Ti | Coefficient of electronic<br>specific heat, $\gamma$<br>(J mole <sup>-1</sup> °K <sup>-2</sup> ) | Debye Temperature<br>$\theta$ (°K) | Atomic susceptibility                        |                                                                                      |
|----------|--------------------------------------------------------------------------------------------------|------------------------------------|----------------------------------------------|--------------------------------------------------------------------------------------|
|          |                                                                                                  |                                    | $\frac{\chi(\text{Nb-Ti})}{\chi(\text{Ti})}$ | $\frac{\chi(\text{Nb-Ti}, 10^\circ\text{K})}{\chi(\text{Nb-Ti}, 300^\circ\text{K})}$ |
| 96       | 4.3                                                                                              | 340                                | 1.05                                         | 0.92                                                                                 |

[Ref. 15532]



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# NIOBIUM-TITANIUM

## ELECTRICAL RESISTIVITY

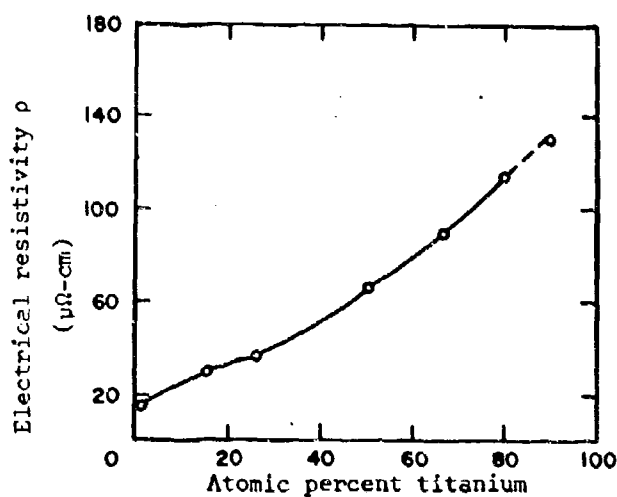
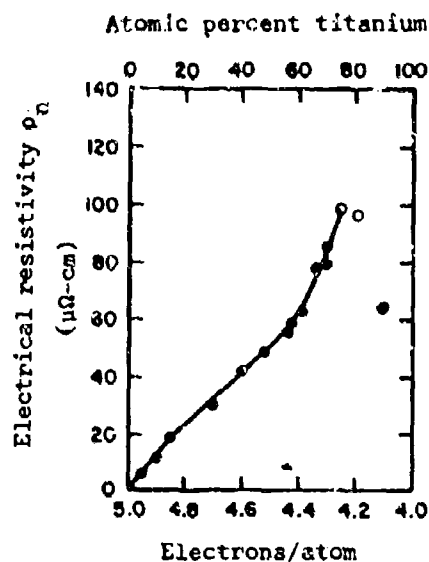
Electrical resistivity for the niobium-titanium

Data taken at 1.2°K.

Standard sample preparation.

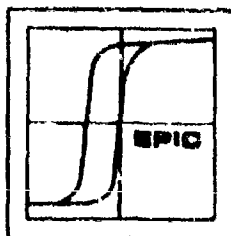
- two phase
- single phase

[Ref. 11924]

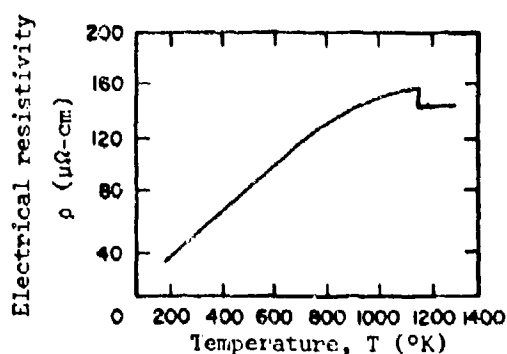


Electrical resistivity for the niobium-titanium system as a function of titanium content.

[Ref. 21728]

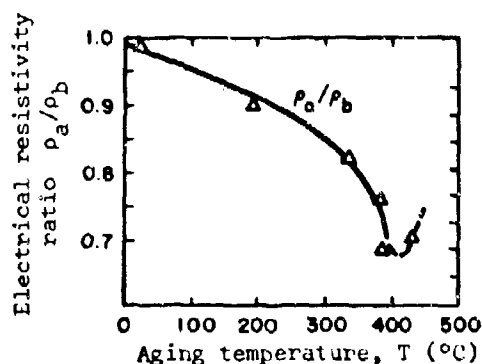


NIOBIUM-TITANIUM  
ELECTRICAL RESISTIVITY



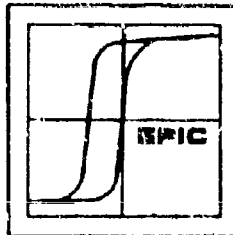
Electrical resistivity for a niobium-titanium alloy with less than ~35% niobium. The samples were arc-melted, worked, annealed for 20 hours at 100°C, then quenched.

[Ref. 21728]



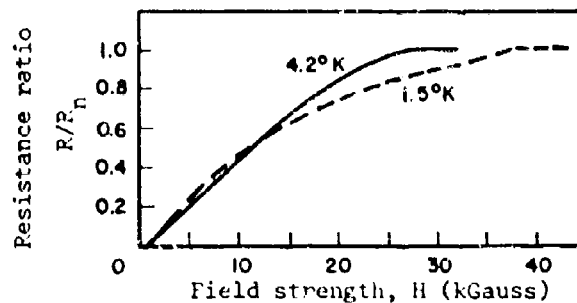
A niobium-titanium alloy (79.3 at.% Ti) is prepared as follows: The components are arc-melted together, machined, slightly rolled and recrystallized at 800°C. The sample then undergoes further rolling (80%) and aging at the temperature shown on the graph.  $\rho_a$  is the resistivity prior to aging and  $\rho_b$  after aging.

[Ref. 19868]



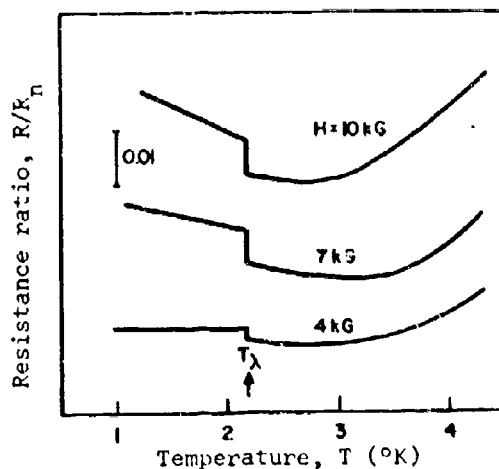
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NIOBIUM-TITANIUM  
ELECTRICAL RESISTIVITY



Resistance ratio as a function of field strength for highly annealed  $\text{Nb}_{.9}\text{Ti}_{.1}$  with small amount of defects.

[Ref. 21841]

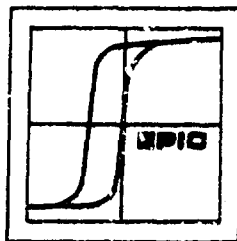


Resistance minima for  $\text{Nb}_{.9}\text{Ti}_{.1}$ , highly annealed with small amount of defects.  $R/R_n$  is relative, with the vertical scale corresponding to  $R/R_n = 0.01$ . The discontinuity in the constant field curves corresponds to the  $\lambda$  point of liquid helium,  $T_\lambda = 2.19^\circ\text{K}$ .

[Ref. 21841]

SECTION 1  
NIOBIUM-CALCIUM &  
NIOBIUM GERMANIUM SYSTEMS





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## NIBIUM ALLOYS AND COMPOUNDS

### NIBIUM-GALLIUM AND NIBIUM-GERMANIUM SYSTEMS

#### GENERAL

**Nb-Ga** Niobium-gallium in the  $\beta$ -tungsten structure shows a transition temperature near 14°K. None of the other Nb-Ga compositions give any indication of being superconductive. The data given in this section also show the effect of alloying  $\text{Nb}_3\text{Ga}$  with germanium and tin.

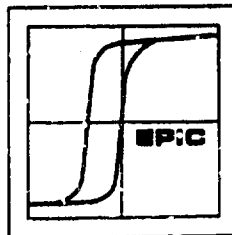
**Nb-Ge** Three compounds are formed in the niobium-germanium systems,  $\text{Nb}_3\text{Ge}$  with a  $\beta$ -tungsten phase, tetragonal  $\text{Nb}_5\text{Ge}_3$  and hexagonal  $\text{NbGe}_2$ . The exact nature of the eutectic points and decomposition temperature of these niobium compounds has not been determined. Much of the work by Carpenter [Ref. 20020 and 20022] has helped, but explicit phase diagram data is still lacking.

Carpenter [Ref. 20022] claims that the solid solution range of  $\text{Nb}_3\text{Ge}$  extends from  $\text{NbGe}_{0.15 \pm 0.01}$  to  $\text{NbGe}_{0.22 \pm 0.02}$  i.e., from 13 to 18 atomic percent germanium. The lattice constants in this range are given.

Of the three structures, the  $\beta$ -tungsten ( $\text{Nb}_3\text{Ge}$ ) shows the highest transition temperature in the 5-7°K range. This temperature is raised markedly by the addition of other elements, such as tin and aluminum. The tetragonal  $\text{Nb}_5\text{Ge}_3$  compound shows no transition temperature above 1°K even with the addition of carbon or zirconium.

[Ref. 12216]





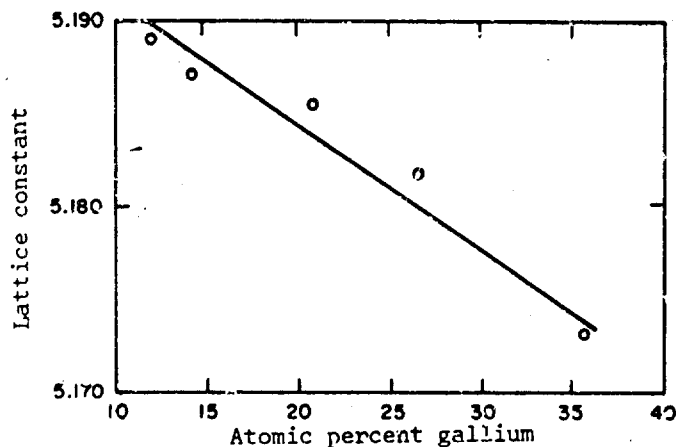
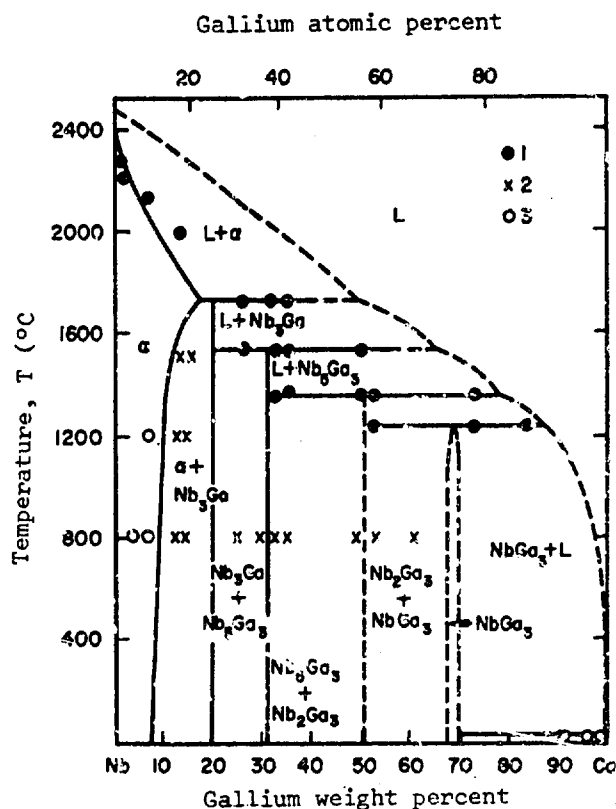
# NIOBIUM-GALLIUM

## GENERAL

Phase diagram for the  
niobium-gallium  
system.

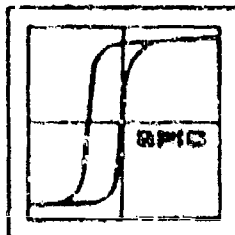
- 1 thermal analysis results
- 2 two phase alloys
- 3 single phase alloys

[Ref. 21729]



Lattice constant of  $Nb_3Ga$  as a  
function of niobium content.  
The sample was prepared by  
chemical vapor deposition  
method.

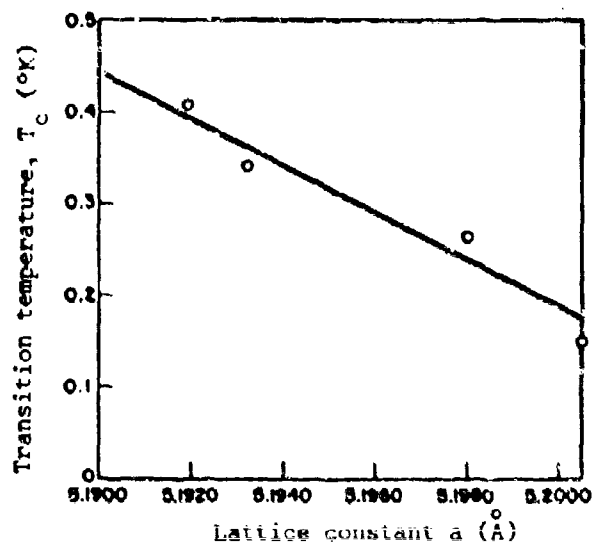
[Ref. 21843]



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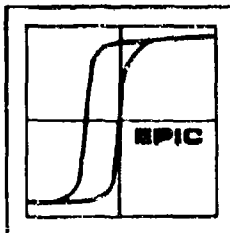
# NIOBIUM-GALLIUM

## TRANSITION TEMPERATURE



Transition temperature as a function of lattice constant for  
chemical vapor-deposited  $Nb_3Ga$ .

[Ref. 21843]



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NIOBIUM-GALLIUM-M

LATTICE CONSTANT AND TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

| Formula                | Symmetry          | Lattice<br>Constant<br>$a_0$ | Transition<br>Temperature<br>$T_c$ | width | Notes                                                          | Ref.  |
|------------------------|-------------------|------------------------------|------------------------------------|-------|----------------------------------------------------------------|-------|
| $Nb_3Ga$               | $\beta$ -tungsten | $5.171 \pm .002$             | 14.5                               | -     | Nb powder melted w/Ga at 1200°C, fused in He atm. arc furnace. | 14387 |
| $Nb_3Ga$               | "                 | "                            | 13.2                               | 4.6   | 3 hours at 1800°C                                              | 13155 |
| $Nb_{3Ga_{.5}Ge_{.5}}$ | "                 | 5.175                        | 7.3                                | -     | Formed at 1800°C                                               | 13155 |
| $Nb_6GaSb$             | -                 | -                            | 9.2 - 10.6                         |       | Prepared by HCl transparent                                    | 21843 |
| $Nb_6GaP$              | -                 | -                            | 9.3 - 11.2                         |       | Prepared by HCl transparent                                    | 21843 |

|                    |                             |                  |                |              |                    |                       |
|--------------------|-----------------------------|------------------|----------------|--------------|--------------------|-----------------------|
| $Nb_3Ga_{1-x}Sn_x$ | -                           | -                | -              | -            | -                  | 13155                 |
|                    | Gallium<br>component<br>$x$ | 16 hours, 1200°C |                |              | 3 hours, 1500°C    |                       |
|                    |                             | $a_0$            | $T_c$          | $\Delta T_c$ | $a_0$              | $T_c$ $\Delta T_c$    |
|                    | 1.00                        |                  |                |              | $\dagger 12.5^a$   | 1.6                   |
|                    | .8                          |                  |                |              | $\dagger 13.1$     | 2.6                   |
|                    | .6                          |                  | $\dagger 14.0$ | 4.7          | 5.230              | 14.6 0.6              |
|                    | .4                          | 5.287            | 13.5           | 3.3          | 5.262              | 16.0 0.7              |
|                    | .3                          | **5.272          |                |              |                    |                       |
|                    | .2                          | 5.282            | 17.8           | 0.9          | 5.282 <sup>a</sup> | 17.4 0.7              |
|                    | .1                          | **5.274          | 18.1           | 0.9          |                    | 15.3 <sup>b</sup> 1.0 |

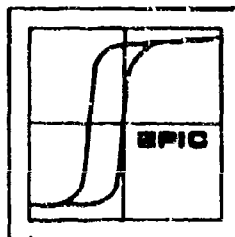
\*  $\Delta T_c$  width of the transition region

$\dagger$  not single phase

\*\* [Ref. 7888]

a after 1200°C firing the sample was refired for 7 hours at 1500°C

b after 1200°C firing the sample was refired for 3 hours at 1500°C

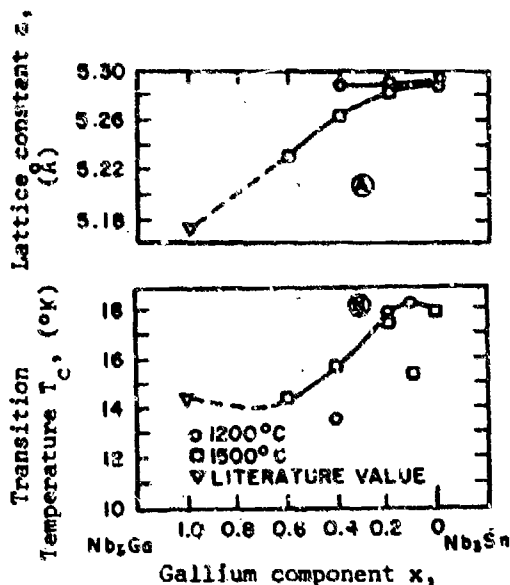


# NIOBIUM-GALLIUM-M

## LATTICE CONSTANT AND TRANSITION TEMPERATURE

Lattice constant and transition temperature as a function of  $x$ ,  $Nb_3GaSn_{1-x}$ . Samples sintered.

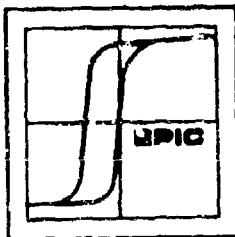
[Ref. 13155]



# NIOBIUM-GERMANIUM-M

## LATTICE CONSTANT AND TRANSITION TEMPERATURE

| Formula                | At. % Ge | Crystal-<br>lography | Lattice<br>constant (Å)<br>$a_0$ | Lattice<br>constant (Å)<br>$c_0$ | Transition<br>Temperature<br>$T_c$ (°K) | Notes                                 | Ref.  |
|------------------------|----------|----------------------|----------------------------------|----------------------------------|-----------------------------------------|---------------------------------------|-------|
| $Nb_5Ge_3 + C$         | 42.5     | $D6_8$               | 7.6                              | 5.3                              | <1.1                                    | --                                    | 17475 |
| $Nb_{2.5}Zn_{2.5}Ge_3$ | 42.5     | --                   | 7.89                             | 5.43                             | <1.1                                    | --                                    | "     |
| $Nb_3Ge_{.5}Ga_{.5}$   | 12.5     | $\beta$ -tungsten    | 5.175                            | --                               | 7.3                                     | Prepared at 1800°C                    | 13155 |
| $Nb_3Ge_{.5}Al_{.5}$   | 12.5     | $\beta$ -tungsten    | 5.175                            | --                               | 12.6                                    | Pressed & sintered<br>3 hours, 1500°C | "     |
| $Nb_3Ge_{.5}Sn_{.5}$   | 12.5     | $\beta$ -tungsten    | 5.236                            | --                               | 12.6                                    | Arc-melted                            | "     |
| $Nb_3Ge_{.5}Sn_{.5}$   | 12.5     | $\beta$ -tungsten    | --                               | --                               | 11.3                                    | --                                    | 10704 |



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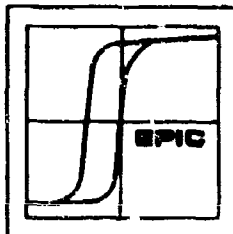
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NIOBIUM-GERMANIUM

TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

| At. % Ge | Symmetry   | Lattice constant (Å) |              | Transition Temperature $T_c$ (°K) | Notes                                               | Ref.  |
|----------|------------|----------------------|--------------|-----------------------------------|-----------------------------------------------------|-------|
|          |            | $a_o$                | $c_o$        |                                   |                                                     |       |
| 13.63    | β-tungsten | 5.1756 ± .001        | -            | -                                 | Nb <sub>3</sub> Ge w/ excess Nb                     | 20022 |
| 13.75    |            | 5.174                | -            | 4.9                               | NbGe .159 ± .003                                    | 7888  |
| 18.0     |            | 5.166                | -            | 5.4                               | Nb <sub>3</sub> Ge .55Nb .45 heated                 | 7888  |
| 18.9     |            | -                    | -            | 5.3                               | 1600°C, 6 hours                                     | 12421 |
| 25.0     |            | 5.168 ± .002         | -            | -                                 | Nb <sub>3</sub> Ge .72Nb .28                        | 20020 |
| "        |            | -                    | -            | 6.9                               | NbGe .22                                            | 12216 |
| "        |            | -                    | -            | 12.6                              | Nb <sub>3</sub> Ge stable to 1910°C                 | 7888  |
| ~29      |            | 5.149                | -            | >17                               | Arc-cast rapidly quenched and annealed up to 1000°C | 21469 |
| 37.5     | tetragonal | 10.148               | 5.152        | <1.02                             | Nb <sub>5</sub> Ge <sub>3</sub>                     | 12216 |
| 67       | hexagonal  | 4.966 ± .003         | 6.781 ± .003 | -                                 | NbGe <sub>2</sub> decomposes at 1483 ± 15°C         | 20020 |

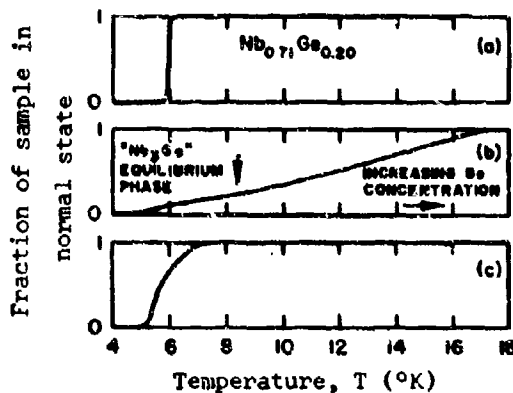


## NIOBIUM-GERMANIUM

### TRANSITION TEMPERATURE

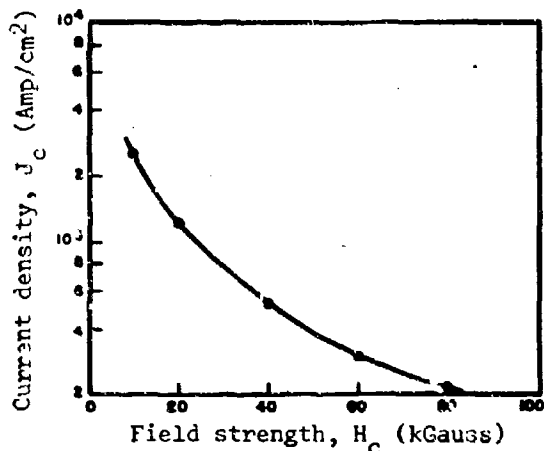
Stoichiometric niobium germanium compounds were formed with a normal composition of 25-29% Ge. (a) shows the transition when the samples were arc-cast, (b) shows the same samples rapidly quenched and variously annealed up to 1000°C, (c) show the results of annealing this same sample to 1100°C for three days.

[Ref. 21469]



## NIOBIUM-GALLIUM

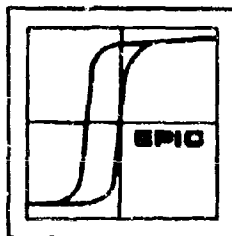
### CURRENT DENSITY



Current density as a function of field strength for cast Nb<sub>3</sub>Ga at 4.2°K.

These  $J_c$  values are highly dependent upon sample preparation.

[Ref. 10708]



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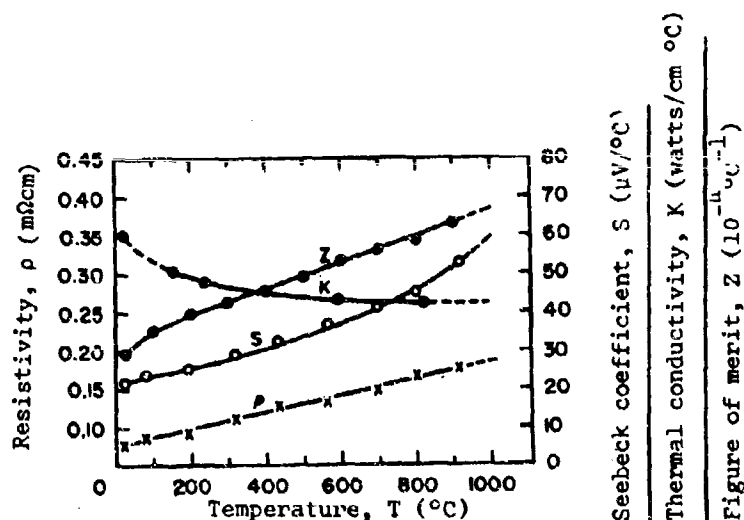
# NIOBIUM-GERMANIUM-SILICON

## THERMOELECTRIC PROPERTIES

| Formula                               | Lattice constants (Å) |                | Electrical resistivity (mΩ-cm) |       | Seebeck coefficient (μV/°C) | Thermal conductivity K (watts/cm °C) | Figure of merit (10 <sup>-5</sup> °C <sup>-1</sup> ) |
|---------------------------------------|-----------------------|----------------|--------------------------------|-------|-----------------------------|--------------------------------------|------------------------------------------------------|
|                                       | a <sub>0</sub>        | c <sub>0</sub> | 25°C                           | 196°C |                             | 25°C                                 |                                                      |
| NbGe <sub>2</sub> *                   | 4.943                 | 6.778          | 0.067                          | 0.031 | + 12                        | 0.31                                 | 0.70                                                 |
| NbGe <sub>1.5</sub> Si <sub>0.5</sub> | 4.910                 | 6.730          | 0.077                          | 0.063 | + 17                        | 0.19                                 | 2.0                                                  |
| NbGe <sub>1.0</sub> Si <sub>1.0</sub> | 4.885                 | 6.682          | 0.081                          | 0.065 | + 22                        | 0.16                                 | 3.7                                                  |
| NbGe <sub>0.5</sub> Si <sub>1.5</sub> | 4.834                 | 6.635          | 0.060                          | 0.047 | + 20                        | 0.20                                 | 3.3                                                  |
| NbSi <sub>2.0</sub>                   | 4.803                 | 6.604          | 0.098                          | 0.063 | + 19                        | 0.42                                 | 0.9                                                  |

\* These materials have a C 40 type structure

[Ref. 20159]



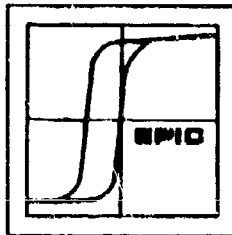
Thermoelectric properties of NbSi<sub>1.0</sub>Ge<sub>1.0</sub> as a function of temperature. The samples were pressed and sintered.

x - Resistivity    o - Seebeck coefficient    ⊙ - Thermal conductivity  
● - Figure of merit

[Ref. 20159]

SECTION 4  
NIOBIUM-CHROMIUM &  
NIOBIUM-IRON SYSTEMS





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## NIOBIUM ALLOYS AND COMPOUNDS

### NIOBIUM-CHROMIUM AND NIOBIUM-IRON SYSTEMS

#### GENERAL

**Nb-Cr** Niobium when alloyed with chromium shows little promise as superconducting material. As the chromium content increases the transition temperature drops linearly from the  $T_c$  value for niobium and appears to reach zero at 20 at.% chromium.

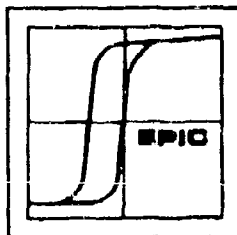
The niobium-chromium system shows only one compound,  $NbCr_2$  with a cubic  $MgCu_2$  (C 15) type structure. This compound exists beyond the alloy region of superconductivity.

**Nb-Fe** Lattice constants are given for only intermetallic phase in the niobium-iron system. Wallbaum\* gives  $a_0 = 4.830 \text{ \AA}$  and  $c_0 = 7.882 \text{ \AA}$  for  $NbFe_2$  ( $MgZn_2$  type structure). These values are corroborated by Elliot†;  $a_0 = 4.834$  and  $c_0 = 7.880$ .

Other phases are reported to exist in this binary system but they are stable only at high temperatures and lattice constants are not available.

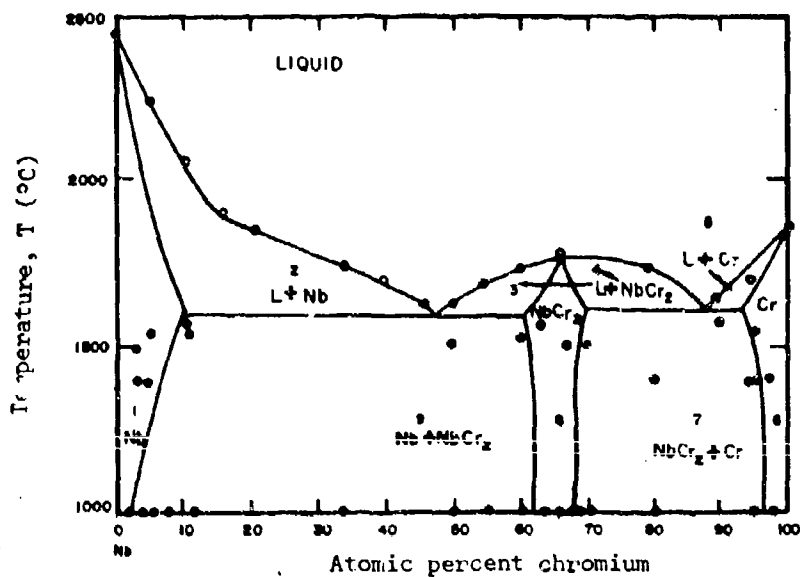
\* Wallbaum, A.J., Z. KRIST., v. 103, 1941. p. 391-402.

† Elliot, R.F., Armour Research Foundation, Chicago. TR1 OSR Technical note OSR-TN-247, August 1964. p. 19.



# NIOBIUM-CHROMIUM

## GENERAL

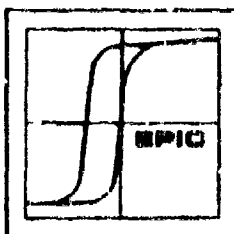


Phase diagram for niobium-chromium system.  $\text{NbCr}_2$  ranges from 64-70 at.% chromium.

○ measured melting points

● identified alloys

[Ref. 19469]



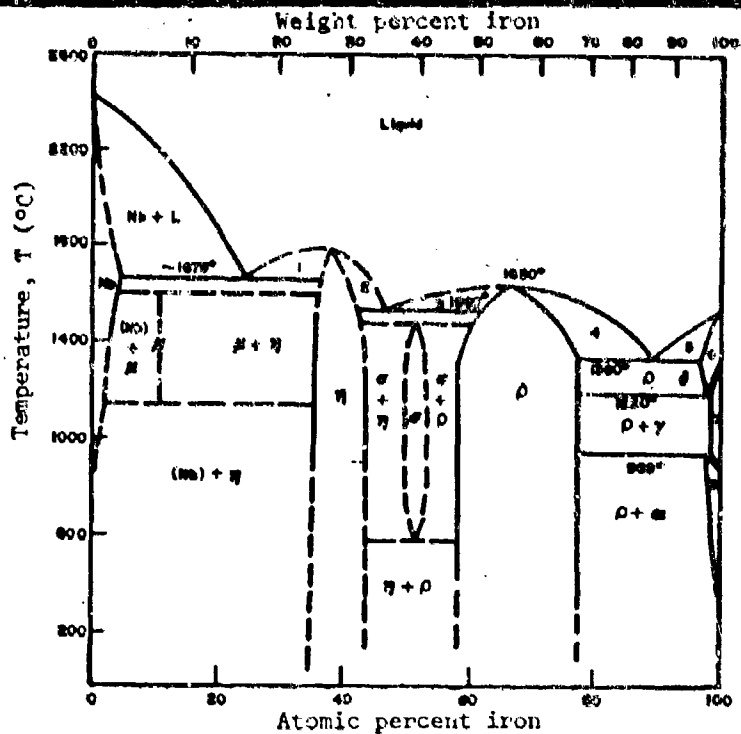
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# NIOBIUM-IRON

## GENERAL

Phase diagram for the niobium-iron system

- 1) L +  $\eta$
- 2)  $\eta$  + L
- 3)  $\rho$  + L
- 4)  $\rho$  + L
- 5)  $\delta$  + L
- 6)  $\delta$
- 7)  $\gamma$
- 8)  $\alpha$



[Ref. 19926]

# NIOBIUM-CHROMIUM

## GENERAL

### Lattice Constants

Lattice constant ( $\text{\AA}$ )  
 $a_o$

Formula

Ref.

$\text{Nb} \frac{1}{2} \text{NbCr}_2$

7.001

19469

$\text{NbCr}_2$

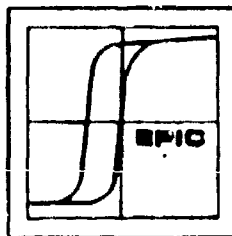
6.985

Hansen

$\text{NbCr}_2 \frac{1}{2} \text{Cr}$

6.981

19469

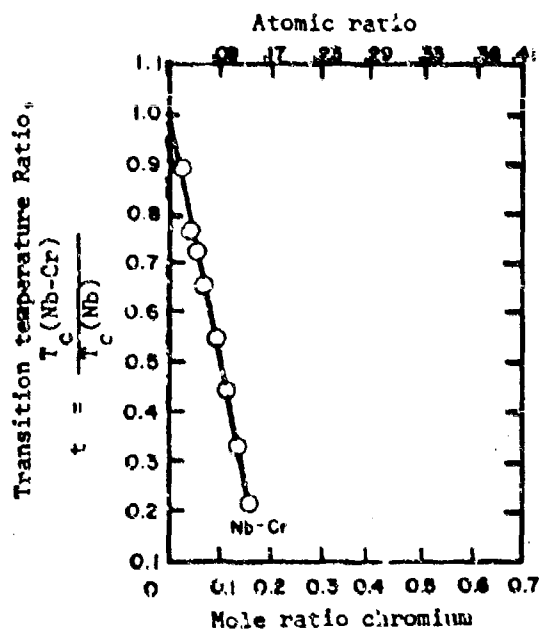
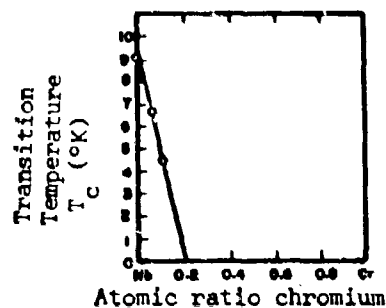


# NIOBIUM-CHROMIUM

## TRANSITION TEMPERATURE

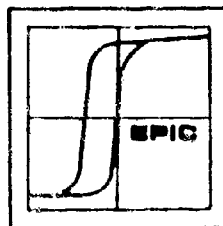
Transition temperature of  
niobium-chromium samples,  
arc-melted and unannealed.

[Ref. 12583]



Transition temperature of niobium  
chromium systems, arc melted and  
unannealed.

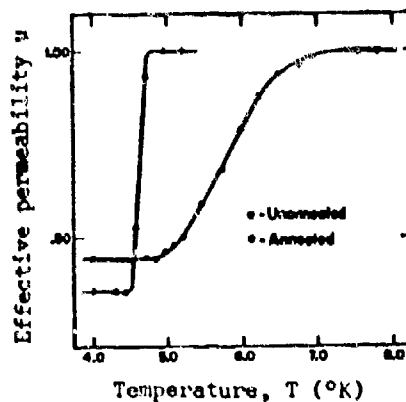
[Ref. 10778]



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# NIOBIUM-CHROMIUM

## TRANSITION TEMPERATURE

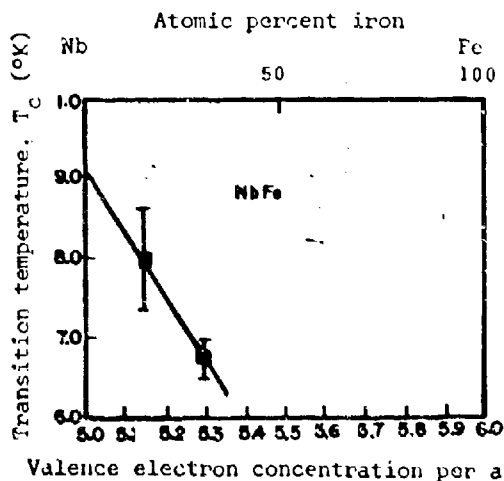


Annealing effect on the transition temperature of a 10 at.% chromium alloy.

[Ref. 12583]

# NIOBIUM-IRON

## TRANSITION TEMPERATURE



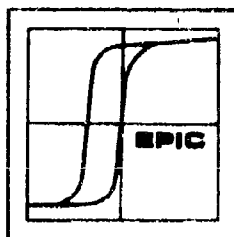
Transition temperature of niobium-iron samples.

[Ref. 14468]



SECTION 4  
NIOBIUM ARSENIC &  
NIOBIUM-SELENIUM SYSTEMS





## NIOBIUM ALLOYS AND COMPOUNDS

### NIOBIUM-ARSENIC AND NIOBIUM-SELENIUM SYSTEM

#### GENERAL

**Nb-As** Although niobium and arsenic form "mono" and "di" arsenides, neither shows superconductivity. The only data given here are for the lattice constants and magnetic susceptibility.

**Nb-Se** The niobium selenium system in the niobium rich region shows no evidence of being superconducting above 4.2°K [Ref. 13150]. In the  $\text{NbSe}_{1.90}$  -  $\text{NbSe}_{2.25}$  region there is an indication that a transition temperature exists near 4.2°K. Single crystals of the system in this range, prepared by a vapor transport method, show a nominal  $\text{NbSe}_2$  composition and have a  $T_c$  of 4.2°K.

This system forms into layer type crystals with various polytypes. The lattice constants and transition temperature are given for some compounds.

#### NIOBIUM-ARSENIC

##### GENERAL

| Compound          | At. % As | Symmetry   | Lattice constants (Å) |             |              |         | $\beta$ | Notes |
|-------------------|----------|------------|-----------------------|-------------|--------------|---------|---------|-------|
|                   |          |            | $a_o$                 | $b_o$       | $c_o$        |         |         |       |
| NbAs              | 50       | tetragonal | 3.45 ± .001           | --          | 11.65 ± 0.02 | --      |         | *     |
| NbAs <sub>2</sub> | 67       | monoclinic | 9.365 ± 0.02          | 3.38 ± 0.01 | 7.809 ± 0.02 | 119°26' | --      |       |

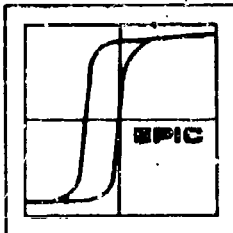
Ref. Saint, G.S., et al. CAN. J. CHEM., v. 42, p. 630, 1964. \* single crystal

#### NIOBIUM-SELENIUM

##### GENERAL

| Formula                     | Lattice constant (Å) |        |
|-----------------------------|----------------------|--------|
|                             | $a_o$                | $c_o$  |
| $\alpha$ -NbSe <sub>2</sub> | 3.449                | 12.998 |
| $\beta$ -NbSe <sub>2</sub>  | 3.439                | 25.188 |

[Ref. 21796]



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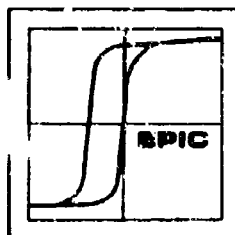
NIOBIUM-SELENIUM

TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

| Lattice constant (Å)<br>$a_o$ | Transition temperature<br>$T_c$ (°K) |       |          | At. % Se | Symmetry | Notes                                                                                   | Ref.  |
|-------------------------------|--------------------------------------|-------|----------|----------|----------|-----------------------------------------------------------------------------------------|-------|
|                               | midpoint                             | onset | complete |          |          |                                                                                         |       |
| 3.437                         | --                                   | --    | --       | 50       | hex      | --                                                                                      | 21796 |
| 3.44                          | 5.47                                 | 5.62  | 5.15     | 67       | "        | Powders were sealed in evacuated quartz ampules & sintered for 72 hours at 600 - 800°C. | 13150 |
| 3.44 ± .01                    | 6.0                                  | --    | --       | 67       |          | Vapor transport process.                                                                | 18755 |



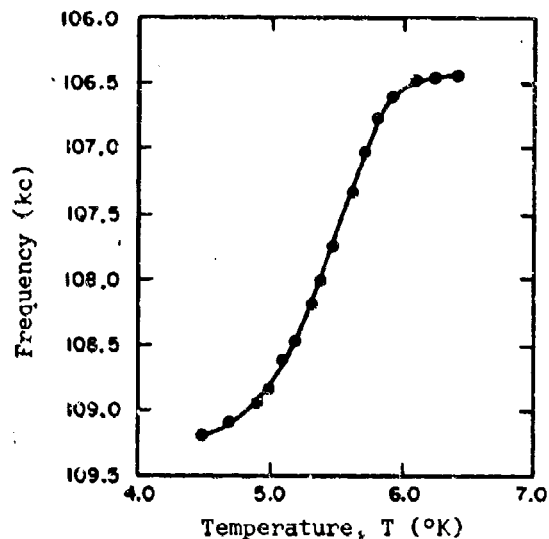


# NIOBIUM-SELENIUM

## TRANSITION TEMPERATURE

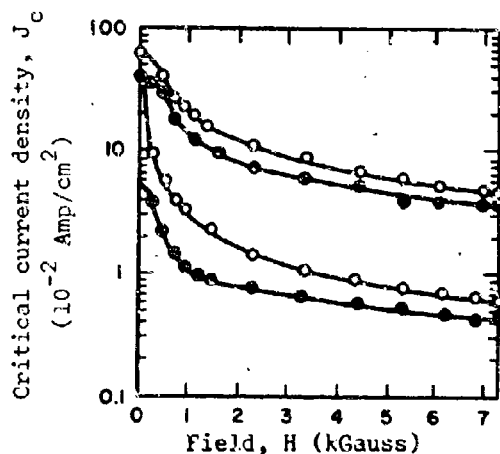
Transition curve for  $\text{NbSe}_2$  from resonance coil measurements. Nb and Se powders were sealed in evacuated ampules and sintered for 72 hours at 600-800°C.

[Ref. 13150]



# NIOBIUM-SELENIUM

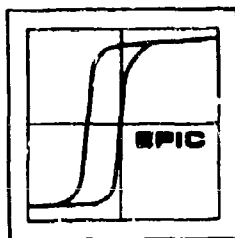
## CURRENT DENSITY



Critical current density for two  $\text{NbSe}_2$  crystals.

- width to thickness ratio = 9
- o =  $w/t = 15$
- (a)  $H \perp c$ -axis
- (b)  $H \parallel c$ -axis
- $T = 4.2^\circ\text{K}$
- $J \parallel a$ -axis

[Ref. 18755]

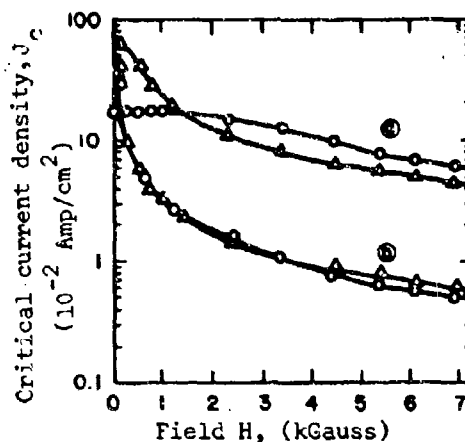


# NIOBIUM-SELENIUM

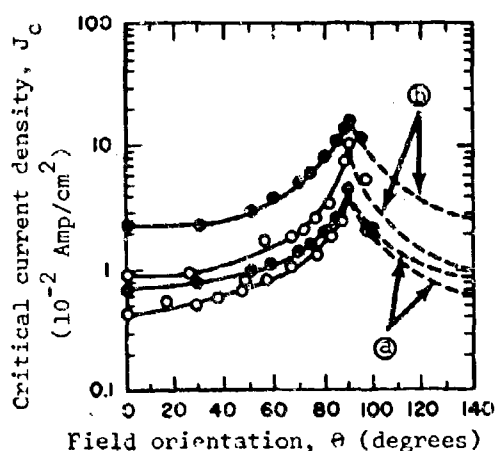
## CURRENT DENSITY

Critical current density for a  $\text{NbSe}_2$  crystal  
with different leads.

- $\Delta$  Cu leads; indium soldered
- $\circ$  Ni leads; spot welded
- (a)  $H \perp c$ -axis
- (b)  $H \parallel c$ -axis
- $T = 4.2^\circ\text{K}$
- $w/t = 9$
- $J \parallel a$ -axis



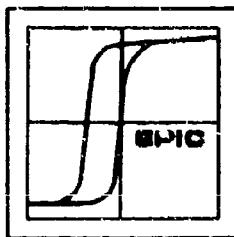
[Ref. 18755]



Critical current density for two  $\text{NbSe}_2$  Crystals.

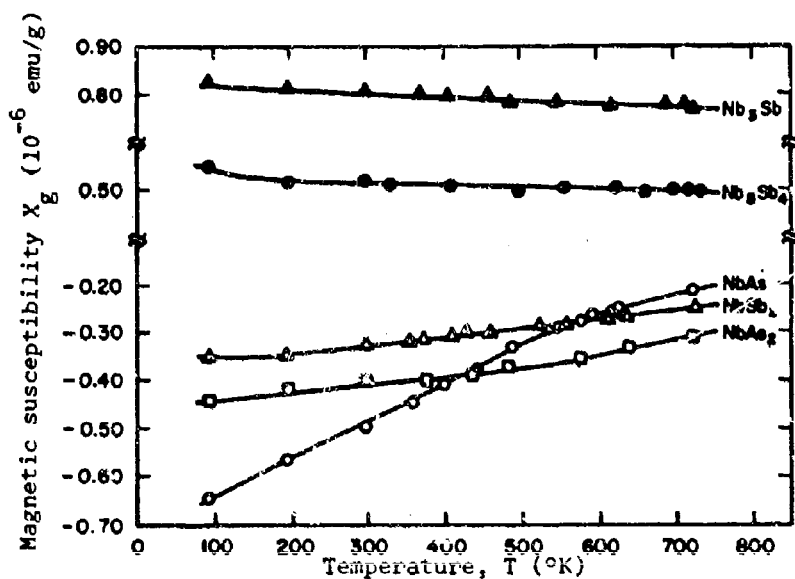
- $\bullet$  =  $w/t = 9$
- $\circ$  =  $w/t = 15$
- $T = 4.2^\circ\text{K}$
- $J \parallel a$ -axis
- a)  $H = 1.4$  kGauss
- b)  $H = 7.25$  kGauss

[Ref. 18755]



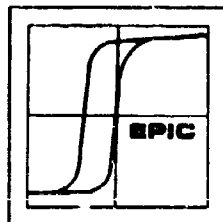
# NIOBIUM-ARSENIC

## MAGNETIC SUSCEPTIBILITY



Magnetic susceptibility for niobium antimonides and arsenides as a function of temperature. The antimonides were prepared by heating niobium and antimony at 1000°C for 2 days, 800°C for 14 days and quenching in water. The arsenides were prepared by heating niobium and arsenic at 1000°C for 2 days, 720°C for 14 days and quenching in water.

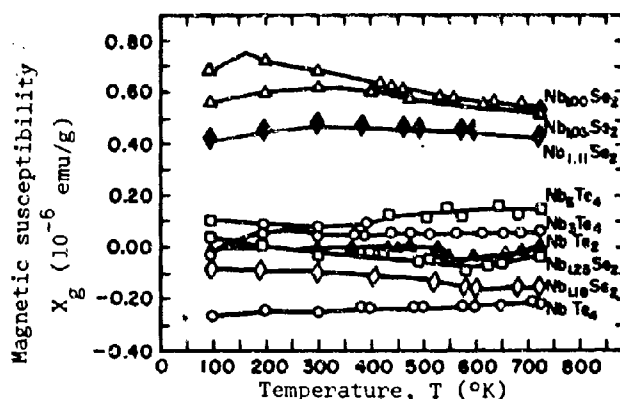
[Ref. 21797]



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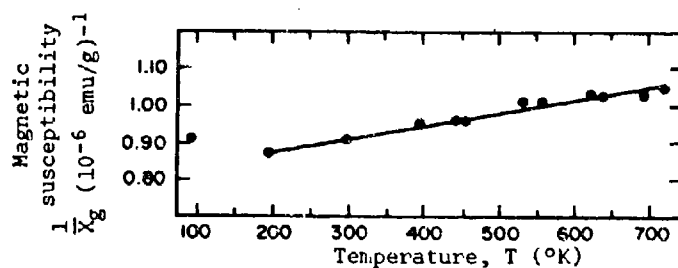
# NIOBIUM-SELENIUM

## MAGNETIC SUSCEPTIBILITY



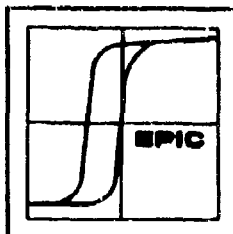
Magnetic susceptibility for various niobium selenides and tellurides. These values have not been corrected for induced diamagnetism.

[Ref. 21738]



Reciprocal of the corrected magnetic susceptibility for NbSe<sub>2</sub> as a function of temperature.

[Ref. 21738]



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NIOBIUM-SELENIUM

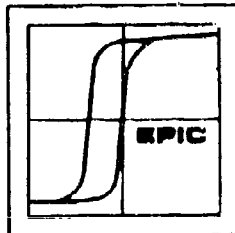
SEMICONDUCTING PROPERTIES

| Electrical<br>Resistivity<br>$\rho$ (m $\Omega$ -cm) | Mobility<br>$\mu$<br>(cm <sup>2</sup> /V sec) | Seebeck coefficient<br>$S$ ( $\mu$ V/ $^{\circ}$ C) | Hall coefficient<br>$R \times 10^{-4}$ (cm <sup>3</sup> /coul) | Notes                                                 | Ref.   |
|------------------------------------------------------|-----------------------------------------------|-----------------------------------------------------|----------------------------------------------------------------|-------------------------------------------------------|--------|
|                                                      |                                               | <u>NbSe</u>                                         |                                                                |                                                       |        |
| 5                                                    | --                                            | 2.7                                                 | --                                                             | 100 $^{\circ}$ C                                      | 13958  |
|                                                      |                                               | <u>NbSe<sub>2</sub></u>                             |                                                                |                                                       |        |
| 0.18                                                 | --                                            | --                                                  | --                                                             | -196 $^{\circ}$ C                                     | 21796* |
| 0.35                                                 | --                                            | --                                                  | --                                                             | 25 $^{\circ}$ C                                       | "      |
| --                                                   | --                                            | -12.0                                               | --                                                             | Polycrystalline "<br>25 $^{\circ}$ - 130 $^{\circ}$ C |        |
| .5                                                   | --                                            | - 1.4                                               | --                                                             | 100 $^{\circ}$ C                                      | 13958  |
| .44                                                  | --                                            | - 6.9                                               | --                                                             | 150 $^{\circ}$ max                                    | "      |
| .58                                                  | --                                            | - 0.2                                               | --                                                             | 600 $^{\circ}$ C                                      | "      |
| 2.04                                                 | <10**                                         | -5                                                  | <20                                                            | Stoich,<br>300 $^{\circ}$ K                           | 15399  |
| --                                                   | 8 <sup>†</sup>                                | --                                                  | --                                                             | 300 $^{\circ}$ K                                      | 13958  |

\*\* Thermal conductivity,  $K = 0.021$  w/ $^{\circ}$ C-cm. Figure of merit,  $Z = 1.96 \times 10^{-5}$  cm<sup>-1</sup>

\*  $n = 3 \times 10^{21}$ /cm<sup>3</sup>

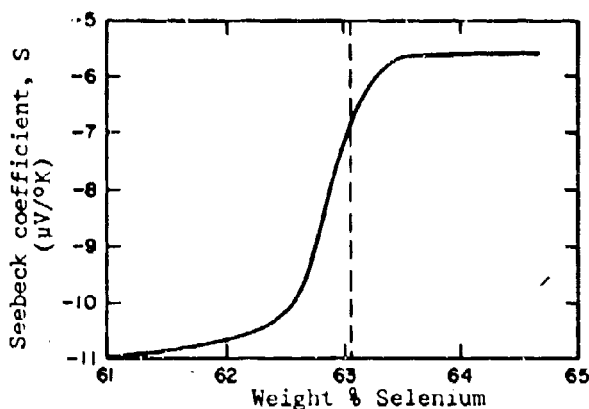
†  $n = 2 \times 10^{21}$ /cm<sup>3</sup>



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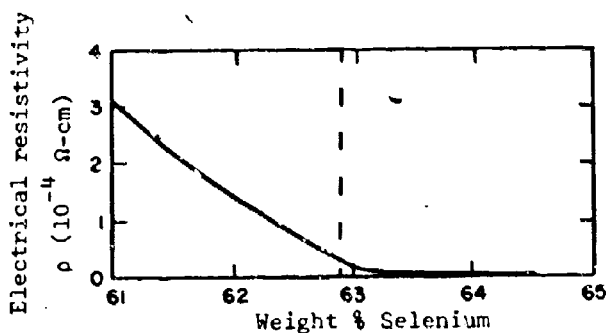
# NIOBIUM-SELENIUM

## SEMICONDUCTING PROPERTIES



Seebeck coefficient for the niobium selenium system with 61-65 wt.% Se. Data taken at 300°K, sample sintered 16 hours at 900°C. The dashed line represents stoichiometric ratio.

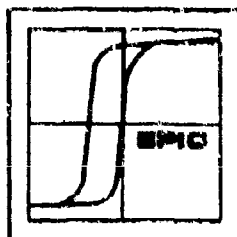
[Ref. 15399]



Electrical resistivity for the niobium selenium system with 61-65 wt.% Se. Data taken at 300°K, sample sintered 16 hours at 900°C. The dashed line represents stoichiometric ratio.

[Ref. 15399]





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## NIOBIUM ALLOYS AND COMPOUNDS

### NIOBIUM-MOLYBDENUM, NIOBIUM-TECHNETIUM, AND NIOBIUM-RUTHENIUM SYSTEMS

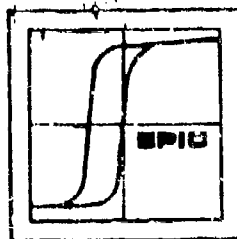
#### GENERAL

**Nb-Mo** In a 1961 article by Hulm and Blaugher [Ref. 12583] the transition temperature of the niobium-molybdenum system was extrapolated to zero near 40 at.% Mo. Since then, work by Hein et al [Ref. 14469] in 1964 has shown that  $T_c$  reaches a minimum of 0.016°K at 70 at.% Mo and then rises to 1°K for pure molybdenum. The niobium-molybdenum system shows only the bcc crystal phase.

**Nb-Tc** The only transition temperature available for the niobium technetium system is given for  $NbTc_3$ ,  $T_c = 10.5^\circ K$ , the lattice constant,  $a_0 = 9.625 \pm 0.002$  [Ref. 12711]. The other data given are for magnetic susceptibility.

**Nb-Ru** The niobium-ruthenium system is body centered cubic up to 40 at.% ruthenium, takes on a body centered tetragonal to about 55% and remains hexagonal close packed to non-alloyed ruthenium. The transition temperature does not follow this change in phase. At 7.5% Ru,  $T_c = 4.20^\circ K$ , falls to  $< 1^\circ K$  at 20%, and reappears again at 40%, thus ignoring the cubic structure,

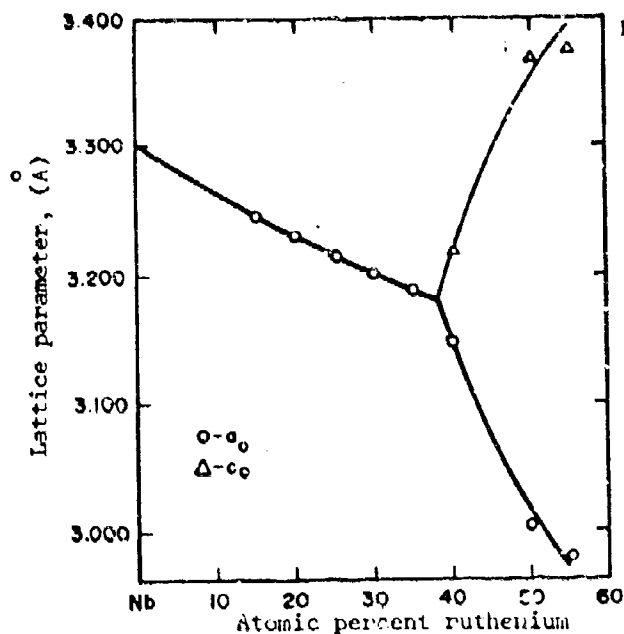




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# NIOBIUM-RUTHENIUM

## GENERAL

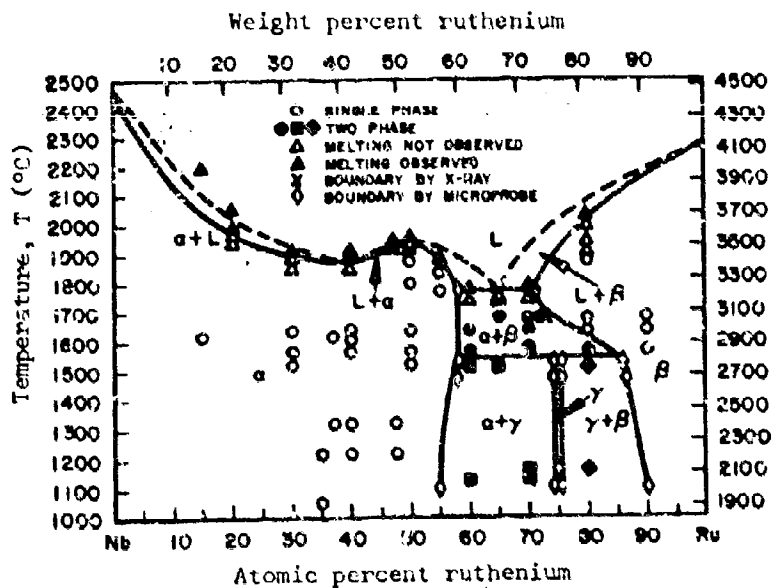


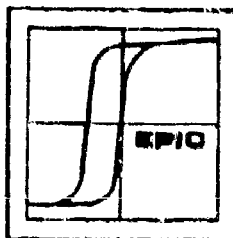
Lattice constants for  $\alpha$ -niobium-ruthenium alloys. The system is a body centered cubic to 40 at.% ruthenium and body centered tetragonal to about 55 at.% ruthenium. [Ref. 21255]

$\text{Nb}_3\text{Ru}$ ,  $\text{Cu}_3\text{Au}$  type,  $a_0 = 4.207 \text{ \AA}$   
HCl transport method. [Ref. 21843]

Phase diagram for the niobium-ruthenium system.

[Ref. 21255]





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# NIOBIUM-MOLYBDENUM

## GENERAL

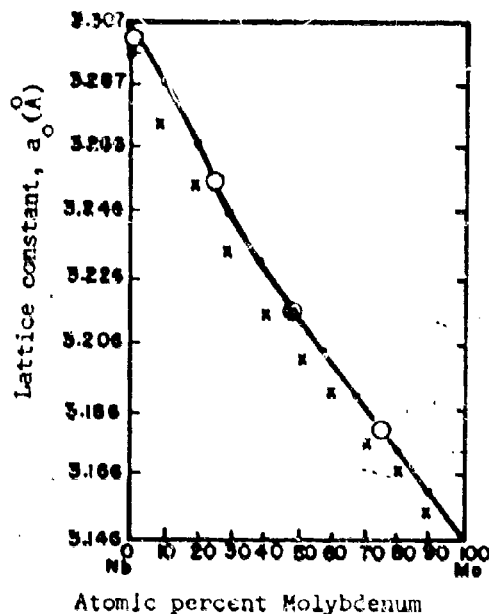
Lattice constants for niobium-molybdenum system as a function of molybdenum content.

[Ref. 19469]

- This Ref.
- Buckle\*
- x Eremenko†

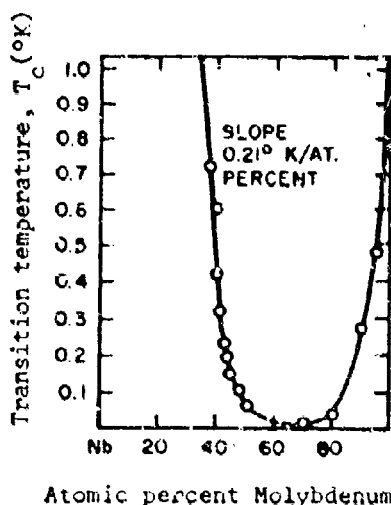
\* Buckle, H. METALLFORSCHUNG, v. 1, no. 53, 1946.

† Eremenko, V. N. UKRAIN. KHEM. ZHUR., v. 20, no. 227, 1954.



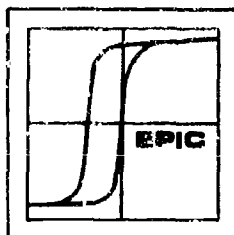
# NIOBIUM-MOLYBDENUM

## TRANSITION TEMPERATURE



The values plotted here represent the midpoints of the transition region for these alloys. Mo and Nb<sub>0.3</sub>Mo<sub>0.7</sub> samples were electron-beam refined, all other samples are from electron-beam refined Mo and Nb, individually melted.

[Ref. 14469]



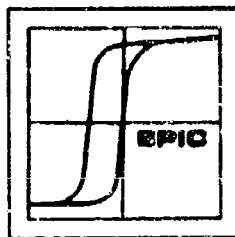
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NIOBIUM-MOLYBDENUM

TRANSITION TEMPERATURE

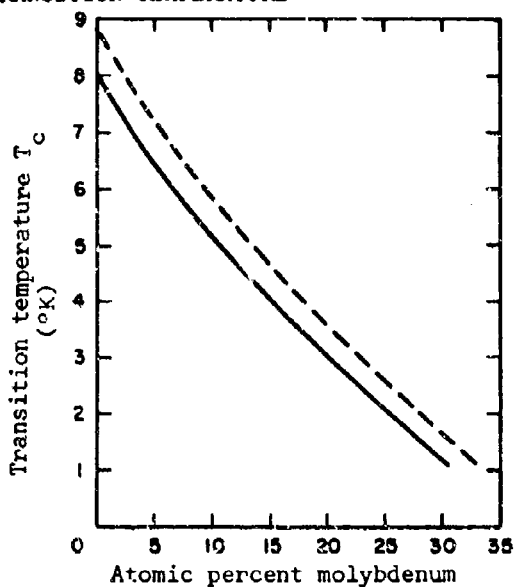
Transition Temperature

| At. % Mo | Value ( $^{\circ}\text{K}$ )<br>$T_c$ | Sample                                              | Ref.  |
|----------|---------------------------------------|-----------------------------------------------------|-------|
| 0        | 9.17                                  | -                                                   | 15259 |
| 10       | 5.3                                   | -                                                   | 7686  |
| 25       | 3.4                                   | -                                                   |       |
| 38       | .76                                   | -                                                   |       |
| 40       | .50                                   | -                                                   |       |
| 40       | .60                                   | Arc melted                                          | 15259 |
| 42       | .31                                   | -                                                   | 7686  |
| 43       | .181                                  | -                                                   | 20520 |
| 44       | .158                                  | -                                                   |       |
| 45       | .148                                  | -                                                   |       |
| 48       | .108                                  | -                                                   |       |
| 60       | <.05                                  | Arc melted                                          | 15259 |
| 60       | <.03                                  | Formed from electron-beam<br>zone-refined elements. | 14469 |
| 70       | .016                                  | Electron zone-refined after<br>forming.             |       |
| 80       | ~.04                                  | Formed from electron zone-<br>refined elements.     |       |
| 90       | ~.28                                  | -                                                   |       |
| 100      | .945                                  | Electron zone-refined after<br>forming.             |       |



# NIOBIUM-MOLYBDENUM

## TRANSITION TEMPERATURE



Transition temperature of (Nb-Mo) and  
(Nb-Mo)<sub>0.99</sub>Fe<sub>0.01</sub> as a function of molybdenum  
content.

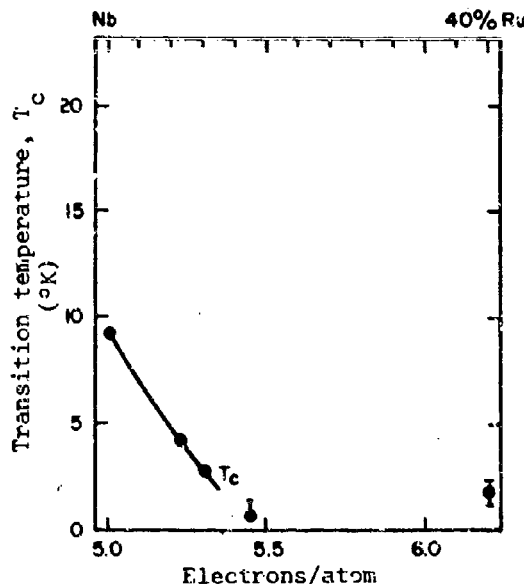
[Ref. 11937]

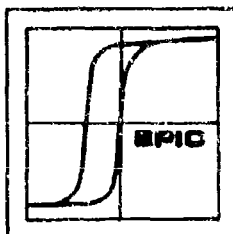
--- no iron  
— 10% iron

# NIOBIUM-RUTHENIUM

Transition temperature for the niobium-  
ruthenium system to 40 at.% ruthenium.  
Samples were electron-beam melted at high  
temperature in less than  $10^{-8}$  mm Hg  
vacuum.

[Ref. 15512]





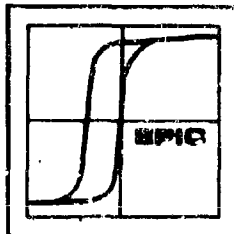
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NIOBIUM-RUTHENIUM

TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

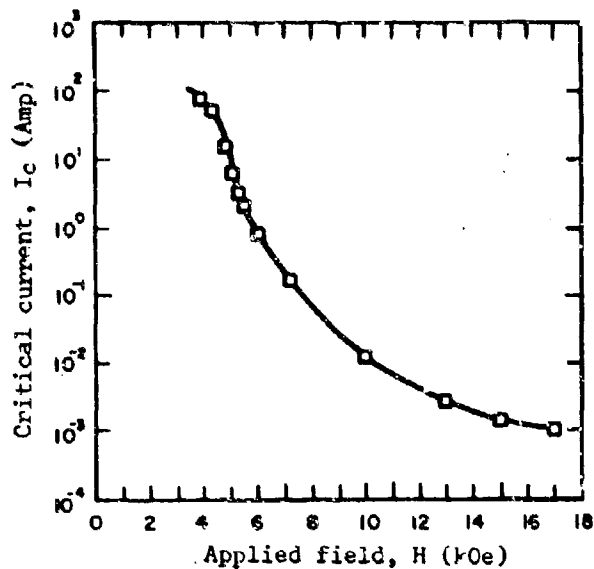
| At.% Ru | Symmetry | Lattice Constant |           | Transition<br>Temperature<br>$T_c$ (°K) | Notes              | Ref.  |
|---------|----------|------------------|-----------|-----------------------------------------|--------------------|-------|
|         |          | $a_0$ (Å)        | $c_0$ (Å) |                                         |                    |       |
| 0       | bcc      | 3.301            | -         | -                                       | -                  | 21255 |
| 7.5     | ↓        | -                | -         | 4.20                                    | -                  | 15512 |
| 10      | ↓        | -                | -         | 2.8                                     | -                  | "     |
| 20      | ↓        | 3.230            | -         | -                                       | -                  | 21255 |
| "       | ↓        | -                | -         | <1                                      | -                  | 15512 |
| 30      | ↓        | 3.200            | -         | -                                       | -                  | 21255 |
| "       | ↓        | -                | -         | <1                                      | -                  | 15512 |
| 40      | bct      | -                | -         | $1.2 \pm 2.2$                           | -                  | "     |
| "       | ↓        | 3.147            | 3.218     | -                                       | -                  | 21255 |
| 55      | ↓        | 2.978            | 3.378     | -                                       | -                  | "     |
| 60      | ↓        | -                | -         | 2.5                                     | 6.8 electrons/atom | 9686  |
| 71      | β hcp    | 2.762            | 4.432     | -                                       | -                  | 21255 |
| 75      | γ hcp    | 2.750            | 4.418     | -                                       | -                  | ↓     |
| 80      | β hcp    | 2.747            | 4.389     | -                                       | -                  | ↓     |
| 100     | "        | 2.706            | 4.282     | -                                       | -                  | ↓     |



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# NIOBIUM-MOLYBDENUM

## CRITICAL CURRENT



Critical current for a niobium-molybdenum alloy (1% molybdenum) arc-melted as a function of a transverse applied field.

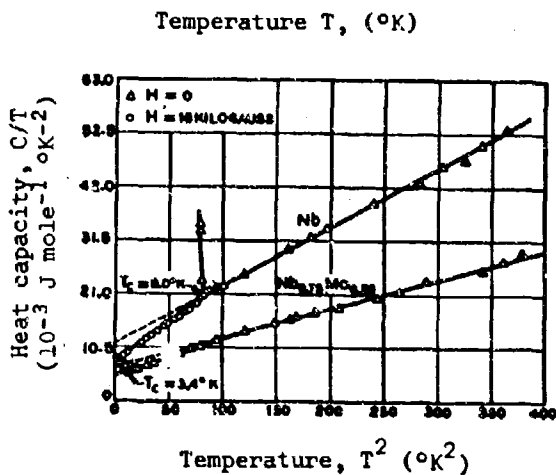
[Ref. 10778]

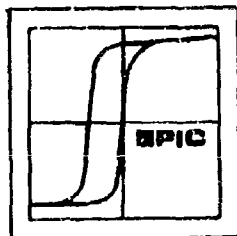
# NIOBIUM- MOLYBDENUM

## SPECIFIC HEAT

Heat capacity for niobium and niobium-molybdenum alloy.  $T_c$  marks the change in slope of these curves.

[Ref. 7686]



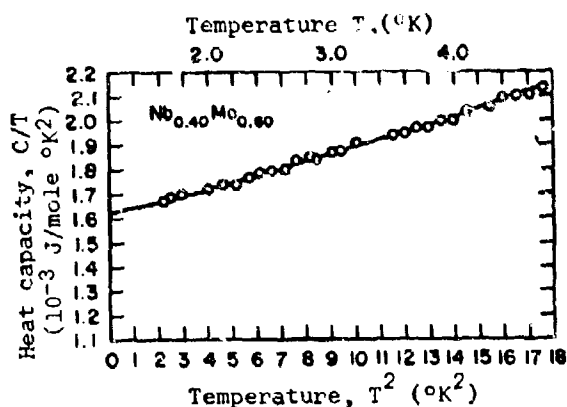


# NIOBIUM-MOLYBDENUM

## SPECIFIC HEAT

Heat capacity for a niobium-molybdenum alloy ( $\text{Nb}_{0.40}\text{Mo}_{0.60}$ ) arc-melted and annealed 20 hours at 2000°C in  $10^{-5}$  mm Hg vacuum.

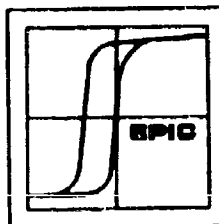
[Ref. 15259]



## Debye Temperature and Specific Heat

| At% Mo | Debye Temperature<br>$\theta$ (°K) |       |         | Coefficient of Electronic Specific Heat<br>$\gamma$ (10 <sup>-4</sup> J/mole °K <sup>2</sup> ) |      |         | Ref.   |
|--------|------------------------------------|-------|---------|------------------------------------------------------------------------------------------------|------|---------|--------|
|        | Measuring Temperature (°K)         |       |         | Measuring Temperature (°K)                                                                     |      |         |        |
|        | <9.5                               | >9.5  | 1.0-4.2 | <9.5                                                                                           | >9.5 | 1.0-4.2 |        |
| 10     | 267                                | 290   | -       | 5.88                                                                                           | 9.24 | -       | 7686   |
| 25     | 290                                | 320   | -       | 4.54                                                                                           | 6.72 | -       | 15259* |
| 38     | 320                                | 330   | -       | 3.28                                                                                           | 3.70 | -       |        |
| 40     | -                                  | 340   | -       | -                                                                                              | 3.02 | -       |        |
| "      | -                                  | -     | 371.1   | -                                                                                              | -    | 2.87    |        |
| 42     | -                                  | 340   | -       | -                                                                                              | 2.69 | -       | 7686   |
| 50     | -                                  | 380   | -       | -                                                                                              | 2.02 | -       | "      |
| 60     | -                                  | -     | 429.4   | -                                                                                              | -    | 1.62    | 15259  |
| 80     | -                                  | 405.0 | -       | -                                                                                              | 1.68 | -       | 7686   |
| "      | -                                  | -     | -       | -                                                                                              | -    | 1.0-2.3 | 15259  |

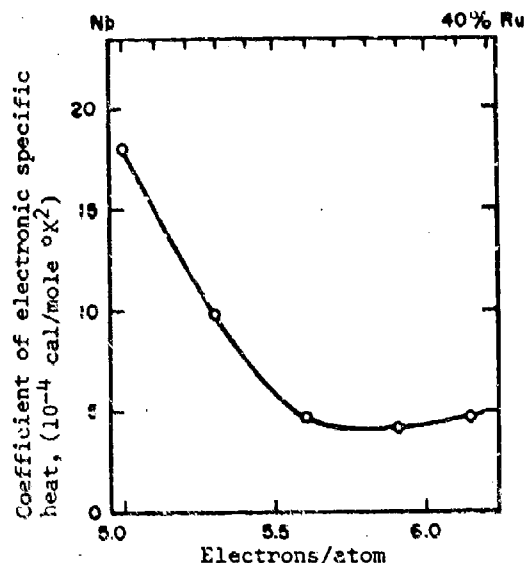
\* Samples arc-melted and annealed,  $10^{-5}$  mm Hg vacuum, 20 hr at 2000 °C.



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# NIOBIUM-RUTHENIUM

## SPECIFIC HEAT



Coefficient of electronic specific heat for the niobium-ruthenium system. Samples were electron-beam melted in high vacuum and annealed at high temperature below  $10^{-8}$  mm Hg.

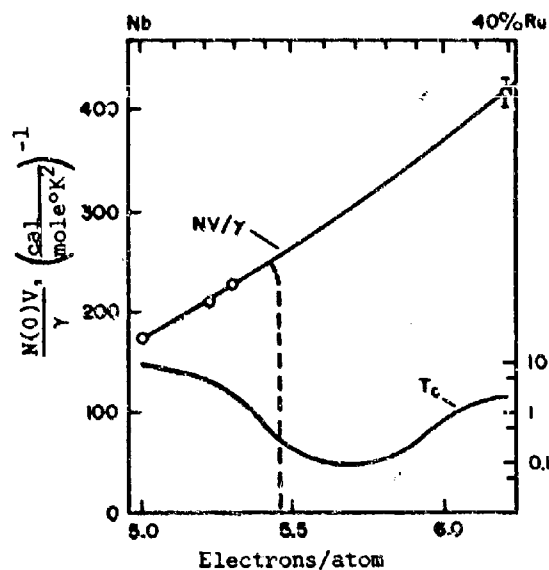
[Ref. 15512]

The expression  $\frac{N(0)V}{\gamma}$  is calculated from  $\gamma$  and  $T_c$  in the following expression:

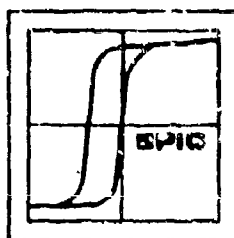
$$kT_c = 1.4 \langle \hbar\omega \rangle e^{-1/N(0)V};$$

$\langle \hbar\omega \rangle$  is assumed to be  $3/4 k\theta^2$ ,  $\theta$  is the Debye temperature. If  $T_c$  is extrapolated linearly to zero, then the dotted line would hold.  $T_c$  is calculated.

[Ref. 15512]







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# NIOBIUM-RUTHENIUM

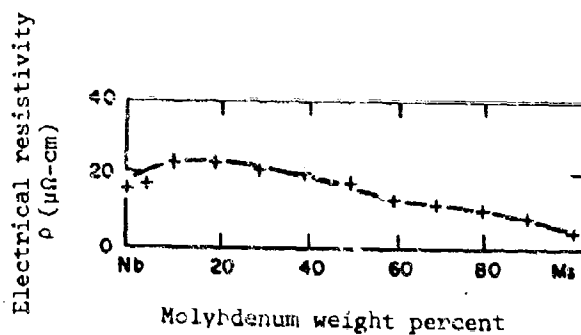
## SPECIFIC HEAT

Measured and calculated values used in the graphs on page 156.

| At. % Ru | $\gamma$<br>( $10^{-4}$ cal/mole $^{\circ}\text{K}^2$ ) | $\theta(^{\circ}\text{K})$<br>( $\sim 4^{\circ}\text{K}$ ) | $T_c$<br>( $^{\circ}\text{K}$ ) | $\frac{N(0)\gamma}{\gamma}$<br>(cal/mole $^{\circ}\text{K}^2$ ) $^{-1}$ | Ref.  |
|----------|---------------------------------------------------------|------------------------------------------------------------|---------------------------------|-------------------------------------------------------------------------|-------|
| 7.5      | (11.7)                                                  | (290)                                                      | 4.20                            | 210                                                                     | 15512 |
| 10.0     | 9.7 $\pm$ 0.3                                           | 304 $\pm$ 10                                               | 2.6                             | 228 $\pm$ 7                                                             |       |
| 20.0     | 4.54 $\pm$ 0.1                                          | 330 $\pm$ 10                                               | <1                              | -                                                                       |       |
| 30.0     | 3.98 $\pm$ 0.04                                         | 372 $\pm$ 10                                               | <1                              | -                                                                       |       |
| 36.0     | 4.45 $\pm$ 0.1                                          | 405 $\pm$ 15                                               | -                               | -                                                                       |       |
| 40.0     | (4.5)                                                   | (410)                                                      | 1.2 $\pm$ 2.2                   | 425                                                                     |       |

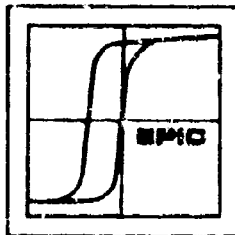
# NIOBIUM-MOLYBDENUM

## ELECTRICAL RESISTIVITY



Electrical resistivity in the niobium-molybdenum system,  
standard sample preparation.

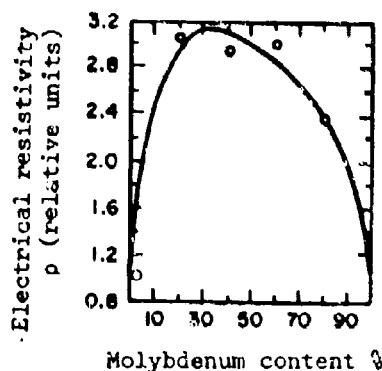
[Ref. 21798]



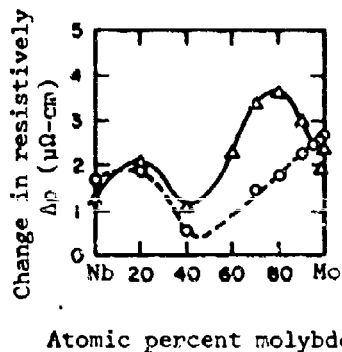
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# NIOBIUM-MOLYBDENUM

## ELECTRICAL RESISTIVITY



Electrical resistivity for the niobium-molybdenum system at 20°C. [Ref. 21567]



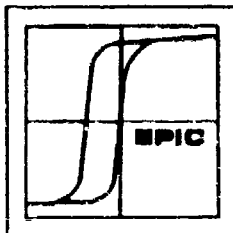
$\Delta\rho$  is the change in resistivity in Nb-Mo system with iron and ruthenium added.

$$\Delta\rho = \rho_{300} \left[ \frac{\rho'_{77}/\rho'_{300} - \rho_{77}/\rho_{300}}{1 - \rho'_{77}/\rho'_{300}} \right]$$

(where  $\rho'$  and  $\rho$  are the resistivities with and without additional components respectively.

- 1.0% iron
- - 1.0% ruthenium

[Ref. 16140]

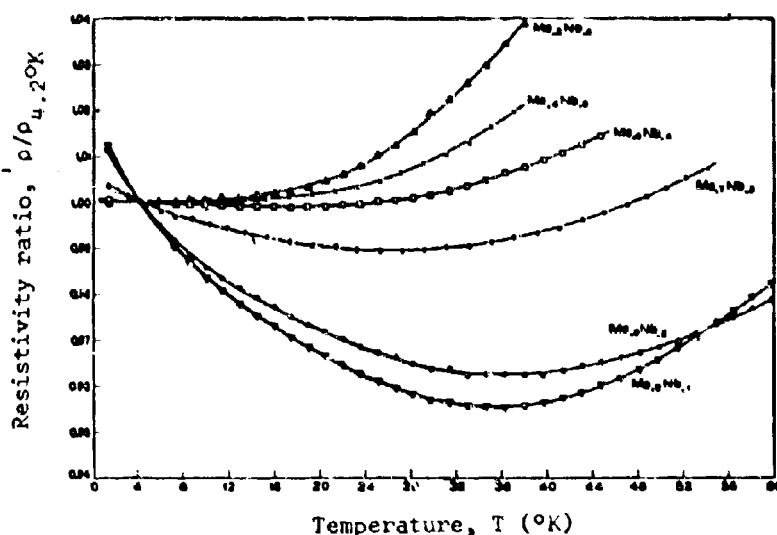


# NIOBIUM-MOLYBDENUM

## ELECTRICAL RESISTIVITY

Resistivity as a function of temperature for niobium-molybdenum system with 1 at.% iron added. The samples were arc-melted in an argon atmosphere, and remelted several times to insure homogeneity.

[Ref. 16140]

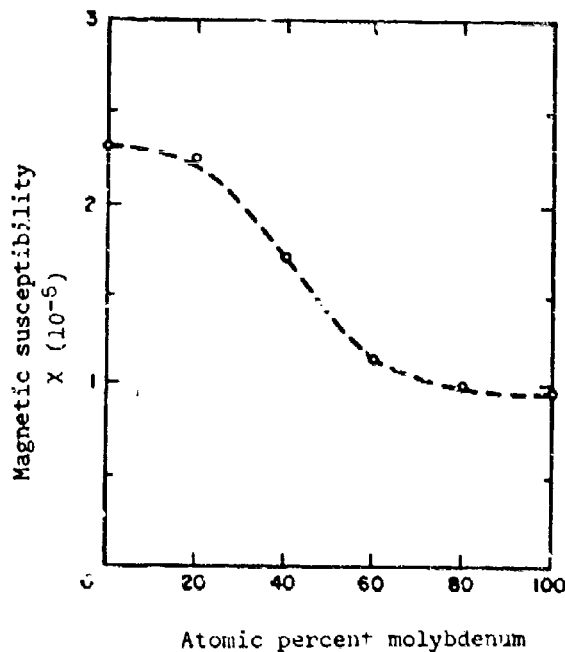


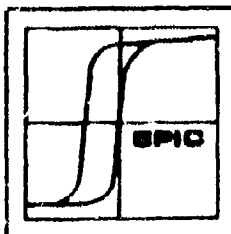
# NIOBIUM-MOLYBDENUM

## MAGNETIC SUSCEPTIBILITY

Room temperature susceptibility for Nb-Mo with 1% iron added, as a function of the molybdenum content.

[Ref. 11937]





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## NIOBIUM-MOLYBDENUM

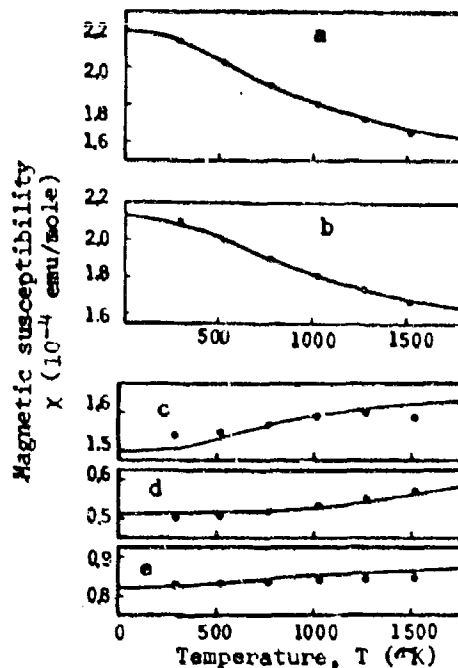
### MAGNETIC SUSCEPTIBILITY

Susceptibility for Nb, Mo, and three Nb-Mo alloys.

Orbital susceptibility

|                                          | $\chi_{orb}$ ( $10^{-4}$ emu/mole) |
|------------------------------------------|------------------------------------|
| a) Nb                                    | 0.980                              |
| b) Nb <sub>0.75</sub> Mo <sub>0.25</sub> | 0.980                              |
| c) Nb <sub>0.50</sub> Mo <sub>0.50</sub> | 1.221                              |
| d) Nb <sub>0.25</sub> Mo <sub>0.75</sub> | 0.521                              |
| e) Mo                                    | 0.544                              |

[Ref. 19617]

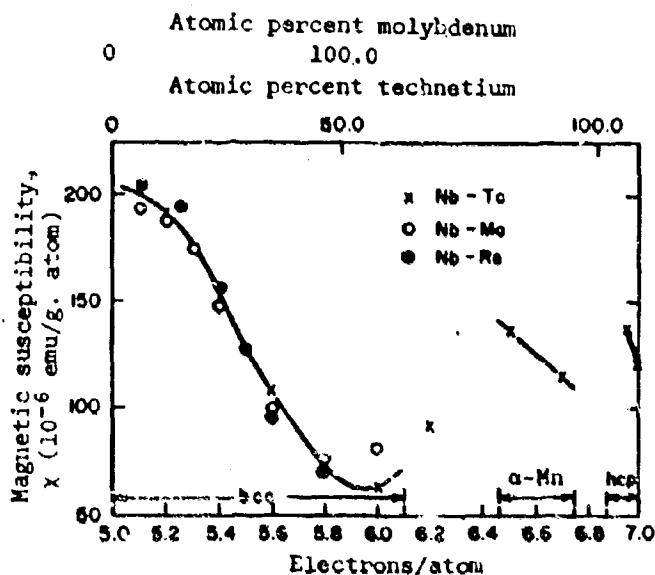


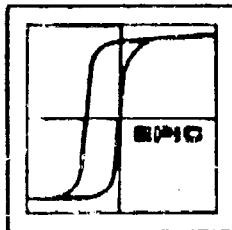
## NIOBIUM-MOLYBDENUM AND NIOBIUM-TECHNETIUM

### MAGNETIC SUSCEPTIBILITY

Susceptibility of niobium-technetium and niobium-molybdenum systems. NbTc samples were arc-melted in argon, homogenized 1 week at 1050°C and heat treated 1 week at 700°C. Nb-Re data are given for comparison.

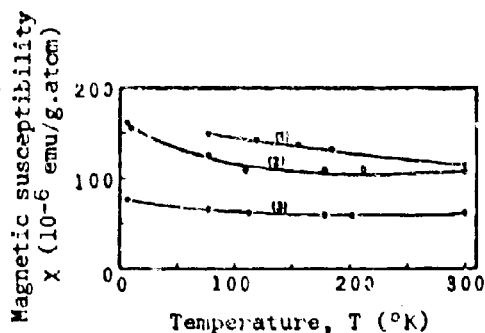
[Ref. 19617]





NIOBIUM-TECHNETIUM

MAGNETIC SUSCEPTIBILITY



Temperature dependence of the susceptibility of three Nb-Tc alloys. The samples were arc-melted in argon, homogenized 1 week at 1050°C and heat treated 1 week at 700°C.

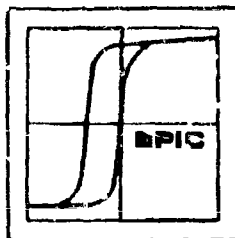
- 1) Nb<sub>0.15</sub>Tc<sub>0.85</sub>
- 2) Nb<sub>0.70</sub>Tc<sub>0.30</sub>
- 3) Nb<sub>0.50</sub>Tc<sub>0.50</sub>

[Ref. 19617]

Lattice Constant and Magnetic Susceptibility

| At. % T <sub>c</sub> | Symmetry   | X<br>(10 <sup>-6</sup> emu/g.at)<br>(25°C) | Lattice constant (Å) |                |
|----------------------|------------|--------------------------------------------|----------------------|----------------|
|                      |            |                                            | a <sub>0</sub>       | c <sub>0</sub> |
| 0                    | bcc        | 204.4                                      | 3.304                | -              |
| 5                    |            | 195.8                                      | -                    | -              |
| 10                   |            | 191.7                                      | 3.276                | -              |
| 20                   |            | 150.6                                      | 3.244                | -              |
| 30                   |            | 108.9                                      | 3.217                | -              |
| 40                   |            | 73.4                                       | 3.192                | -              |
| 50                   |            | 63.3                                       | 3.170                | -              |
| 60                   | bcc + α Mn | 91.7                                       | 3.159                | -              |
| 75                   | α Mn       | 136.5                                      | -                    | -              |
| 85                   | "          | 114.8                                      | 9.547                | -              |
| 97                   | hcp        | 138.3                                      | -                    | -              |
| 100                  | "          | 120.8                                      | 2.743                | 4.400          |

[Ref. 19617]



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# NIOBIUM-RUTHENIUM

## MAGNETIC SUSCEPTIBILITY

### Magnetic Susceptibility

|                | Value                                       | At. % Ru | Notes                                                | Ref.  |
|----------------|---------------------------------------------|----------|------------------------------------------------------|-------|
| $\chi_{tot}^*$ | $176 \times 10^{-6}$ emu/g.at.              | 10       | 5.3 electrons/atom,<br>A 2 type/structure.           | 14464 |
| $\chi_{add}$   | $140 \times 10^{-6}$ emu/g.at.              | "        | " "                                                  | "     |
| $\chi$         | $60 \times 10^{-6}$ cm <sup>3</sup> /g      | 60       | 6.8 electrons/atom,<br>sample cooled from<br>1300°C. | 9686  |
| $\chi_{at}$    | $5900 \times 10^{-6}$ cm <sup>3</sup> /mole | "        | " "                                                  | "     |

$$* \chi_{tot} = \chi_{ion} + \chi_{pauli} + \chi_{L.P.} + \chi_{add}$$

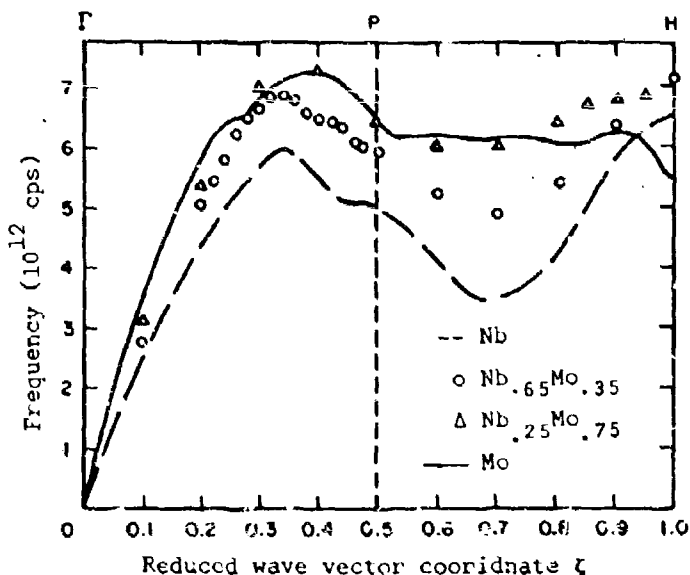
$\chi_{tot}$  is taken as the sum of the various susceptibility contributions. The authors state that  $\chi_{add}$  is probably due to the orbital paramagnetism.

# NIOBIUM-MOLYBDENUM

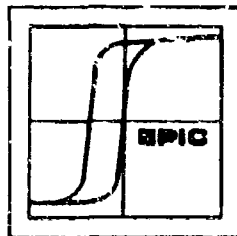
## PHONON DISPERSION

The  $A_1$  branch of the measured phonon dispersion curves of Mo, Nb and two Nb-Mo alloys. The neutron scattering measurements were made at 300°K.

[Ref. 21842]



SECTION 5  
NIOBIUM RHODIUM &  
NIOBIUM PALLADIUM SYSTEMS



## NIOBIUM-RHODIUM AND NIOBIUM-PALLADIUM

### GENERAL

**Nb-Rh** The niobium-rhodium system is very complicated, showing nine different phases. The tetragonal (40% Rh) has the highest transition temperature  $\sim 10.0^\circ\text{K}$ ; while  $\beta$ -tungsten,  $\text{Nb}_3\text{Rh}$ , has a  $T_c$  of only  $\sim 2.5^\circ\text{K}$ . Ziegler [Ref. 18750] has alloyed  $\text{Nb}_3\text{Al}$  with other elements; the lattice constants and transition temperatures for these ternary alloys are given.

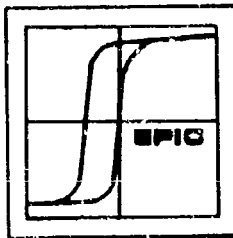
**Nb-Pd** The niobium-palladium system has a transition temperature of about  $2^\circ\text{K}$  at a composition of 40 at.% palladium. The only other niobium-palladium data available were in the palladium-rich region. The following values are taken from this Zwingman paper [Ref. 21799].

| Property                                         | Symbol             | Value                                       |
|--------------------------------------------------|--------------------|---------------------------------------------|
| Change in resistivity                            | $\Delta\rho/a^*$   | 2.96 ( $\Omega\text{-cm/at.}\%$ )           |
| Change in thermoelectric effect                  | $\Delta\epsilon/a$ | +0.6 ( $\mu\text{V}/^\circ\text{C-at.}\%$ ) |
| Change in temperature coefficient of resistivity | $\Delta\alpha/a$   | -1.35 ( $10^{-3}/^\circ\text{C-at.}\%$ )    |

\* a is atomic percent niobium

The coefficient of electronic specific heat and Debye temperature are given for 40 at.% palladium:  $\gamma = 7.13 \pm 0.08 \times 10^{-4} \text{ cal}/^\circ\text{K}^2 \text{ mole}$ ; and  $\theta = 333 \pm 5^\circ\text{K}$  [Ref. 15323].





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NIOBIUM-RHODIUM

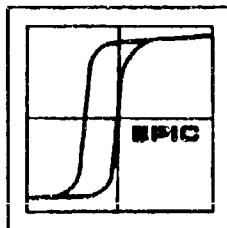
TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

| At% Rh | Symmetry      | Phase                       | $a_0$             | Lattice Constants<br>$b_0$ $c_0$     | Transition Temperature<br>$T_c$ | Notes                        | Ref.  |
|--------|---------------|-----------------------------|-------------------|--------------------------------------|---------------------------------|------------------------------|-------|
| 12     | cubic         | $\alpha$ Nb                 | $3.265 \pm 0.002$ | -                                    | -                               | -                            | 21253 |
| 18.5   | cubic         | $\alpha$ Nb                 | $3.245 \pm 0.002$ | -                                    | -                               | -                            | -     |
| 24.8   | cubic         | $\alpha$ Nb <sub>3</sub> Rh | $5.120 \pm 0.003$ | -                                    | -                               | -                            | -     |
| 25.0*  | cubic         | $\alpha$ Nb <sub>3</sub> Rh | 5.1317            | -                                    | 2.64                            | -                            | 18750 |
| 25.0   | cubic         | $\alpha$ Nb <sub>3</sub> Rh | 5.115             | -                                    | 2.5                             | -                            | 9620  |
| 29.7   | tetragonal    | $\sigma$                    | $9.869 \pm 0.004$ | -                                    | -                               | -                            | 21253 |
| 40.0   | "             | "                           | 9.86              | -                                    | $4.04 \pm 0.2$                  | 6.6 electrons/atom           | 9868  |
| 40.0   | "             | "                           | -                 | -                                    | 4.1                             | -                            | 7648  |
| 51.3   | tetragonal    | $\alpha 2$                  | $4.019 \pm 0.004$ | -                                    | -                               | -                            | 21253 |
| 55.9   | ortho-rhombic | $\alpha 3$                  | $2.827 \pm 0.002$ | $4.770 \pm 0.005$ $13.587 \pm 0.010$ | -                               | -                            | -     |
| 58.8   | "             | $\alpha 4$                  | $2.813 \pm 0.002$ | $4.808 \pm 0.005$ $4.510 \pm 0.005$  | -                               | -                            | -     |
| 62.3   | monoclinic    | $\alpha 5$                  | $2.806 \pm 0.002$ | $4.772 \pm 0.003$ $20.25 \pm 0.10$   | -                               | $\alpha = 90^\circ \pm 1.5'$ | -     |
| 69.2   | hexagonal     | $\alpha 6$                  | $5.463 \pm 0.003$ | -                                    | -                               | -                            | -     |
| 74.5   | cubic         | $\alpha$ NbRh <sub>3</sub>  | $3.857 \pm 0.002$ | -                                    | -                               | -                            | -     |
| 89.1   | "             | $\alpha$ Rh                 | $3.835 \pm 0.002$ | -                                    | -                               | -                            | -     |

[Ref. 21843]

\* Nb<sub>3</sub>Rh, Cu<sub>3</sub>Au type,  $a_0 = 4.207 \text{ \AA}$ . Sample preparations, HCl transport method



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# NIOBIUM-PALLADIUM

## TRANSITION TEMPERATURE

| At. % Pd | Transition Temperature |            | Symmetry     | Notes                                                  | Ref.  |
|----------|------------------------|------------|--------------|--------------------------------------------------------|-------|
|          | $T_c$ (°K)             | $\Delta T$ |              |                                                        |       |
| † 40     | 1.7                    | -          | $\alpha$ -Mn | -                                                      | 15323 |
| "        | 2.04                   | 0.1        | "            | Cooled from 1000°C<br>7.00 electrons/atom.             | 9686  |
| "        | 2.47                   | 0.4        | "            | Cooled from melting<br>point, 7.00 electrons/<br>atom. | "     |

\*  $\Delta T$  is width of the transition region.

†  $Nb_3Pd$ , 25% Pd,  $Cu_3Au$  type,  $A_0 = 4.207 \text{ \AA}$ , sample prepared by HCl transport method.  
[Ref. 21843]

# NIOBIUM-RHODIUM-M

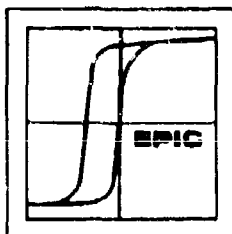
## TRANSITION TEMPERATURE

Lattice Constants and Transition Temperature:  $Nb_3Rh_{1-x}M_x$

| M  | x   | Lattice constant  | Transition Temperature |
|----|-----|-------------------|------------------------|
|    |     | $a_0 \text{ \AA}$ | $T_c$                  |
| Co | .02 | 5.132             | 2.28                   |
|    | .05 | 5.135             | 1.96                   |
|    | .10 | 5.1347            | 1.90†                  |
| Ru | .02 | 5.132             | 2.42                   |
|    | .05 | 5.135             | 2.42                   |
|    | .10 | 5.1346            | 2.44†                  |
| Pd | .02 | 5.133             | 2.50                   |
|    | .05 | 5.134             | 2.49                   |
|    | .10 | 5.1345            | 2.55†                  |

† three phase alloys

[Ref. 18750]



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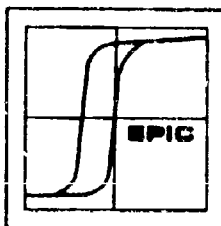
NIORIUM-RHODIUM-M

TRANSITION TEMPERATURE

Lattice Constants and Transition Temperatures  
(Continued)

| M  | x   | Lattice constant<br>$a_o$ | Transition Temperature<br>$T_c$ |
|----|-----|---------------------------|---------------------------------|
| Os | .02 | 5.134                     | 2.42                            |
|    | .05 | 5.132                     | 2.39                            |
|    | .10 | 5.1302                    | 2.30                            |
|    | .30 | 5.1315                    | < 1.7                           |
|    | .50 | 5.1334                    | < 1.7                           |
|    | .70 | 5.1345                    | < 1.7                           |
|    | .90 | 5.1354                    | < 1.7                           |
| Ir | .02 | 5.131                     | 2.43                            |
|    | .05 | 5.132                     | 2.28                            |
|    | .10 | 5.1329                    | < 1.7                           |
|    | .30 | 5.1340                    | < 1.7                           |
|    | .50 | 5.1349                    | < 1.7                           |
|    | .70 | 5.1349                    | < 1.7                           |
|    | .90 | 5.1345                    | < 1.7                           |
| Pt | .02 | 5.132                     | 2.52                            |
|    | .05 | 5.133                     | 2.53                            |
|    | .10 | 5.1336                    | 2.8                             |
|    | .30 | 5.1395                    | 5.1                             |
|    | .50 | 5.1450                    | 6.25                            |
|    | .70 | 5.1487                    | 7.4                             |
|    | .90 | 5.1534                    | 7.9                             |
|    | .95 | 5.160                     | 8.2                             |
|    | .98 | 5.157                     | 9.6                             |
| Au | .02 | 5.133                     | 2.53                            |
|    | .05 | 5.137                     | 2.52                            |
|    | .10 | 5.1412                    | 2.70                            |
|    | .30 | 5.1573                    | 4.6                             |
|    | .50 | 5.1688                    | 6.6                             |
|    | .70 | 5.1827                    | 9.5                             |
|    | .90 | 5.1960                    | 10.8                            |
|    | .95 | 5.200                     | 11.0                            |
|    | .98 | 5.203                     | 10.9                            |

[Ref. 18750]



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# NIOBIUM-RHODIUM AND NIOBIUM-PALLADIUM

## MAGNETIC SUSCEPTIBILITY

### Magnetic Susceptibility

| System                              | $\chi_{\text{tot}}^*(10^{-6}$<br>emu/g.at) | $\chi_{\text{add}}(10^{-6}$<br>emu/g.at) | $\chi^{\dagger}(10^{-6}$<br>cm <sup>3</sup> /g) | $\chi_{\text{at}}(10^{-6}$<br>cm <sup>3</sup> /g) | $\chi(10^{-6})^{**}$ | Symmetry                   |
|-------------------------------------|--------------------------------------------|------------------------------------------|-------------------------------------------------|---------------------------------------------------|----------------------|----------------------------|
| Nb <sub>.60</sub> Rh <sub>.40</sub> | 79                                         | 49                                       | 82                                              | 7900                                              | 810                  | $\sigma$ , DB <sub>b</sub> |
| Nb <sub>.60</sub> Pd <sub>.40</sub> | 50                                         | 29                                       | 50                                              | 5000                                              | 520                  | $\alpha$ -Mn               |

\*  $\chi_{\text{tot}} = \chi_{\text{ion}} + \chi_{\text{Pauli}} + \chi_{\text{L.P.}} + \chi_{\text{add}}$

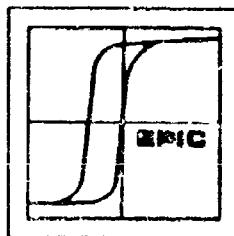
[Ref. 14464]

$\chi_{\text{L.P.}}$  (Landau-Peierls) electronic specific heat contribution

† Nb<sub>.60</sub>Rh<sub>.40</sub> cooled from 1000°C and Nb<sub>.60</sub>Pd<sub>.40</sub> cooled from the melting point [Ref. 9686]

\*\* Volume susceptibility, 300°K

SECTION 5  
NICKELUM-INDIUM SYSTEM

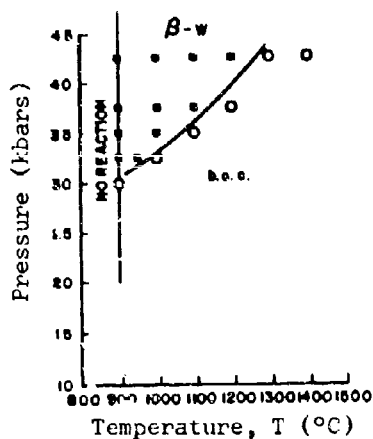


# NIObIUM ALLOYS AND COMPOUNDS

## NIObIUM-INDIUM SYSTEM

### GENERAL

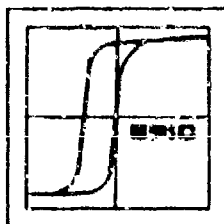
Niobium and indium ( $Nb_3In$ ) show the  $\beta$ -tungsten structure under high pressure, 40-70 kbars, and at an optimum temperature of  $1100^\circ C$ . The lattice constant for this material is given by Banus et al [Ref. 12280] as  $5.303 \pm 0.003 \text{ \AA}$  and the transition temperature is given as  $9.2^\circ K$ .



Pressure-temperature phase diagram  
for  $Nb_3In$ .

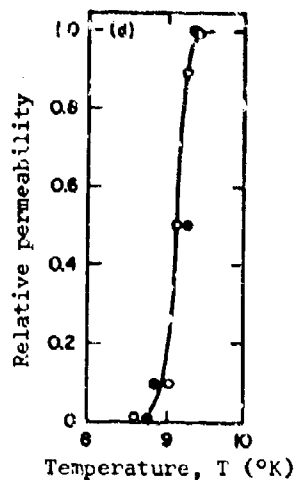
□  $\beta$ -tungsten  
○ bcc

[Ref. 17303]



# NIOBIUM-INDIUM

## TRANSITION TEMPERATURE

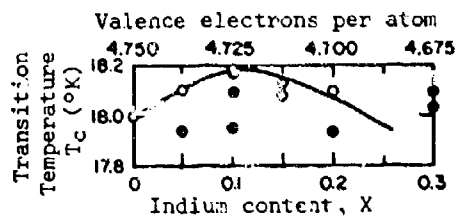


Transition curve for  $\beta$ -tungsten Nb In formed under high pressure conditions.

[Ref. 12280]

# NIOBIUM-INDIUM-TIN

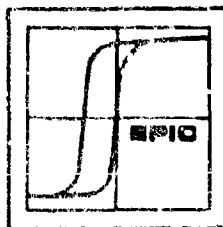
## TRANSITION TEMPERATURE



Transition temperature as a function of indium content,  $Nb_3In_xSn_{1-x}$ .

- Sintered once
- Sintered twice

[Ref. 10749]



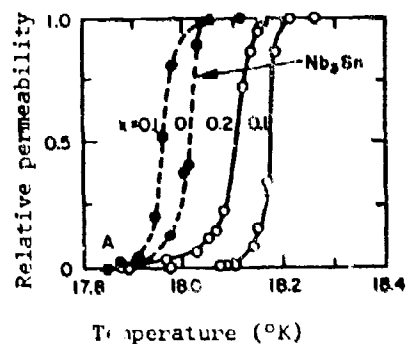
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# NIOBIUM-INDIUM-TIN

## TRANSITION TEMPERATURE

Transition curves for  $\beta$ -tungsten  $Nb_3In_xSn_{1-x}$   
sintered 6 hours at 1200°C:

- sintered once
- sintered twice



[Ref. 10749]

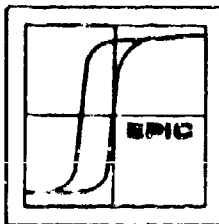
# NIOBIUM-INDIUM-M

## TRANSITION TEMPERATURE

| Compound               | Transition Temperature<br>$T_c$ °K | Notes                                       | Ref.  |
|------------------------|------------------------------------|---------------------------------------------|-------|
| $Nb_3In_{0.5}Zr_{0.5}$ | 6.4                                | -                                           | 10784 |
| $Nb_6InSb$             | 4.2-6.2                            | samples prepared by<br>HCl transport method | 21843 |
| $Nb_6InAs$             | 7.2-7.4                            | "                                           | "     |



SECTION 5  
NIOBIUM-ANTIMONY &  
NIOBIUM-TELLURIUM SYSTEMS



## NIOBIUM ALLOYS AND COMPOUNDS

### NIOBIUM-ANTIMONY AND NIOBIUM-TELLURIUM SYSTEMS

#### GENERAL

**Nb-Sb** Niobium antimonide ( $\text{Nb}_3\text{Sb}$ ) has a predominant  $\beta$ -tungsten crystalline phase, with small amount of other phases present and shows no  $T_c > 1.02^\circ\text{K}$  [Ref. 14387]. These other phases finally disappear and  $T_c$  rises when the antimony is replaced with an alloying agent such as tin.  $\text{Nb}_3\text{Sb}_{1-x}\text{Sn}_x$  shows a single phase  $\beta$ -tungsten structure.

**Nb-Te** The niobium tellurium system does not show a transition temperature. The data are given for this system as an n type semiconductor.

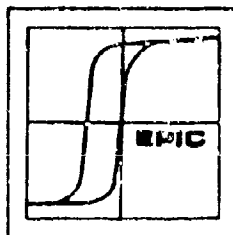
### NIOBIUM-ANTIMONY

#### GENERAL

Lattice Constant

| Formula                | At. % Sb | Crystal-<br>lography | Lattice Constants ( $\text{\AA}$ ) |        |       | $\beta$ | Ref.  |
|------------------------|----------|----------------------|------------------------------------|--------|-------|---------|-------|
|                        |          |                      | $a_o$                              | $b_o$  | $c_o$ |         |       |
| $\text{Nb}_3\text{Sb}$ | 25       | $\beta$ -tungsten    | 5.263                              | -      | -     | -       | 19559 |
| $\text{NbSb}_2$        | 67       | monoclinic           | 10.239                             | 3.6319 | 8.333 | 120.07° | -     |

\* Furuseth, Sigrid & Arne Kjekshus, ACTA CRYST., v. 18, p. 320, 1965.



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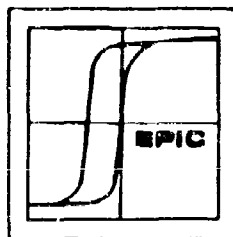
NIOBIUM-ANTIMONY -M

TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

| Formula                                               | Lattice Constant (Å) |                | Transition Temperature<br>T <sub>c</sub> °K | Notes                   | Ref.  |
|-------------------------------------------------------|----------------------|----------------|---------------------------------------------|-------------------------|-------|
|                                                       | a <sub>0</sub>       | c <sub>0</sub> |                                             |                         |       |
| Nb <sub>3</sub> Sb                                    | 5.263                | -              | <1.02*                                      | -                       | 19559 |
| Nb <sub>3</sub> Sb <sub>0.7</sub> Al <sub>0.3</sub>   | -                    | -              | <4.2                                        | -                       | 19559 |
| Nb <sub>3</sub> Sb <sub>0.7</sub> Al <sub>0.3</sub>   | -                    | -              | 7.7                                         | -                       |       |
| Nb <sub>3</sub> Al                                    | 5.183                | -              | 15.7                                        | -                       |       |
| Nb <sub>3</sub> Sb <sub>0.9</sub> Sn                  | 5.267                | -              | -                                           | -                       | 13155 |
| Nb <sub>3</sub> Sb <sub>0.8</sub> Sn <sub>0.2</sub>   | -                    | -              | 0                                           | Powders, 16 hrs. 1200°C | 19614 |
| Nb <sub>3</sub> Sb <sub>0.8</sub> Sn <sub>0.2</sub>   | 5.270                | -              | -                                           | -                       | 13155 |
| Nb <sub>3</sub> Sb <sub>0.75</sub> Sn <sub>0.25</sub> | 5.268                | -              | <5.0                                        | -                       | 13155 |
| Nb <sub>3</sub> Sb <sub>0.7</sub> Sn <sub>0.3</sub>   | 5.270                | -              | 6.8                                         | -                       |       |
| Nb <sub>3</sub> Sb <sub>0.65</sub> Sn <sub>0.35</sub> | 5.268                | -              | 10.5                                        | -                       |       |
| Nb <sub>3</sub> Sb <sub>0.6</sub> Sn <sub>0.4</sub>   | "                    | -              | 12.4                                        | -                       |       |
| Nb <sub>3</sub> Sb <sub>0.4</sub> Sn <sub>0.6</sub>   | 5.273                | -              | 15.8                                        | -                       |       |
| "                                                     | -                    | -              | 12.0                                        | Powders, 16 hrs. 1200°C | 19614 |
| Nb <sub>3</sub> Sb <sub>0.2</sub> Sn <sub>0.8</sub>   | 5.283                | -              | 18.0                                        | -                       | 13155 |
| Nb <sub>3</sub> Sn                                    | 5.292                | -              | "                                           | -                       | "     |

\* [Ref. 14387]



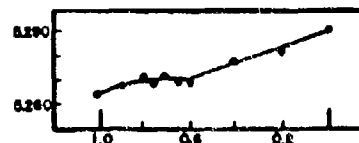
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# NIOBIUM-ANTIMONY-TIN

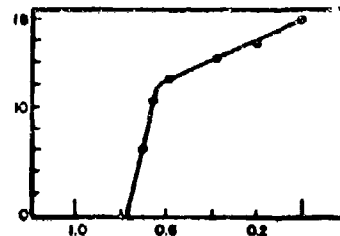
## TRANSITION TEMPERATURE

Lattice constants and transition temperature for  $Nb_3Sb_xSn_{1-x}$  as a function of composition. Powdered samples were fired at 1200°C for 66 hours.

Lattice constant,  
 $a_0$  (Å)

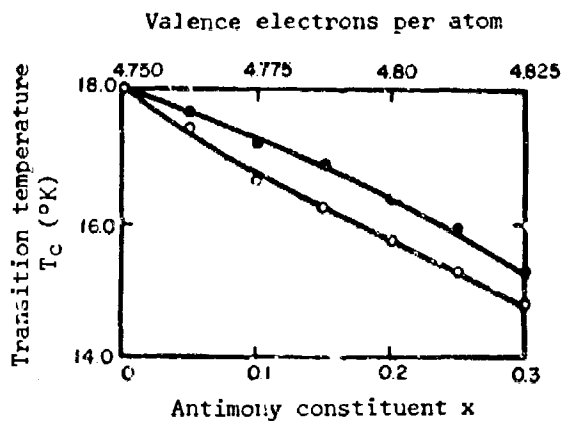


Transition temp.  
 $T_c$  (°K)



Antimony constituent x

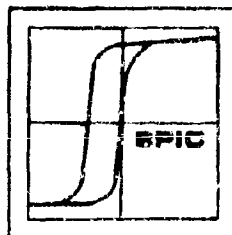
[Ref. 13155]



Transition temperature of  $Nb_3Sb_xSn_{1-x}$  as a function of antimony constituent, powder pressed to 8 tons/cm<sup>2</sup> sintered 5 hours at 1200°C.

- ) inductive measurement
- ) resistive measurement

[Ref. 15343]

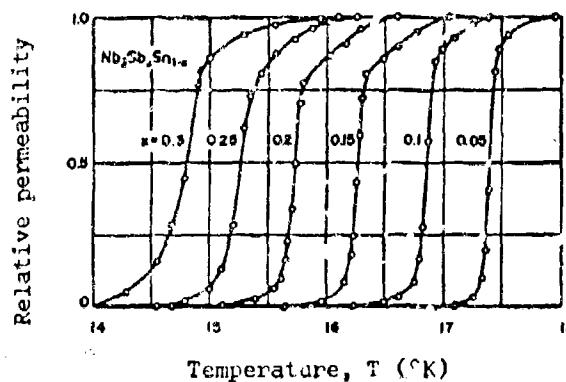


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# NIOBIUM-ANTIMONY-TIN

## TRANSITION TEMPERATURE

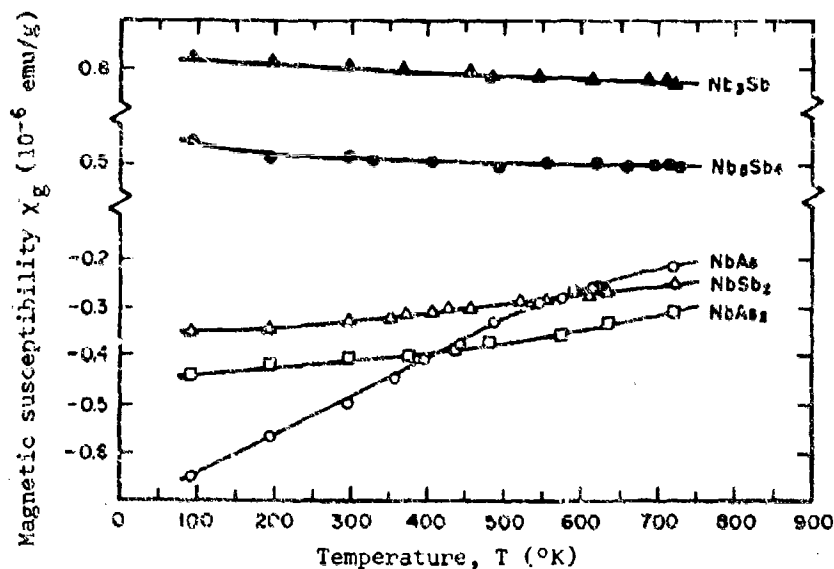
Transition curves of  $Nb_3Sb_xSn_{1-x}$  as a function of the temperature with different amounts of antimony.



[Ref. 15343]

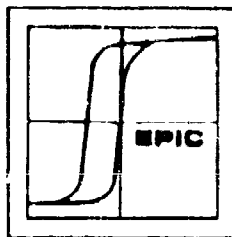
# NIOBIUM-ANTIMONY

## MAGNETIC SUSCEPTIBILITY



Magnetic susceptibility for niobium antimonides and arsenides as a function of temperature. The antimonides were prepared by heating niobium and antimony at 1000°C for 2 days, 800°C for 14 days and quenching in water. The arsenides were prepared by heating niobium and arsenic at 1000°C for 2 days, 720°C for 14 days and quenching in water.

[Ref. 21797]

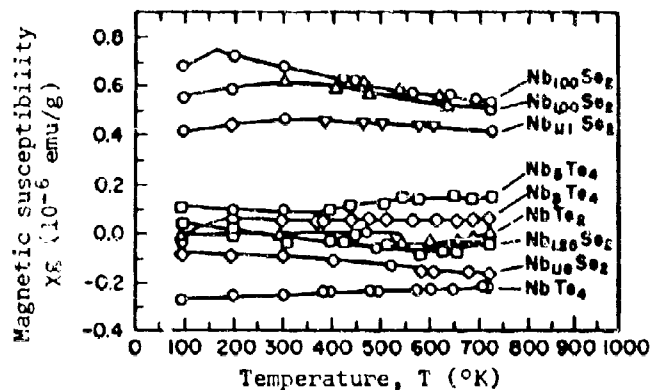


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## NIOBIUM-TELLURIUM

### MAGNETIC SUSCEPTIBILITY

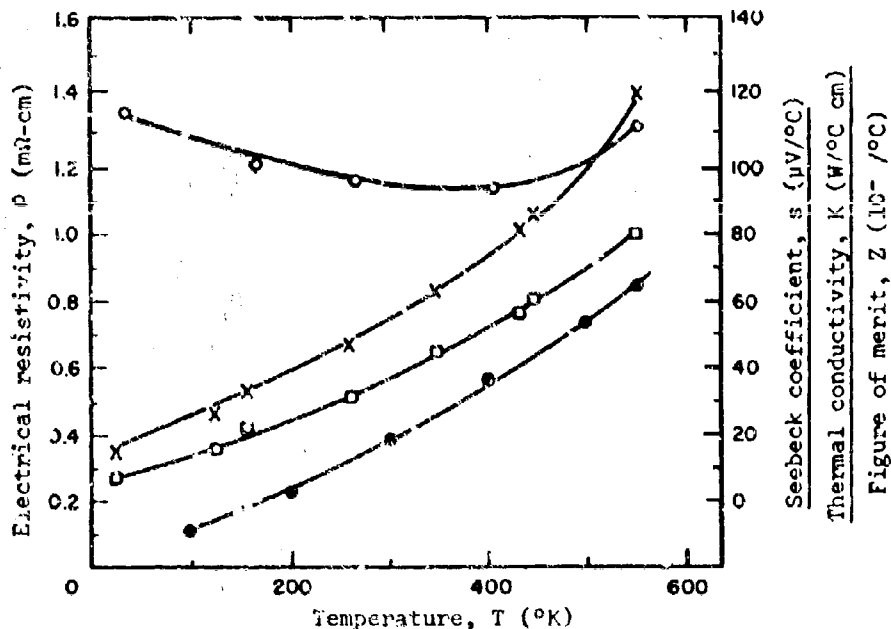
Magnetic susceptibility for various niobium selenides and tellurides. These values have not been corrected for induced diamagnetism.



## NIOBIUM-TELLURIUM

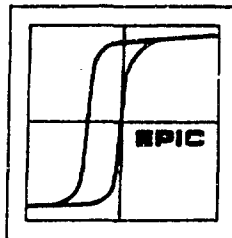
[Ref. 21738]

### ELECTRICAL RESISTIVITY



Thermoelectric properties of  $\text{NbTe}_2$  as a function of temperature single crystals were prepared by vapor transport from polycrystalline niobium telluride.

[Ref. 21796]



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NIOBIUM-TELLURIUM

SEMICONDUCTING PROPERTIES

Semiconducting Properties

| Formula                         | Lattice constant Å |                | Electrical<br>Resistivity<br>$\rho$ (10 <sup>-4</sup> Ω-cm) | Seebeck<br>coefficient S<br>(μV/°C) | Thermal<br>conductivity K<br>(W/°C-cm) | Figure of<br>merit Z<br>(°C <sup>-1</sup> × 10 <sup>-5</sup> ) | Symmetry Ref |
|---------------------------------|--------------------|----------------|-------------------------------------------------------------|-------------------------------------|----------------------------------------|----------------------------------------------------------------|--------------|
|                                 | a <sub>o</sub>     | c <sub>o</sub> |                                                             |                                     |                                        |                                                                |              |
| NbTe                            | -                  | -              | 4.8 <sup>a</sup>                                            | 4.7 <sup>a</sup>                    | -                                      | .0078                                                          | -            |
| NbTe                            | 10.904             | 20.119         | -                                                           | -                                   | -                                      | -                                                              | rhomb. 21796 |
| NbTe <sub>2</sub>               | "                  | 19.888         | 0.26 <sup>c</sup>                                           | 15                                  | 0.019                                  | 4.55                                                           | "            |
| Nb <sub>3</sub> Te <sub>4</sub> | 10.671             | 3.6468         | -                                                           | -                                   | -                                      | -                                                              | hex. *       |
| NbTe <sub>4</sub>               | 2x6.499            | 3x6.837        | -                                                           | -                                   | -                                      | -                                                              | " 21258      |

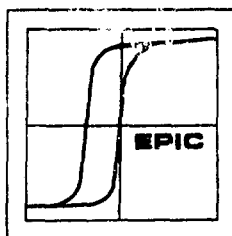
a) 100°C, b) 600°C, d) 25°C, e) - 196°C

\* Selte, Kan and Arne Kjekshus, ACTA. CHEM. SCAND., v. 18, p. 690, 1964.

**THE**

[illegible]





## NIOBIUM ALLOYS AND COMPOUNDS

### NIOBIUM-HAFNIUM, NIOBIUM-TANTALUM AND NIOBIUM-TUNGSTEN SYSTEMS

#### GENERAL

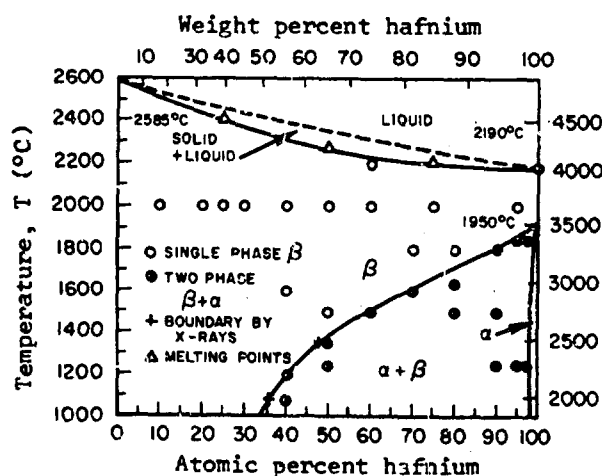
**Nb-Hf** Niobium-hafnium alloys show a transition temperature near that of pure niobium until the hafnium content approaches 70 at.%. In region >70 at.% hafnium, Hf is found with the bcc Nb-Hf solid solution and  $T_c$  data are not available.

**Nb-Ta** The niobium-tantalum system comprises a series of solid solutions with the lattice constant nearly the same throughout. The transition temperature for this system decreases from about 9°K for niobium to about 4.5°K for tantalum.

**Nb-W** Niobium and tungsten form a series of solid solutions throughout the system. The lattice parameters are given to about 25% tungsten content and transition temperatures are given to about 40% tungsten content.

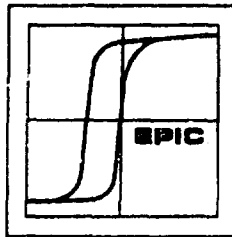
#### NIOBIUM-HAFNIUM

##### GENERAL



Tentative phase diagram for the niobium-hafnium system.

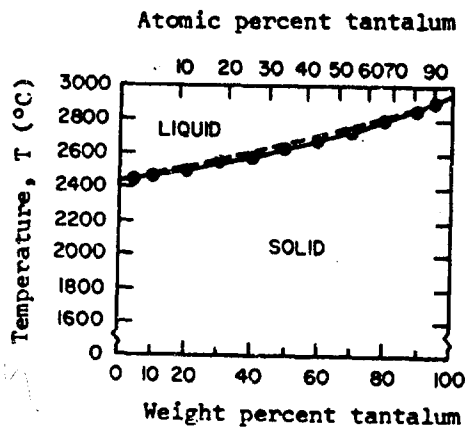
[Ref. 21732]



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## NIOBIUM-TANTALUM

### GENERAL



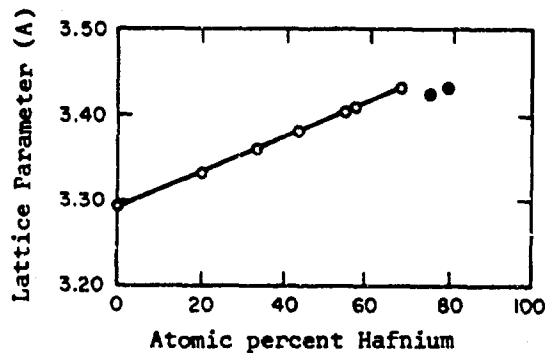
Phase diagram for the niobium-tantalum system.

[Ref. 21262]

## NIOBIUM-HAFNIUM

### GENERAL

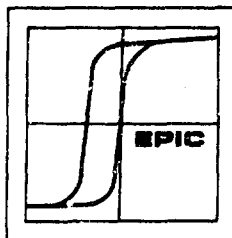
Lattice parameter for niobium-hafnium system as a function of hafnium content. Samples melted in a helium arc furnace and homogenized for 48 hours at 1000°C.



- bcc
- bcc Nb-Hf + hcp Hf

[Ref. 20160]

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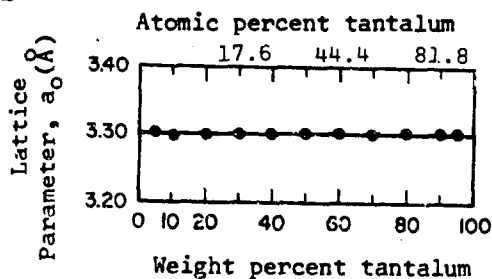


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## NIOBIUM-TANTALUM

### GENERAL



\*Donnay, J., ed. CRYSTAL DATA:  
DETERMINATIVE TABLES. 2d. ed.  
New York, American Crystallographic  
Assoc., 1963. p. 829.

Lattice parameter for niobium-tantalum system.

#### Lattice Constants

$$\text{Nb}, a_0 = 3.302 \text{ \AA} *$$

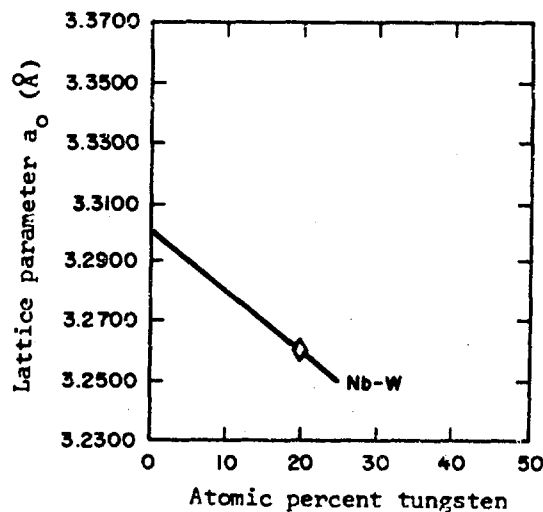
$$\text{Ta}, a_0 = 3.3026 \text{ \AA} *$$

[Ref. 21262]

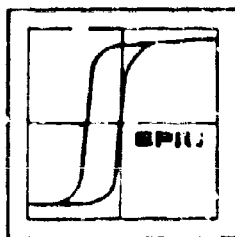
## NIOBIUM-TUNGSTEN

### GENERAL

Lattice parameter for niobium-tungsten  
system as a function of tungsten content.  
Standard sample preparation.



[Ref. 10778]



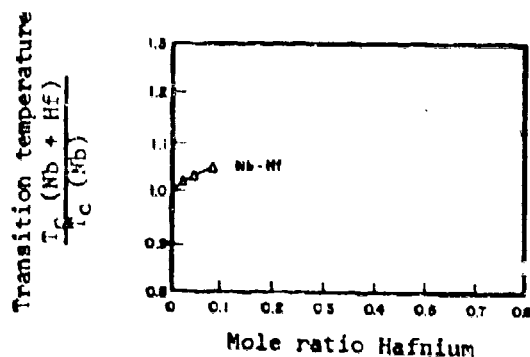
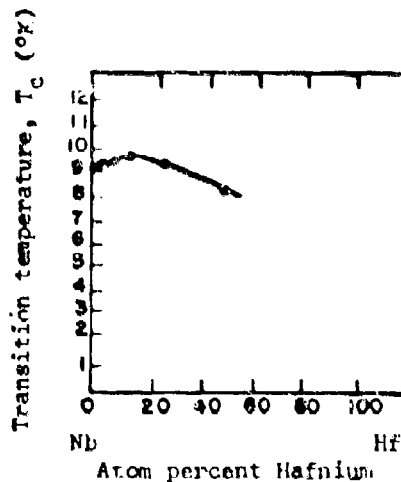
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## NIOBIUM-HAFNIUM

### TRANSITION TEMPERATURE

Transition temperature of niobium-hafnium system as a function of hafnium content.

[Ref. 21583]



Transition temperature of niobium-hafnium system as a function of hafnium content. Standard methods of sample preparation.

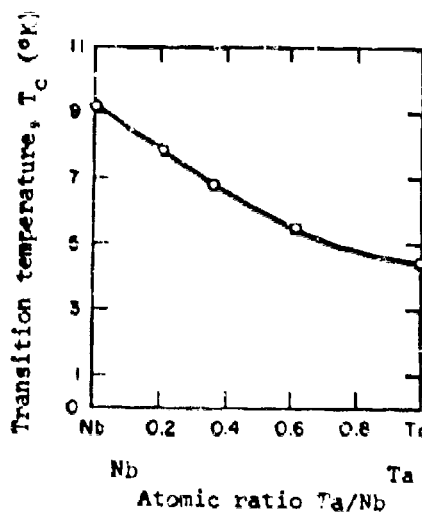
[Ref. 10778]

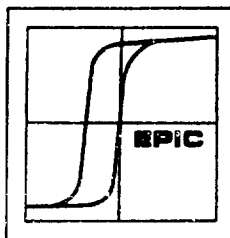
## NIOBIUM-TANTALUM

### TRANSITION TEMPERATURE

Transition temperatures for niobium-tantalum system. The sample preparations were standard.

[Ref. 12583]



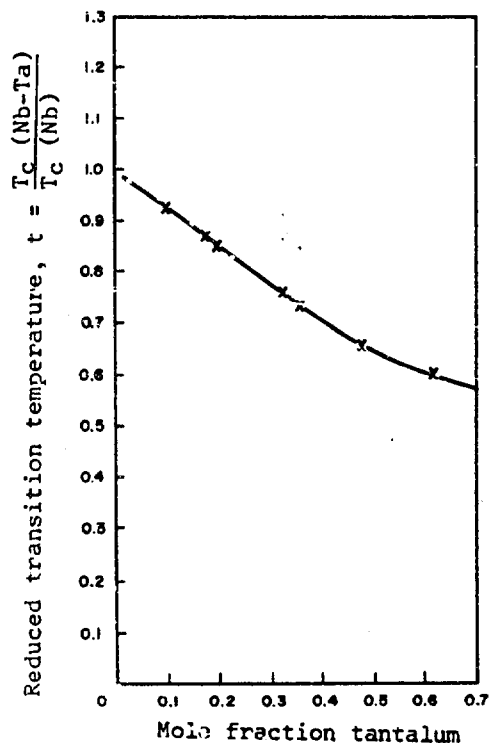
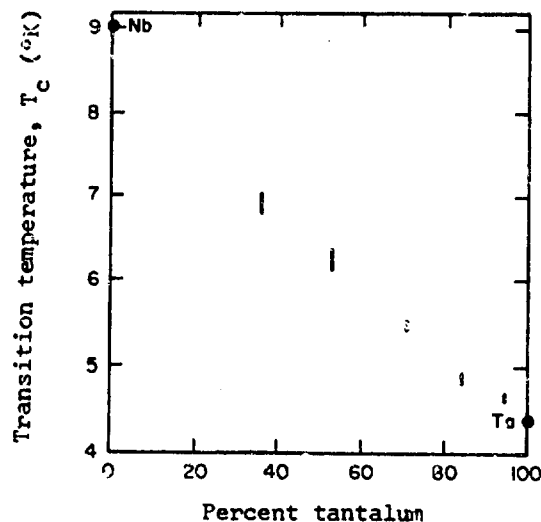


# NIOBIUM-TANTALUM

## TRANSITION TEMPERATURE

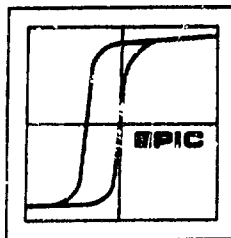
Transition temperatures for the niobium-tantalum system. Powders were pressed into a rod and melted by the floating zone process, after swaging, further zone-melting produced a single crystal.

[Ref. 12452]



Reduced transition temperatures for niobium-tantalum system.

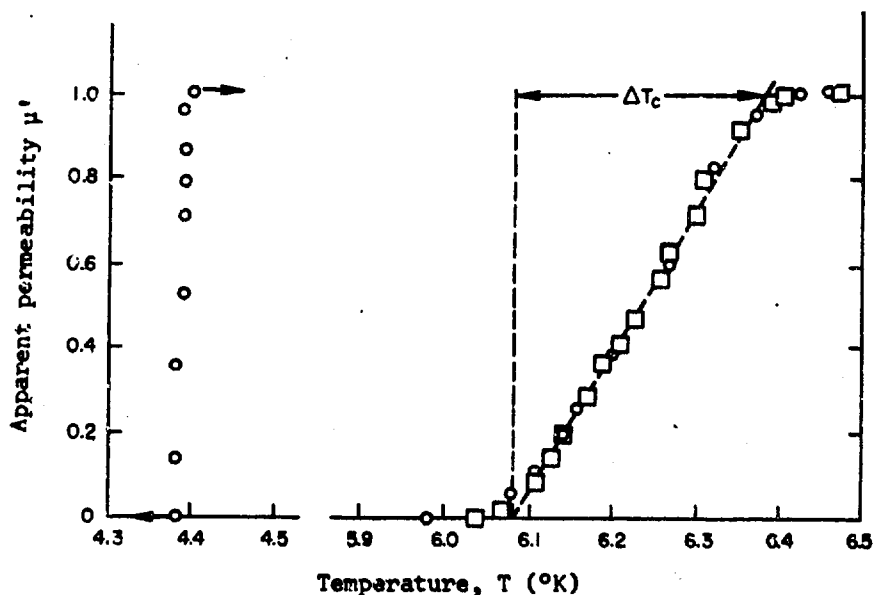
[Ref. 10778]



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# NIOBIUM-TANTALUM

## TRANSITION TEMPERATURE

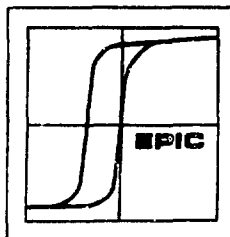


Transition curve for two Nb<sub>47</sub>Ta<sub>53</sub> samples. The data were taken in a small alternating field of about 15 kc, on thin rods with a length to diameter ratio of 15.

|                |     |    |
|----------------|-----|----|
|                | ○   | □  |
| Trapped flux   | 10% | 0% |
| hardness (dhp) | 122 | 76 |

$\mu' = \frac{V - V_s}{V_n - V_s}$ , where V is measured voltage and  $V_n$  &  $V_s$  are the secondary coil voltages in the normal and superconducting states respectively.

[Ref. 12452]



## NIOBIUM-TUNGSTEN

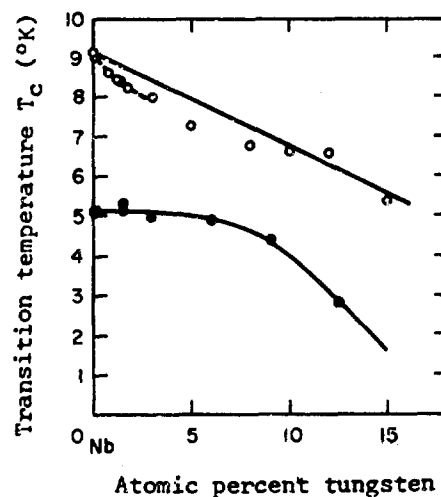
### TRANSITION TEMPERATURE

Transition temperature as a function of tungsten content for a niobium-tungsten system.

#### Initial Material

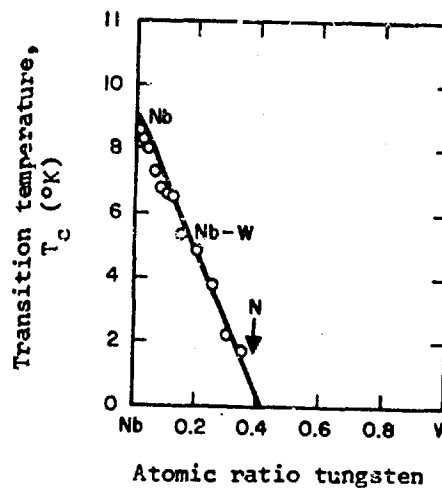
- Zone refined Nb
- Powdered Nb

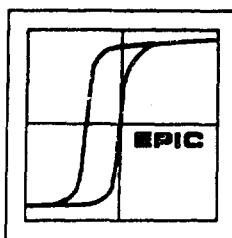
[Ref. 12583]



Transition temperature for niobium-tungsten system.

[Ref. 12583]





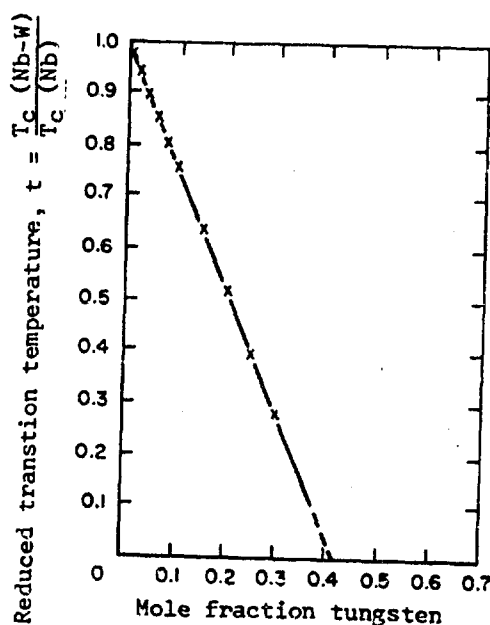
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# NIOBIUM-TUNGSTEN

## TRANSITION TEMPERATURE

Reduced transition temperature for the niobium-tungsten system.

[Ref. 10778]

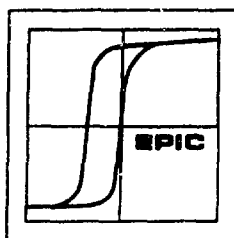


# NIOBIUM-TANTALUM

## PENETRATION DEPTH AND COHERENCE LENGTH

| System                              | Penetration depth<br>$\lambda(0)$ (Å) | Coherence length<br>$\xi$ (Å) | Ref.  |
|-------------------------------------|---------------------------------------|-------------------------------|-------|
| Nb <sub>.64</sub> Ta <sub>.36</sub> | 890                                   | ~142                          | 19930 |
| Nb <sub>.47</sub> Ta <sub>.53</sub> | -                                     | 125                           | "     |
| "                                   | -                                     | 250                           | 21800 |

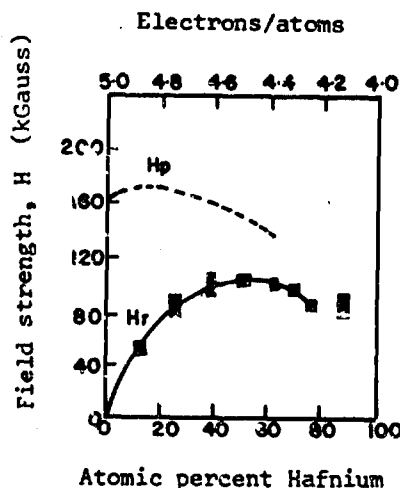




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# NIOBIUM-HAFNIUM

## CRITICAL FIELD



Critical fields for niobium-hafnium alloys as a function of hafnium content,  $J = 10$  (Amp/cm<sup>2</sup>)  $T = 0.2^\circ\text{K}$ . Standard sample preparation.  $H_p$  is the upper limit of the critical field transition range and is defined:

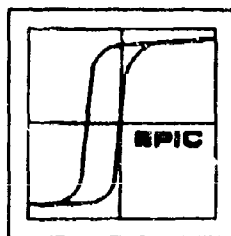
$$H_p = (e_0/\sqrt{2}\mu_B) [1-(T/T_c)^2]$$

The  $H_r$  value is used to denote (1) the field at which resistance is first measured, and (2) the field at which full resistance is restored. The rectangles in the above figure and the two values in the following tables show these  $H_r$  values.

[Ref. 11924]

### Critical Field Strength

| Symbol         | Values<br>(kGauss) |       | at.% Hf | Symmetry       | Notes                                                              | Ref.       |  |
|----------------|--------------------|-------|---------|----------------|--------------------------------------------------------------------|------------|--|
|                | (1)                | (2)   |         |                |                                                                    |            |  |
| H <sub>r</sub> | 62.1               | 69.6  | 12.5    | bcc<br>↑       | arc-melted<br>J = 10 amp/cm <sup>2</sup><br>T <sub>c</sub> = 1.2°K | 11924<br>↓ |  |
|                | 78.9               | 89.6  | 25.0    |                |                                                                    |            |  |
|                | 91.0               | 101.6 | 37.5    |                |                                                                    |            |  |
|                | 102.4              | 109.4 | 50.0    |                |                                                                    |            |  |
|                | 99.5               | 103.5 | 62.5    | ↓<br>hcp + bcc |                                                                    |            |  |
|                | 95.1               | 98.8  | 70.0    |                |                                                                    |            |  |
|                | 83.1               | 89.7  | 75.0    |                |                                                                    |            |  |
|                | 83.0               | 96.0  | 87.5    |                |                                                                    |            |  |



# NIOBIUM-HAFNIUM

## TRANSITION TEMPERATURE AND CRITICAL FIELD

| Compound                            | Transition temperature<br>$T_c(^{\circ}\text{K})$ | Electrical resistivity<br>$\rho_n(4.2^{\circ}\text{K})$ ( $\mu\Omega\text{-cm}$ ) | $H_{ps}^*$ ( $4.2^{\circ}\text{K}$ )<br>(kGauss) | $H_u^{\dagger}$ ( $4.2^{\circ}\text{K}$ )<br>(kGauss) | Sample              |
|-------------------------------------|---------------------------------------------------|-----------------------------------------------------------------------------------|--------------------------------------------------|-------------------------------------------------------|---------------------|
| Nb <sub>.25</sub> Hf <sub>.75</sub> | >4.2                                              | 124                                                                               | 15                                               | >26                                                   | arc-cast            |
| Nb <sub>.25</sub> Hf <sub>.75</sub> | >4.2                                              | 124                                                                               | 17                                               | >28                                                   | cold rolled;<br>2:1 |

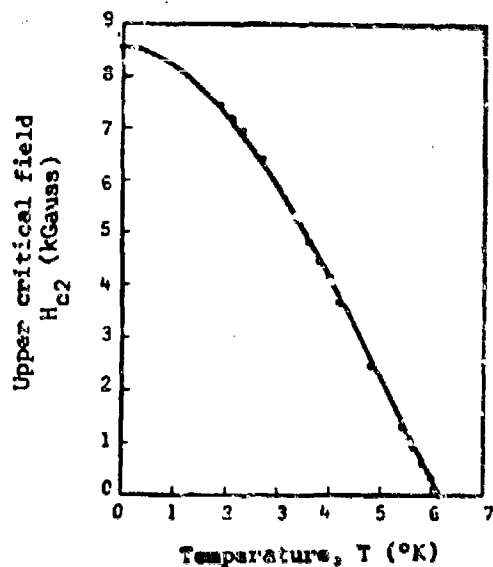
[Ref. 21845]

\* $H_{ps}$  Paramagnetic superconductivity onset field

$\dagger H_u$  Upper critical field

# NIOBIUM-TANTALUM

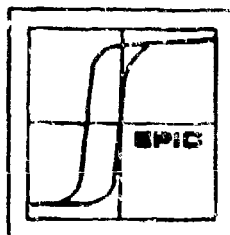
## CRITICAL FIELD



Upper critical field for Nb<sub>.5</sub>Ta<sub>.5</sub> as a function of temperature.  $T_c = 6.15^{\circ}\text{K}$ .

- from  $\rho_f$  graph, 8.6(kGauss)
- theory
- measured by resistivity method

[Ref. 21841]



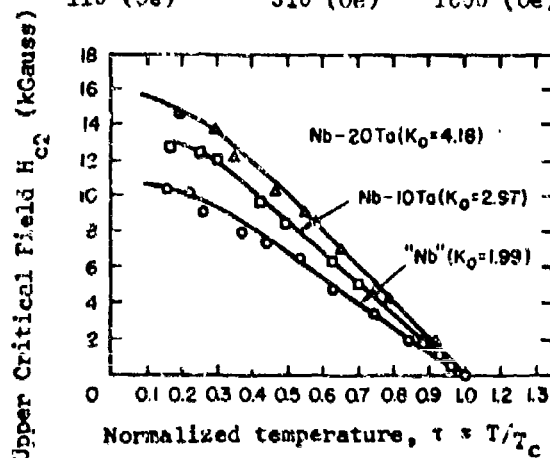
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# NIOBIUM-TANTALUM

## CRITICAL FIELD

### Transition Temperature and Critical Field

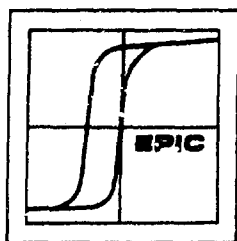
| At. % Ta | Transition temperature<br>$T_c$ (°K) | Critical Field Strength |          |               |               | Ref.  |
|----------|--------------------------------------|-------------------------|----------|---------------|---------------|-------|
|          |                                      | $H_{c1}$                | $H_c$    | $H_{c2}$      | $H_{c3}$      |       |
| 45       | ~6.5                                 |                         |          |               |               | 21261 |
| 50       | 6.25                                 | -                       | -        | -             | -             | 19477 |
| "        | -                                    | -                       | -        | 3.55 (kGauss) | 1.72 $H_{c2}$ | 13481 |
| 67       | 5.6                                  | 110 (Oe)                | 310 (Oe) | 1600 (Oe)     | -             | 14582 |



Upper critical field as a function of temperature for the following samples, as rolled.

$K_0 = x_{e0} + x_{i0}$ , where  $x_{e0}$  is the intrinsic contribution to the order parameter and  $x_{i0}$  is the impurity scattering contribution. The values are given for  $\tau = 0$ ,

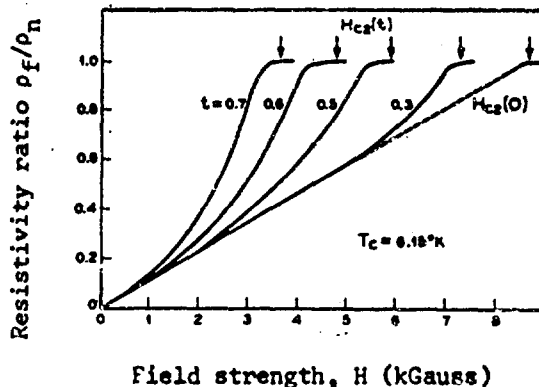
[Ref. 21259]



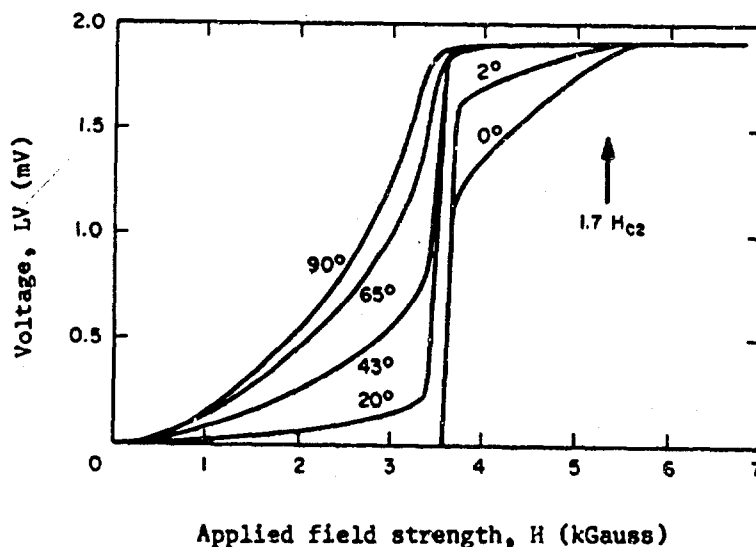
# NIOBIUM-TANTALUM

## CRITICAL FIELD

Ratio of flow resistivity to normal resistivity as a function of field strength  $H$ , for  $Nb_{0.5}Ta_{0.5}$ . The  $t$  values are the ratio  $T/T_c$  for  $T_c = 6.15^\circ K$ .  $H_{c2}$  values are shown for each  $t$  and the dashed line indicates expected behavior at  $t = 0$ .  $H_{c2}(0) = 8.6$  (kGauss).

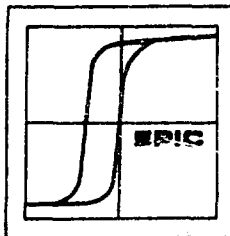


[Ref. 21841]



Resistive transitions in a  $Nb_{0.5}Ta_{0.5}$  sheet  $1.5 \text{ cm} \times 0.25 \text{ cm} \times 716 (10^{-3}) \text{ cm}$ . The data are taken at  $T = 4.2^\circ K$ ,  $I = 500 \text{ mA}$  and  $J = 260 \text{ amp/cm}^2$  and at different  $H$  to  $J$  orientations.  $H_{c2} = 3.55 \text{ kGauss}$  and  $H_{c3} = 1.7 H_{c2}$ , theoretical. The sample was annealed.

[Ref. 13481]



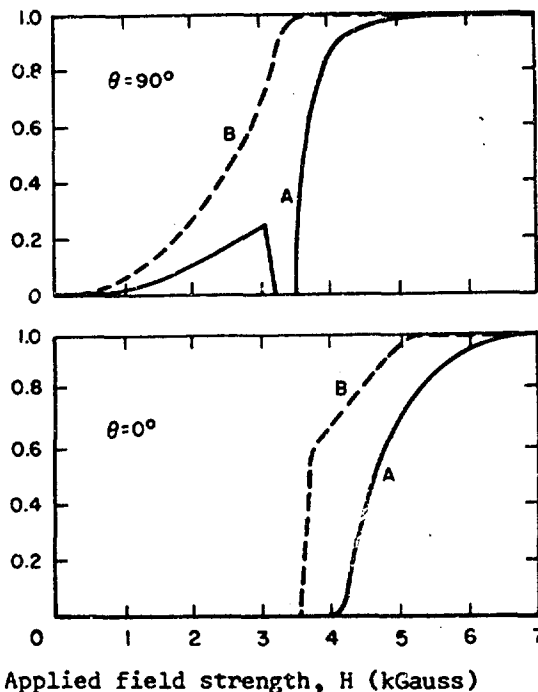
# NIOBIUM-TANTALUM

## CRITICAL FIELD

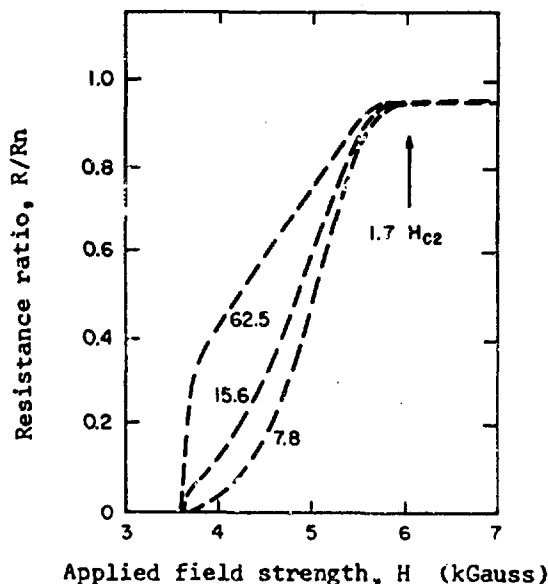
Resistive transitions reduced from voltage measurements, on a Nb<sub>5</sub>Ta<sub>5</sub> sheet. Data taken at  $T = 4.2^\circ\text{K}$  and  $J = 200 \text{ Amp/cm}^2$ . The samples are identical except that (b) has been annealed.

[Ref. 13481]

Resistance ratio  $R/R_n$

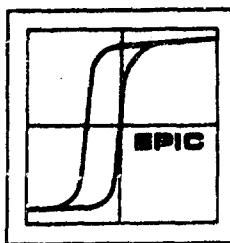


Applied field strength,  $H$  (kGauss)



Resistive transitions in a Nb<sub>5</sub>Ta<sub>5</sub> sheet  $1.5 \times 0.25 \times 7.6 \times 10^{-3} \text{ cm}$ . The data are taken at  $T = 4.2^\circ\text{K}$ ,  $H \parallel J$  and different current strengths. The  $R/R_n$  values are obtained from reduction of the previous voltage data  $H_{c2} = 3.55 \text{ kGauss}$  and  $H_{c3} = 1.7 H_{c2}$ . The sample was annealed.

[Ref. 13481]



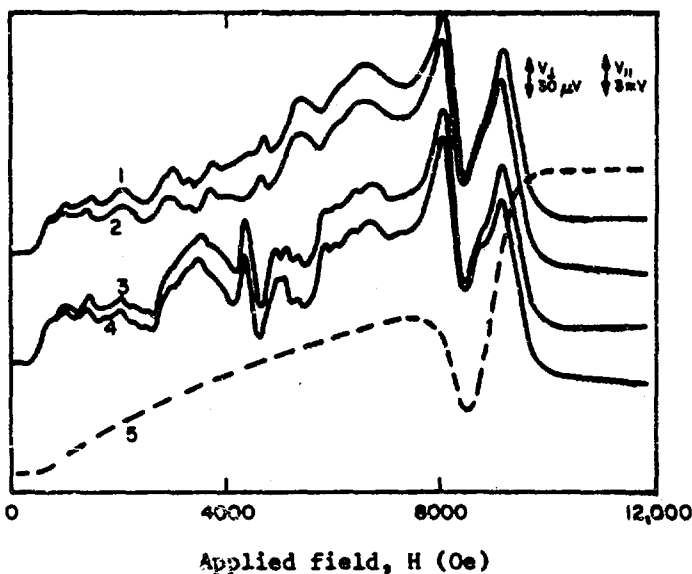
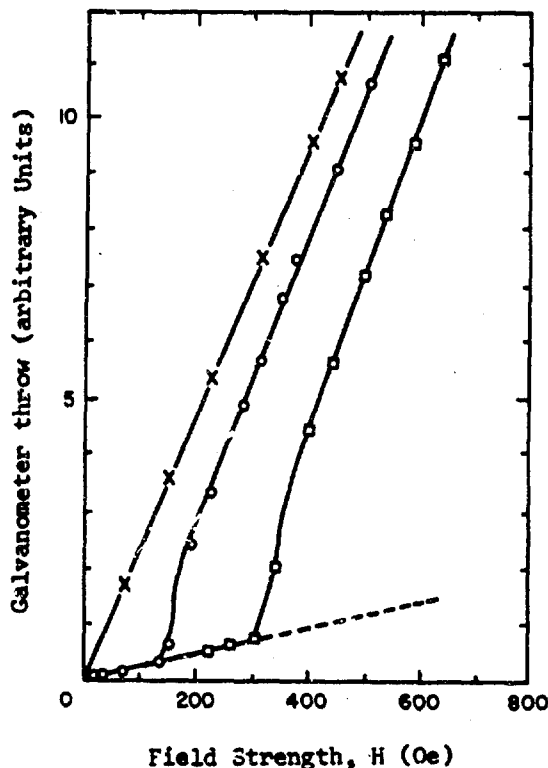
# NIOBIUM-TANTALUM

## CRITICAL FIELD

Flux penetration curves for  $Nb_{.64}Ta_{.36}$  alloy. Cylindrical rods, zone-refined.

- $T = 4.2^{\circ}K$
- $T = 6.0^{\circ}K$
- X  $T = 8.2^{\circ}K$

[Ref. 12452]



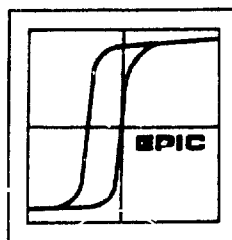
Transverse and longitudinal voltages as a function of magnetic field strength for  $Nb_{.5}Ta_{.5}$  sample. The Hall voltage may be derived by subtracting two corresponding curves. The polarity of the recorder was reversed in (2) and (3).

- (1)  $H_{-}i_{+}$
- (2)  $H_{+}i_{-}$
- (3)  $H_{-}i_{-}$
- (4)  $H_{+}i_{+}$

(5)  $V_{||}$

$T = 1.3^{\circ}K$   
 $J = 3 \times 10^3 \text{ amp/cm}^2$   
 $J_{||} \text{ R.D.}$

[Ref. 21260]



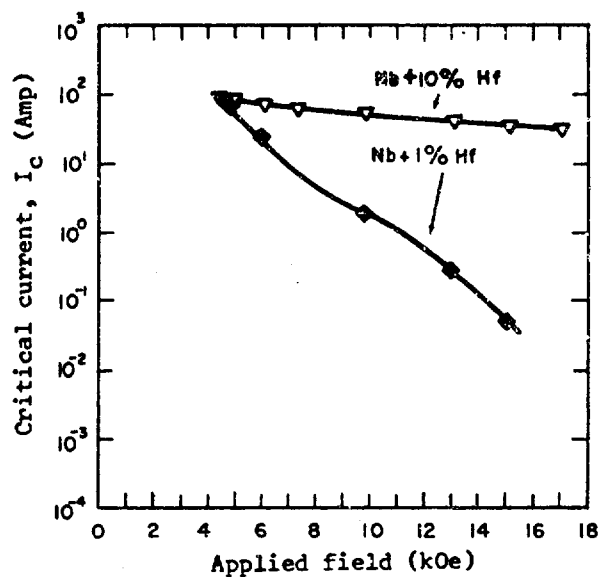
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# NIOBIUM-HAFNIUM

## CURRENT DENSITY

Critical current for two niobium-hafnium wire ( 0.030 in. diam.). The values were taken in a transverse magnetic field on arc-melted samples.

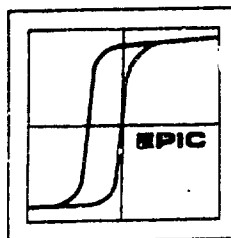
[Ref. 10778]



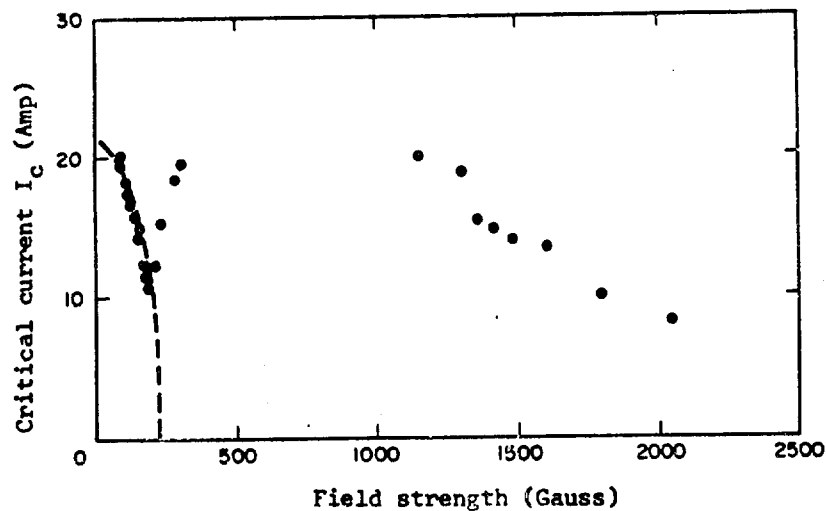
## Critical Current Density

| Symbol         | Values (10 <sup>3</sup> Amp/cm <sup>2</sup> ) |          |      | Samples                                                 | Temperature |
|----------------|-----------------------------------------------|----------|------|---------------------------------------------------------|-------------|
|                | Rolling plane                                 | Unrolled |      |                                                         |             |
|                | H                                             | H ⊥      |      |                                                         |             |
| J <sub>c</sub> | 2.6                                           | 0.08     | 0.08 | 25 at.% Hf alloy<br>arc-melted and<br>inverted 6 times. | 4.2°K       |

[Ref. 10713]

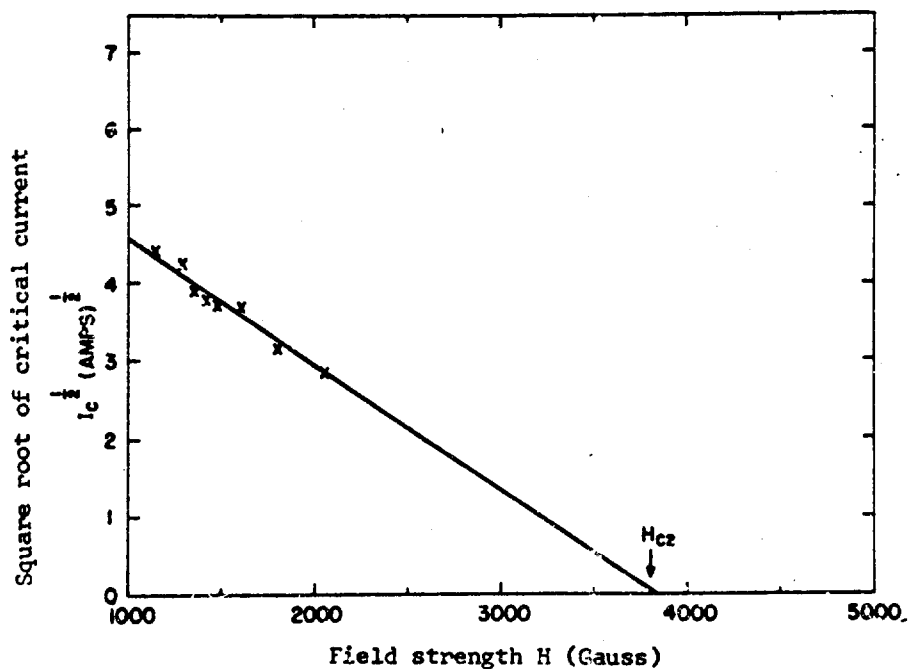


NIOBIUM-TANTALUM  
CURRENT DENSITY



Critical current for  $Nb_{55}Ta_{45}$  as a function of field.

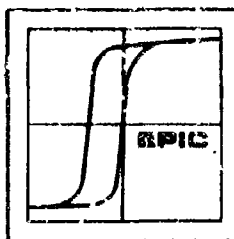
[Ref. 21843]



Square root of critical current as a function of field for  $Nb_{55}Ta_{45}$ .

[Ref. 21843]

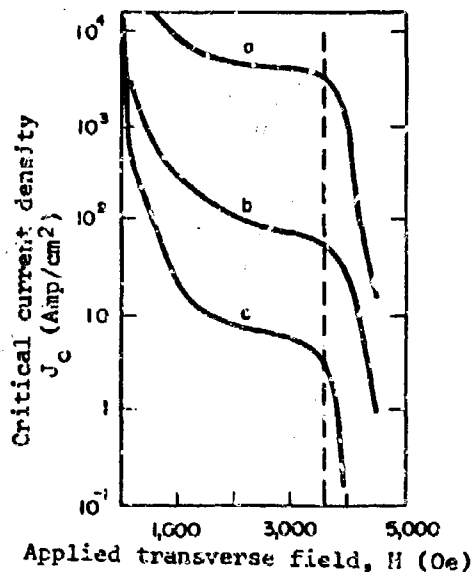




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# NIOBIUM-TANTALUM

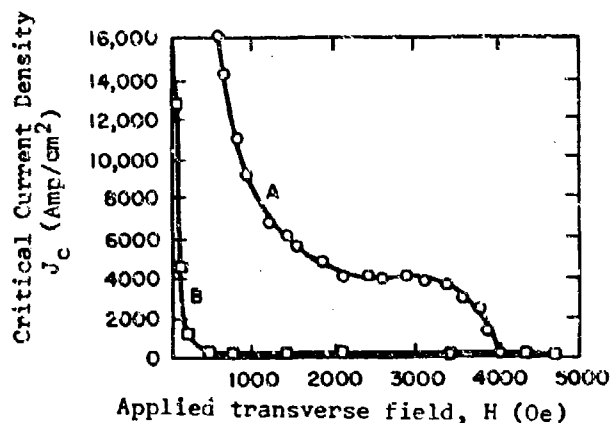
## CURRENT DENSITY



Critical current density for Nb.<sub>55</sub>Ta.<sub>45</sub> wire swaged, drawn and annealed. The effect of annealing time is shown.

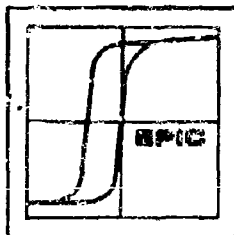
- a) annealed 30 min, 1473°K, 10<sup>-4</sup> - 10<sup>-5</sup> mm Hg
- b) annealed 24 hours, ~1800°K, ~5x10<sup>-2</sup> mm Hg
- c) annealed 48 hours, ~1800°K, ~5x10<sup>-2</sup> mm Hg

[Ref. 21848]



Critical current density for Nb.<sub>55</sub>Ta.<sub>45</sub> alloy cold drawn wires: (a) before annealing (b) after annealing for 25 hrs. hours at 5 x 10<sup>-8</sup> Torr at about 1500°C. Data taken at 4.2°K.

[Ref. 21261]

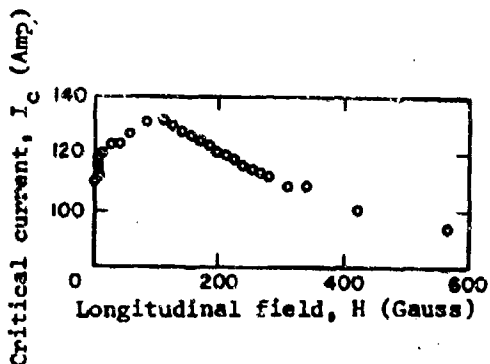
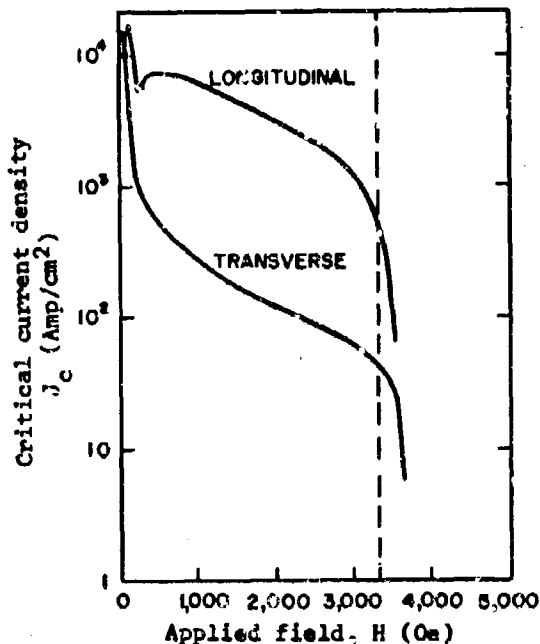


# NIOBIUM-TANTALUM

## CURRENT DENSITY

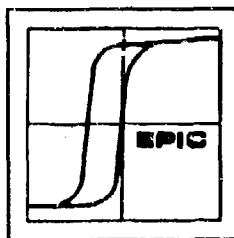
Critical current density for a Nb<sub>0.55</sub>Ta<sub>0.45</sub> wire, annealed 24 hours. The data are shown for longitudinal and transverse fields.

[Ref. 21848]



Critical current for Nb<sub>0.50</sub>Ta<sub>0.50</sub> wire, 0.125 cm diameter, annealed for 1 hour at 1100°C and 10<sup>-6</sup> Torr, resistivity ratio ≈ 30. Data taken at 4.2°K with I || H.

[Ref. 20904]



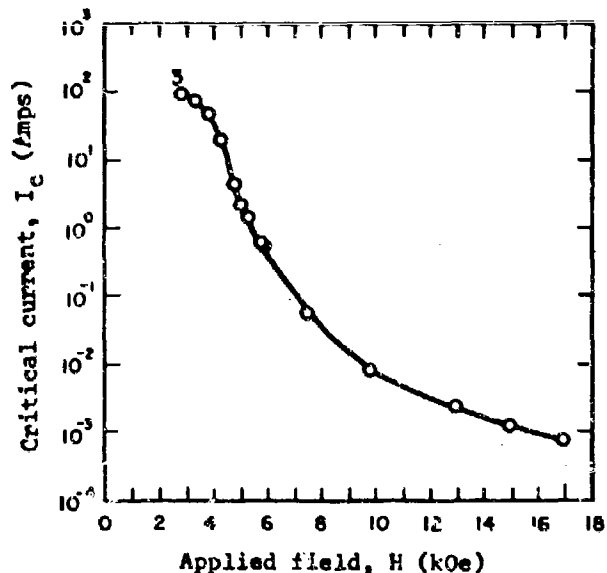
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# NIOBIUM-TUNGSTEN

## CURRENT DENSITY

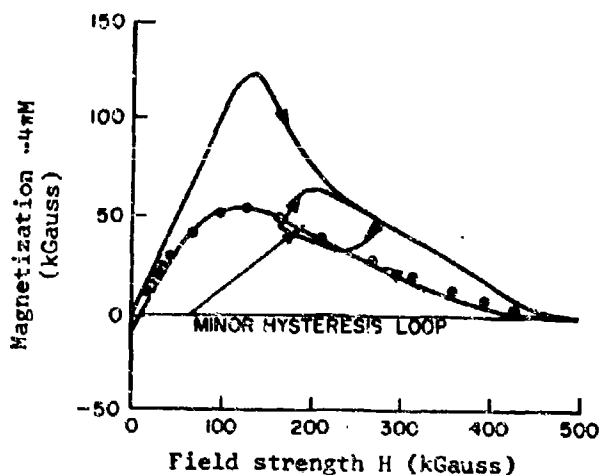
Critical current as a function of transverse field strength for a 1% tungsten, niobium-tungsten alloy.

[Ref. 1077s]



# NIOBIUM-TANTALUM

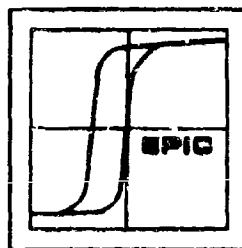
## MAGNETIC HYSTERESIS



Magnetization for Nb.<sub>95</sub>Ta.<sub>05</sub> wires in a longitudinal field. Data taken at 8.4°K.

• cooled in a fixed field

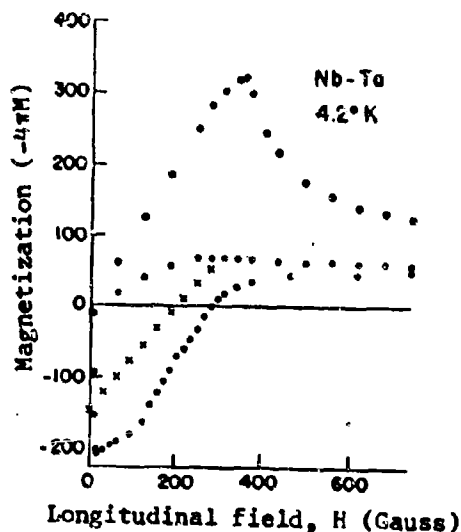
[Ref. 21843]



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# NIOBIUM-TANTALUM

## MAGNETIC HYSTERESIS



Magnetization of Nb<sub>50</sub>Ta<sub>50</sub> wire 0.125 cm diameter, annealed for 1 hour at 1100°C and 10<sup>-6</sup> Torr, resistivity ratio  $\approx 30$ . Data at 4.2°K.

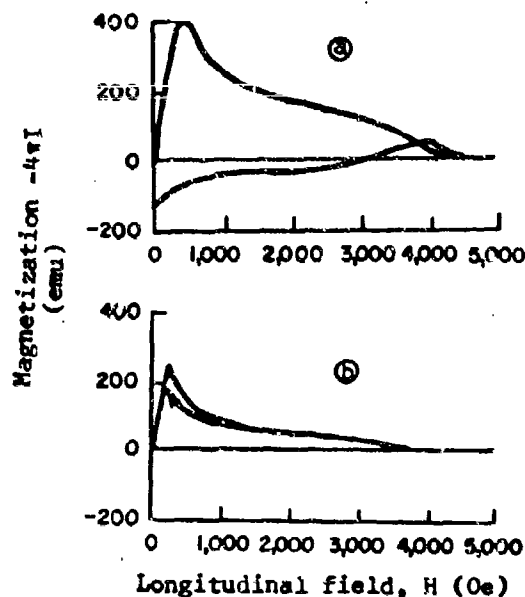
- Magnetization (I=0) H+
- Flux expulsion (Meissner effect) upon cooling in longitudinal field
- x Magnetization after cooling at 0.32 kGauss H+
- Paramagnetic magnetization at I<sub>c</sub>. The sample is cooled through T<sub>c</sub> in constant field.

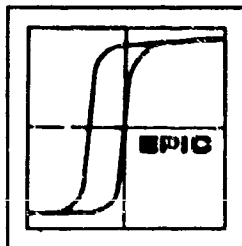
[Ref. 20904]

Magnetization of Nb<sub>55</sub>Ta<sub>45</sub> wire, swaged, drawn and annealed. Data taken at 4.2°K.

- one-stage annealed, 30 min. at 1473°K, 10<sup>-4</sup> - 10<sup>-5</sup> mm Hg vacuum.
- annealed 48 hours at  $\sim 1000^\circ\text{K}$  in  $\sim 5 \times 10^{-8}$  mm Hg vacuum.

[Ref. 21848]

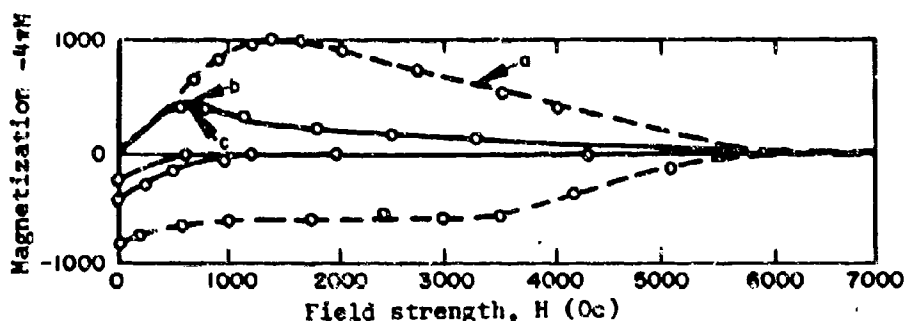




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## NIOBIUM-TUNGSTEN

### MAGNETIC HYSTERESIS



Magnetization as a function of field strength for a niobium-tungsten alloy (9.2 at. % W)

- (a) heavily cold worked
- (b) bulk rods (1.2 cm x 0.6 cm diam.)
- (c) powders 45-60  $\mu$ -size particles

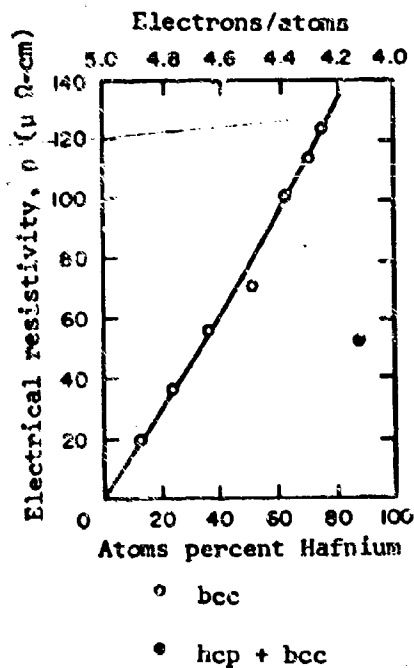
[Ref. 10778]

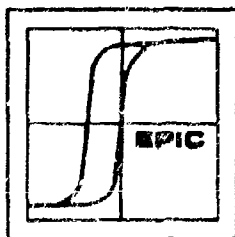
## NIOBIUM-HAFNIUM

### ELECTRICAL RESISTIVITY

Electrical resistivity for niobium-hafnium system as a function of the hafnium content, data taken at 1.2°K.

[Ref. 11924]





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# NIOBIUM-HAFNIUM

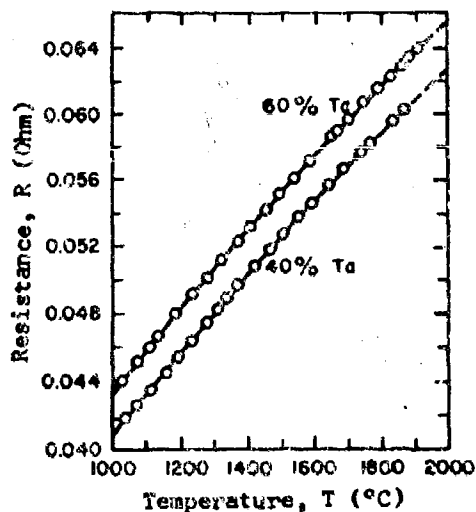
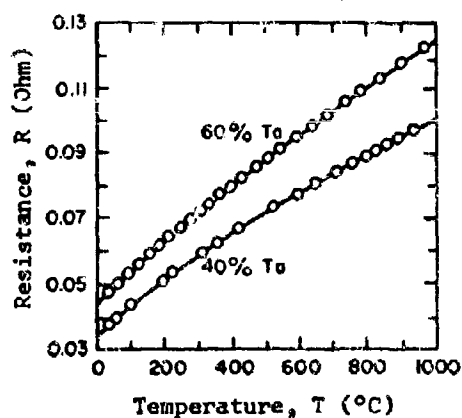
## ELECTRICAL RESISTIVITY

| Symbol | Values ( $\mu\Omega\text{-cm}$ ) | at. % Hf | Symmetry              | Method     |
|--------|----------------------------------|----------|-----------------------|------------|
| $\rho$ | 19.1                             | 12.5     | bcc<br>↓<br>hcp + bcc | arc-melted |
|        | 36.3                             | 25.0     |                       |            |
|        | 57.2                             | 37.5     |                       |            |
|        | 68.0                             | 50.0     |                       |            |
|        | 100.3                            | 62.5     |                       |            |
|        | 114.4                            | 70.0     |                       |            |
|        | 124.4                            | 75.0     |                       |            |
|        | 53.2                             | 87.5     |                       |            |

[Ref. 11924]

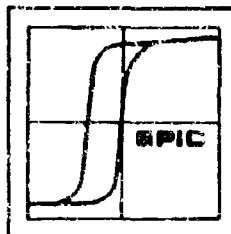
# NIOBIUM-TANTALUM

## ELECTRICAL RESISTIVITY



Resistance for  $\text{Nb}_{60}\text{Ta}_{40}$  and  $\text{Nb}_{40}\text{Ta}_{60}$  alloys from 0-2000°C

[Ref. 21252]



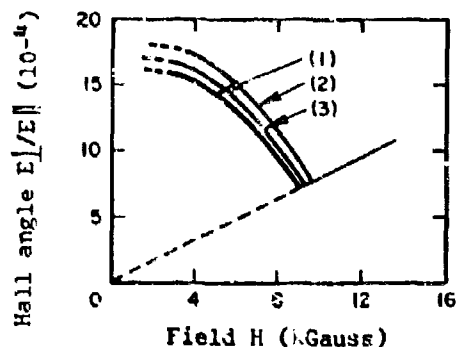
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# NIOBIUM-TANTALUM

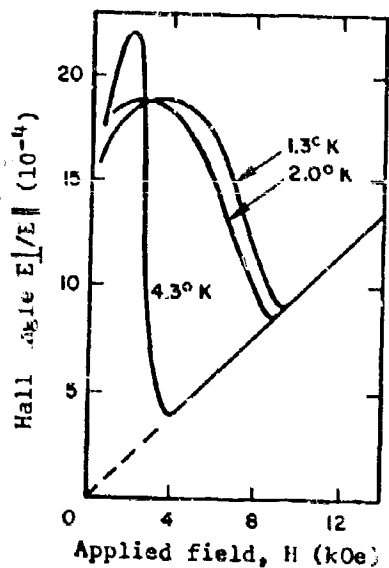
## HALL ANGLE

The Hall angle for  $Nb_{50}Ta_{50}$  as a function of magnetic field strength. Data taken at 1.3°K.

- 1) annealed
- 2) etched
- 3) cold-rolled



[Ref. 20825]

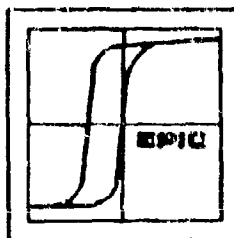


Hall angle as a function of field for  $Nb_{50}Ta_{50}$  alloy, cold rolled sheets 22  $\mu$  thick.

[Ref. 21260]

SECTION 6  
NIOBIUM-RHENIUM &  
NIOBIUM-OSMIUM SYSTEMS





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## NIOBIUM ALLOYS AND COMPOUNDS

### NIOBIUM-RHENIUM AND NIOBIUM-OSMIUM SYSTEMS

#### GENERAL

**Nb-Re** The niobium rhenium system forms two distinct compounds,  $\beta$  in the niobium-rich region and  $\chi$  in the rhenium-rich region. Except for a few values given in the mixed  $\beta+\chi$  region most of the transition temperatures are reported in the  $\chi$  rhenium-rich region of the system.

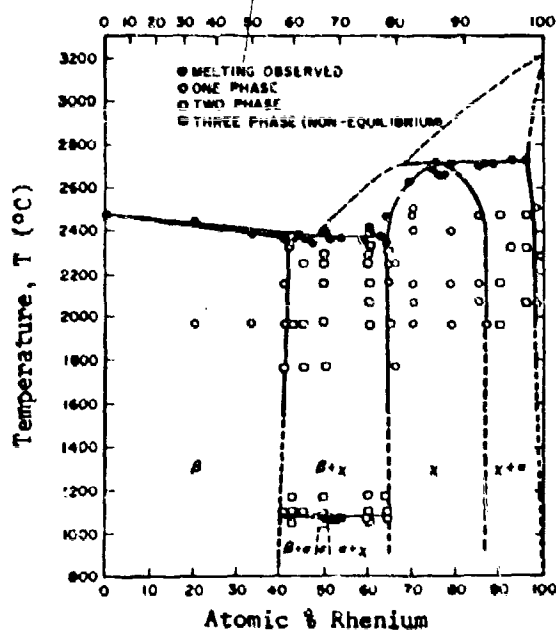
**Nb-Os** The niobium-osmium system forms three primary crystallographic structures,  $\alpha$ -Mn,  $\sigma$ , and  $\beta$ -tungsten [Ref. 17299]. This latter structure gives the lowest  $T_c$  of the three crystalline forms, 1.05°K [Ref. 20332] while the  $\alpha$ -Mn gives the highest  $T_c$ , 2.52°K [Ref. 17299].

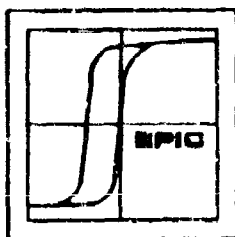
### NIOBIUM-RHENIUM

#### GENERAL

Proposed phase diagram for niobium-rhenium system.

[Ref. 21231]



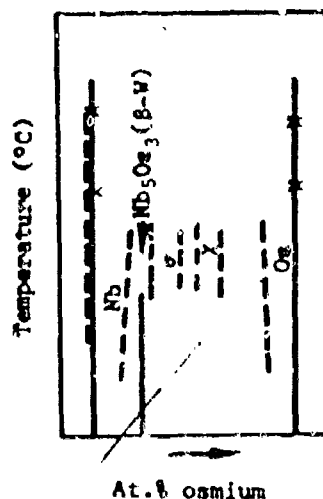


## NIOBIUM-OSMIUM

### GENERAL

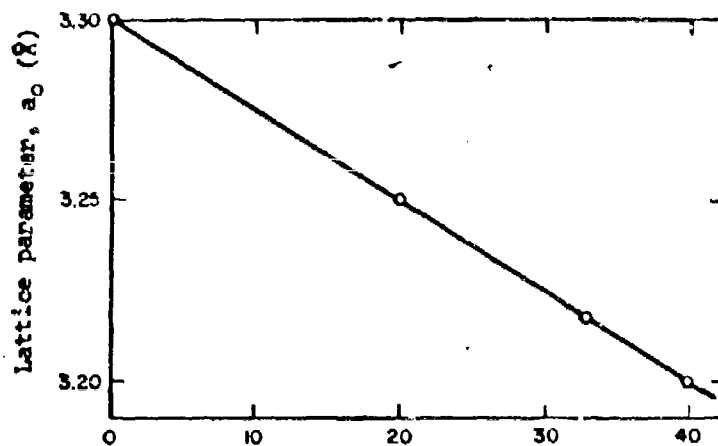
Appearance of different phases in the niobium-osmium system. Sigma phase exists from 30-54% Os and chi phase from 55-65% Os.

[Ref. 20718]



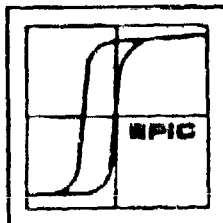
## NIOBIUM-RHENIUM

### GENERAL



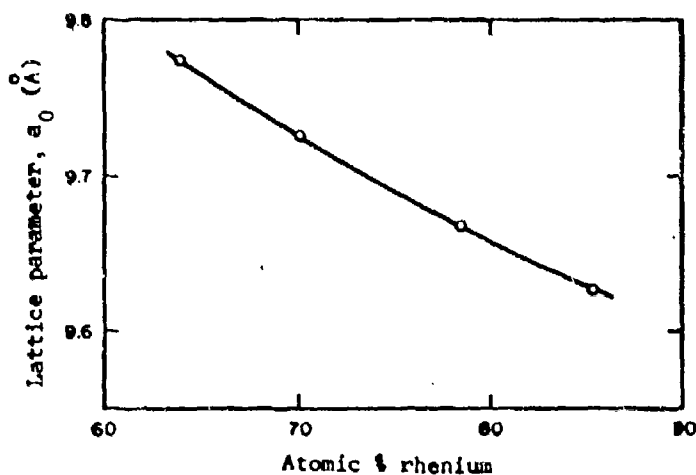
Lattice parameter for Lcc niobium-rhenium system.

[Ref. 21231]



# NIOBIUM-RHENIUM

## GENERAL



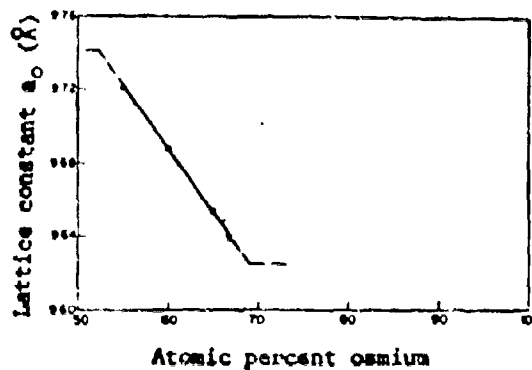
Lattice parameter for  $\alpha$ -Nb, niobium-rhenium system.

[Ref. 21231]

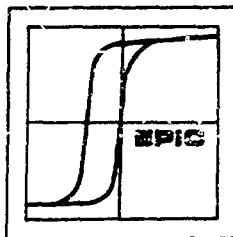
# NIOBIUM-OSMIUM

## GENERAL

Lattice constant for  $\alpha$ -Nb Nb-Os system.



[Ref. 21851]



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NIOBIUM-RHENIUM

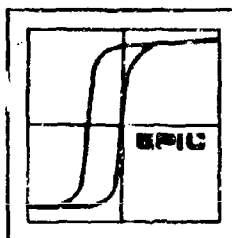
TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

| At. % Re | Lattice constant $\text{\AA}$ |       | Transition Temperature  |                      | Symmetry       | Notes                                                | Ref.  |
|----------|-------------------------------|-------|-------------------------|----------------------|----------------|------------------------------------------------------|-------|
|          | $a_o$                         | $c_o$ | $T_c(^{\circ}\text{K})$ | $\Delta T^{\dagger}$ |                |                                                      |       |
| ~20      | -                             | -     | 4.8                     | -                    | Nb, bcc        | Composition given as $\text{Nb}_{44}\text{Re}$       | 10784 |
| 25*      | 3.228                         | -     | -                       | -                    | "              | As melted, annealed $1000^{\circ}\text{C}$ , 7 days. | 20625 |
| 50       | 3.194                         | -     | -                       | -                    | "              | As melted.                                           | 20625 |
| "        | 9.783                         | 5.115 | -                       | -                    | $\sigma$ -tetr | "                                                    | 20625 |
| "        | 9.79                          | 5.10  | 3.8-2.0                 | -                    | "              | Cooled from $1250^{\circ}\text{C}$ .                 | 9686  |
| 60       | 9.781                         | -     | 2.36                    | 0.2                  | $\alpha$ -Mn   | Cooled from $1250^{\circ}\text{C}$ .                 | 9686  |
|          | -                             | -     | 2.0                     | -                    | "              | -                                                    | 7648  |
|          | 3.773                         | -     | -                       | -                    | "              | Cooled from melting point, 6.2 electrons/atom.       | 9686  |
|          | 9.77                          | 5.14  | 2.5                     | 0.2                  | $\sigma$ -tetr | "                                                    | 9686  |
| 62       | -                             | -     | 2.45                    | -                    | $\alpha$ -Mn   | 6.24 electrons/atom.                                 | 15323 |
| 82       | -                             | -     | 8.89                    | -                    | "              | -                                                    | 7648  |

$^{\dagger}\Delta T$  is the width of the transition region

\*  $\text{Nb}_3\text{Re}$ ,  $\text{Cu}_3\text{Au}$  type,  $a_o = 4.207 \text{ \AA}$ , sample preparation HCl transport method [Ref. 21843]



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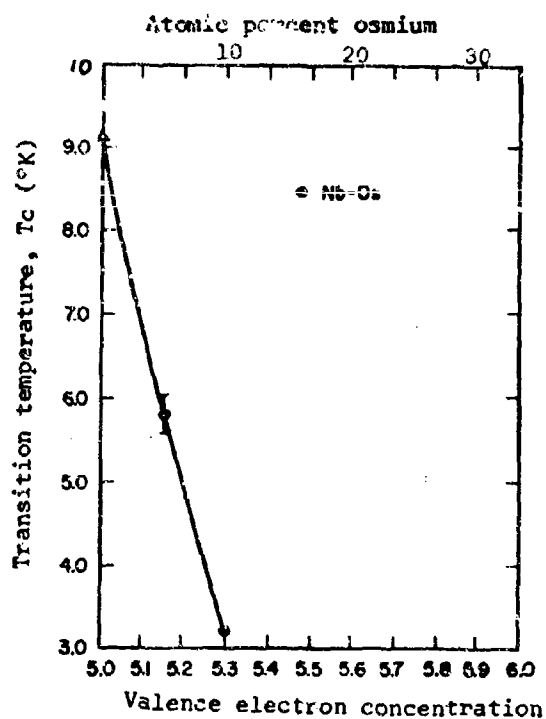
# NIOBIUM-OSMIUM

## TRANSITION TEMPERATURE

### Lattice Constant and Transition Temperature

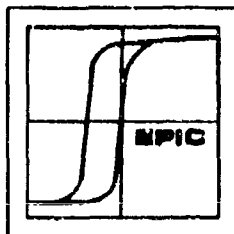
| At. % Os | Symmetry            | Lattice Constant (Å) |       | Transition temperature<br>$T_c$ (°K) | Electrons/atom | Notes                                      | Ref.  |
|----------|---------------------|----------------------|-------|--------------------------------------|----------------|--------------------------------------------|-------|
|          |                     | $a_0$                | $c_0$ |                                      |                |                                            |       |
| 25*      | $\beta$ -tungsten   | -                    | -     | 1.05                                 | 5.8            | -                                          | 9620  |
| "        | "                   | 5.1359               | -     | < 1.7                                | "              | Standard sample preparation.               | 18750 |
| 40       | $\sigma$ tetragonal | 9.853                | 5.066 | -                                    | 6.2            | Arc-melted in a gettered argon atmosphere. | 20625 |
| "        | tetragonal          | 9.844                | 5.056 | 1.78                                 | "              | -                                          | 17299 |
| 50       | $\alpha$ manganese  | 9.778                | -     | -                                    | 6.5            | Arc-melted in a gettered argon atmosphere. |       |
| 67       | "                   | -                    | -     | 2.32                                 | 7.0            |                                            | 17299 |

\*  $Nb_3Os$ ,  $Cu_3Au$  type,  $a_0 = 4.207 \text{ \AA}$ , sample prepared by HCl transport method [Ref. 21843]



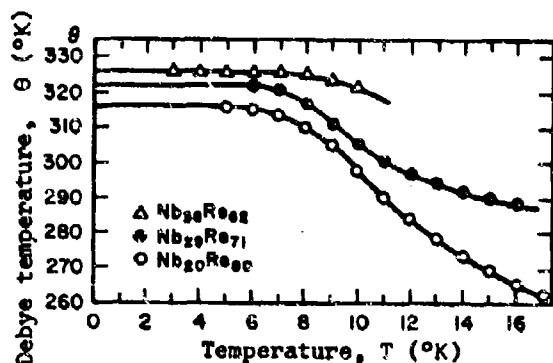
Transition temperature for niobium-osmium system.

[Ref. 14468]



# NIOBIUM-RHENIUM

## DEBYE TEMPERATURE



Debye temperature for three niobium-rhenium alloys with A 12-type crystal structure.

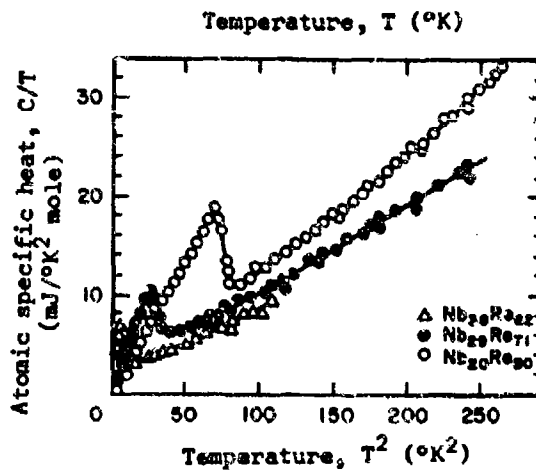
[Ref. 14464]

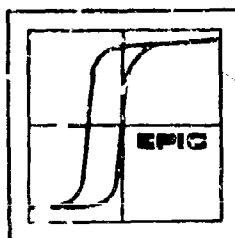
# NIOBIUM-RHENIUM

## SPECIFIC HEAT

Atomic specific heat for these niobium-rhenium alloys with A 12-type crystal structure.

[Ref. 14464]





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# NIOBIUM-RHENIUM

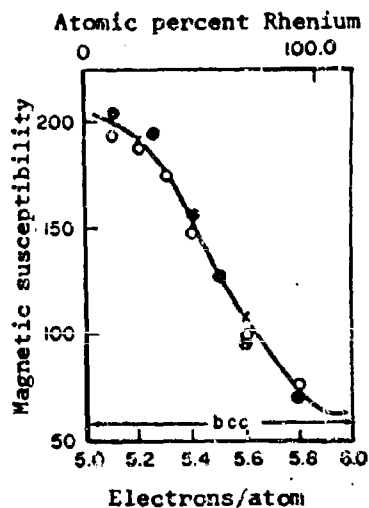
## SPECIFIC HEAT

### Thermal Properties

| Formula                             | Coefficient of Electronic<br>Specific Heat.           | Debye Temperature                | $\frac{N(0)V}{\gamma}$                            | Ref.  |
|-------------------------------------|-------------------------------------------------------|----------------------------------|---------------------------------------------------|-------|
|                                     | $(10^{-4} \text{ cal/}^\circ\text{K}^2 \text{ mole})$ | $\theta$<br>( $^\circ\text{K}$ ) | $(\text{cal/}^\circ\text{K}^2 \text{ mole})^{-1}$ |       |
| Nb <sub>.38</sub> Re <sub>.62</sub> | 6.4                                                   | $300 \pm 10$                     | 340                                               | 15323 |

# NIOBIUM-RHENIUM

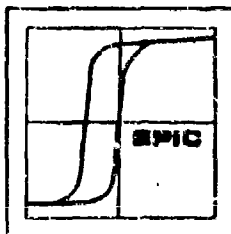
## MAGNETIC SUSCEPTIBILITY



Susceptibility of niobium-rhenium system. Data are given for Nb-Tc and Nb-Mo for comparison.

- Nb-Re
- x Nb-Tc
- Nb-Mo

[Ref. 19617]



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# NIOBIUM-RHENIUM AND NIOBIUM-OSMIUM

## MAGNETIC SUSCEPTIBILITY

| <u>Formula</u>                      | <u><math>\chi</math> (<math>10^{-6}</math><br/><math>\text{cm}^3/\text{g}</math>)</u> | <u><math>\chi</math> at (<math>10^{-6}</math><br/><math>\text{cm}^3/\text{g}</math>)</u> | <u><math>\chi</math> (<math>10^{-6}</math>)*</u> | <u>Symmetry</u> | <u>Notes</u>         |
|-------------------------------------|---------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|--------------------------------------------------|-----------------|----------------------|
| Nb <sub>.50</sub> Re <sub>.50</sub> | 61                                                                                    | 8500                                                                                     | 880                                              | $\alpha$ -Mn    | Cooled from 1250°C.  |
| Nb <sub>.40</sub> Re <sub>.60</sub> | 66                                                                                    | 9800                                                                                     | 1000                                             | $\sigma$        | Cooled from ~2400°C. |
| Nb <sub>.50</sub> Os <sub>.40</sub> | 74                                                                                    | "                                                                                        | 990                                              | "               | "                    |
| Nb <sub>.50</sub> Os <sub>.50</sub> | 60                                                                                    | 8500                                                                                     | 890                                              | $\alpha$ -Mn    | "                    |

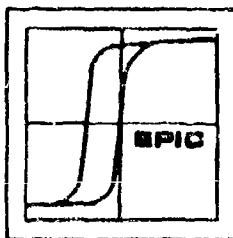
\* Volume susceptibility, 300°K.

[Ref. 9686]



SECTION 6  
NIOBIUM IRIIDIUM &  
NIOBIUM PLATINUM SYSTEMS





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NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-IRIDIUM AND NIOBIUM-PLATINUM SYSTEMS

LATTICE CONSTANT AND TRANSITION TEMPERATURE

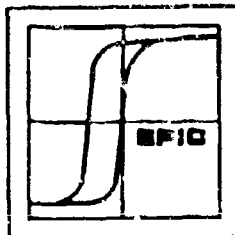
Nb-Ir

| At.% Ir | Formula                         | Symmetry          | Lattice Constant Value ( $\text{\AA}$ ) |       | Transition temperature $^{\circ}\text{K}$ | Notes            | Ref.  |
|---------|---------------------------------|-------------------|-----------------------------------------|-------|-------------------------------------------|------------------|-------|
|         |                                 |                   | $a_0$                                   | $c_0$ |                                           |                  |       |
| 15      | Nb + Ir                         | bcc               | 3.262                                   | -     | -                                         | as melted        | 20625 |
| 25      | Nb <sub>3</sub> Ir              | $\beta$ -tungsten | -                                       | -     | 1.7                                       | -                | 9625  |
| "       | "                               | "                 | 5.139                                   | -     | -                                         | as melted        | 20625 |
| 37      | -                               | $\sigma$ tetr.    | -                                       | -     | 7.9                                       | -                | 7648  |
| "       | -                               | "                 | 9.86                                    | 5.06  | 2.4 midpoint                              | -                | 9686  |
|         |                                 |                   | -                                       | -     | 0.1 width                                 | -                | "     |
| 40      | Nb <sub>3</sub> Ir <sub>2</sub> | fcc               | 9.834                                   | 5.052 | 9.8                                       | -                | 17299 |
| 50      | -                               |                   | 3.895                                   | -     | -                                         | annealed         | 20625 |
| 75      | NbIr <sub>3</sub>               |                   | 3.893                                   | -     | -                                         | 3 days<br>1200°C | 20331 |

Nb-Pt

| At.% Pt | Symmetry          | Lattice constant ( $\text{\AA}$ ) |       |       | Transition temperature $T_c$ ( $^{\circ}\text{K}$ ) | Notes                  | Ref.  |
|---------|-------------------|-----------------------------------|-------|-------|-----------------------------------------------------|------------------------|-------|
|         |                   | $a_0$                             | $b_0$ | $c_0$ |                                                     |                        |       |
| 25*     | $\beta$ -tungsten | 5.153 $\pm$ .003                  | -     | -     | 9.2                                                 | -                      | 20332 |
| 37.5    | $\sigma$ -tetr    | 9.91                              | -     | 5.12  | 3.73                                                | -                      | 17299 |
| "       | "                 | -                                 | -     | -     | 4.2                                                 | -                      | 15323 |
| 38.0    | "                 | 9.91                              | -     | 5.13  | 4.01                                                | annealed &<br>quenched | 9686  |
| 52.0    | orthorhombic      | 2.780                             | 4.983 | 4.611 | -                                                   | -                      | 20357 |
| 75.0    | "                 | 5.534                             | 4.873 | 4.564 | -                                                   | -                      | "     |
| "       | monoclinic        | 5.537                             | 4.870 | 27.33 | -                                                   | -                      | "     |

\* Nb<sub>3</sub>Pt, Cu<sub>3</sub>Au type,  $a_0 = 4.207 \text{ \AA}$ , sample prepared by HCl transport method [Ref. 21843]



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# NIOBIUM-PLATINUM

## THERMAL PROPERTIES

| Formula                              | Coefficient of Electronic<br>Specific Heat<br>$\gamma \times 10^{-4}$<br>( $10^{-4}$ cal/mole $^{\circ}$ K $^2$ ) | Debye Temperature<br>$\theta$<br>( $^{\circ}$ K) | $\frac{N(\epsilon)V}{\gamma}$<br>(cal/mole $^{\circ}$ K $^2$ ) $^{-1}$ | Ref.  |
|--------------------------------------|-------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|------------------------------------------------------------------------|-------|
| Nb. <sub>62</sub> Pt. <sub>375</sub> | 9.1 $\pm$ 0.2                                                                                                     | 335 $\pm$ 10                                     | 260                                                                    | 15323 |

$\gamma$ ,  $\theta$ , and  $T_c$  from preceding table were all taken on one sample.

# NIOBIUM-PLATINUM

## MAGNETIC SUSCEPTIBILITY

| System                                           | $\chi_{tot}^*$ ( $10^{-6}$<br>emu/g. at) | $\chi_{add}$ ( $10^{-6}$<br>emu/g. at) | $\chi$ ( $10^{-6}$<br>cm $^3$ /g) | $\chi_{at}$ ( $10^{-6}$<br>cm $^3$ /g) | $\chi$ ( $10^{-6}$ )** | Crystal-<br>lography |
|--------------------------------------------------|------------------------------------------|----------------------------------------|-----------------------------------|----------------------------------------|------------------------|----------------------|
| Nb. <sub>62</sub> Pt. <sub>38</sub> <sup>†</sup> | 67                                       | 40                                     | 51                                | 6700                                   | 660                    | $\sigma$             |

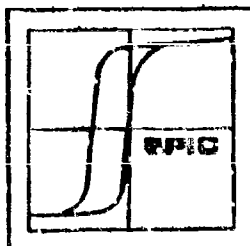
\*  $\chi_{tot} = \chi_{ion} + \chi_{Pauli} + \chi_{L.P.} + \chi_{add}$  [Ref. 14464]

$\chi_{L.P.}$  (Landau-Feieris) electronic specific heat contribution.

<sup>†</sup> Nb.<sub>62</sub>Pt.<sub>38</sub> cooled from 1300 $^{\circ}$ K. [Ref. 9686]

\*\* Volume susceptibility, 300 $^{\circ}$ K.

SECTION 6  
NICKELUM-GOLD SYSTEM



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## NIOBIUM ALLOYS AND COMPOUNDS

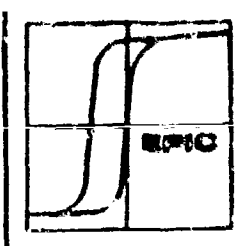
### NIOBIUM-GOLD SYSTEM

#### GENERAL

Nb-Au Of the four niobium-gold compounds only the Nb Au shows a transition temperature. This compound takes on the  $\beta$ -tungsten structure primarily; however, by quenching carefully an A 2 structure is formed which shows a much lower  $T_c$ .

#### Niobium-Gold Crystalline Phases

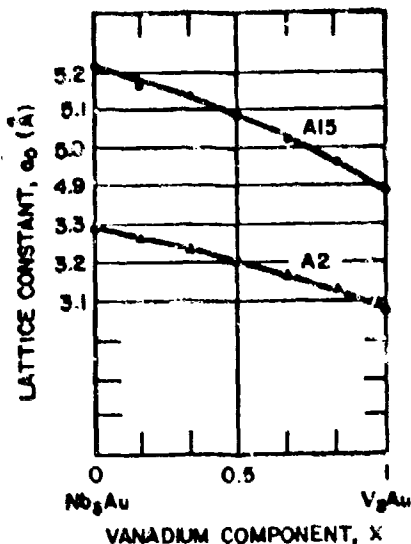
| <u>Compound</u> | <u>Structure</u> | <u>Crystal</u>                 |
|-----------------|------------------|--------------------------------|
| $Nb_3Au$        | Cubic            | A 15 ( $\beta$ -W)             |
| $Nb_3Au$        | Cubic            | A 2                            |
| $Nb_3Au_2$      | Tetragonal       | D <sub>17</sub> $I4/mmm$<br>4h |
| $Nb_{11}Au_9$   | Cubic            | $\beta$ -Mn                    |
| $NbAu_2$        | Hexagonal        | $AlB_2$                        |



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# NIOSBIUM-GOLD

## GENERAL



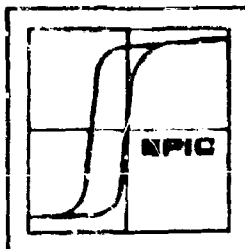
Lattice constant of  $(Nb_{1-x}V_x)_3Au$  as a function of composition.

- A 15 crystal structure, annealed
- A 2 crystal structure, quenched

[Ref. 15189]

Both binary compounds  $Nb_3Au$  and  $V_3Au$ , as well as the ternary  $Nb_3Au-V_3Au$ , form into the A 15 structure when prepared and left "as cast". Bucher et al [Ref. 15189] were able to convert this A 15 sample to an A 2 type structure with a quenching method of blowing cold argon onto the melt immediately after interrupting the primary current. The return of these A 2 samples to A 15 structure was accomplished by annealing:

|                |                  |
|----------------|------------------|
| $Nb_3Au$       | 20 hrs at 1050°C |
| "              | 1/2 hr at 800°C  |
| $Nb_3Au-V_3Au$ | 27 hrs at 850°C  |
| $V_3Au$        | 8 hrs at 760°C   |



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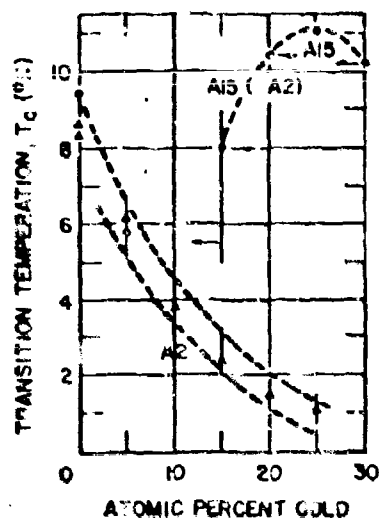
# NIOBIUM-GOLD

## TRANSITION TEMPERATURE

### Lattice Constants and Transition Temperature

| At. % Au | Formula                          | Lattice constants (Å) |          | Transition Temperature<br>$T_c$ (°K) | Symmetry                                          | Ref.  |
|----------|----------------------------------|-----------------------|----------|--------------------------------------|---------------------------------------------------|-------|
| $a_0$    | $c_0$                            |                       |          |                                      |                                                   |       |
| 25*      | Nb <sub>3</sub> Au               | 5.21 ± .001           | -        | -                                    | β-tungsten (A 15)                                 | 20025 |
|          |                                  | -                     | -        | 10.6                                 |                                                   | 15608 |
|          |                                  | -                     | -        | 11.5                                 |                                                   | 9620  |
|          |                                  | -                     | -        | 11.0                                 |                                                   | 15189 |
|          |                                  | 3.29                  | -        | 1.2                                  | A 2                                               | "     |
| 40       | Nb <sub>3</sub> Au <sub>2</sub>  | 3.38                  | 5 x 3.04 | -                                    | D <sub>4h</sub> <sup>17</sup> I <sub>4</sub> /mmm | 20226 |
| 45       | Nb <sub>11</sub> Au <sub>9</sub> | 7.05                  | -        | -                                    | β-manganese                                       | "     |
| 67       | NbAu <sub>2</sub>                | 4.61                  | 2.72     | -                                    | AlB <sub>2</sub>                                  | "     |

\* Nb<sub>3</sub>Au, Cu<sub>3</sub>Au type,  $a_0 = 4.207 \text{ Å}$ , sample prepared by HCl transport method [Ref. 21843]



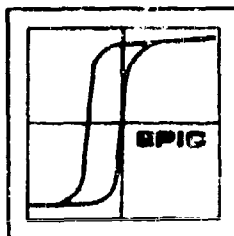
Transition temperature of niobium-gold system as a function of atomic percent gold. Below 25 at. % gold there are traces of A 2 structure present in the A 15 structure.

- A 15 crystal structure, annealed
- △ A 2 crystal structure, quenched

[Ref. 15189]

SECTION 6  
NIOBIUM-BISMUTH SYSTEM





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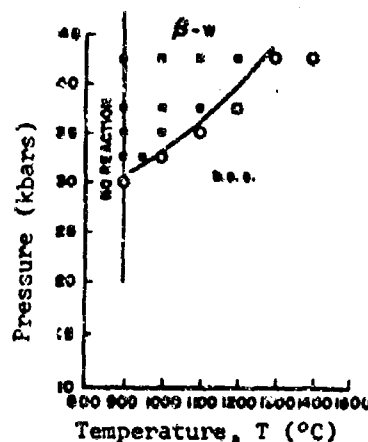
# NIOBIUM-BISMUTH

## GENERAL

Pressure-temperature phase diagram for  $Nb_3Bi$ .

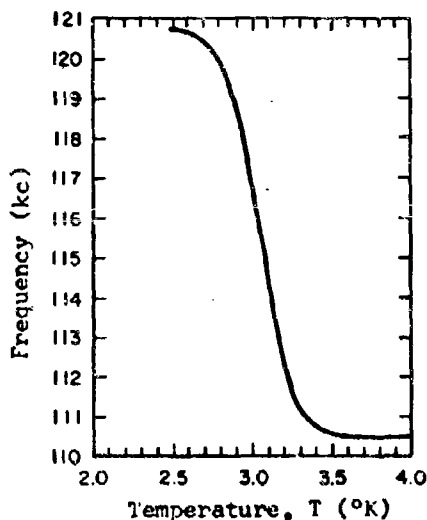
- $\beta$ -tungsten
- bcc

[Ref. 17303]



# NIOBIUM-BISMUTH

## TRANSITION TEMPERATURE



Transition temperature for bcc  $Nb_3Bi$ , measured by the Schawlow and Devlin susceptibility technique. The circuitry of this experiment is such that the transition curve shows a higher frequency at the lower temperatures.\*

\* Private communication with D.H. Killpatrick now with Douglas Aircraft Co. Santa Monica California.

[Ref. 17303]



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