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Report on
THE PHYSICAL PROPERTIES OF TITANIUM
AND TITANIUM ALLOYS

by

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to

OFFICE OF ASSISTANT SECRETARY OF DEFENSE
FOR RESEARCH AND DEVELOPMENT

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ABSTRACT

This report summarizes the information in the literature on the physical properties of titanium and titanium alloys. In some cases, an evaluation of the published results was made so that the most accurate value for the properties could be indicated. In other instances, insufficient background information accompanied the original data to permit an evaluation. The latter was the usual case when information on commercial alloys was presented.

Report on

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AND TITANIUM ALLOYS

INTRODUCTION

This report contains a compilation of the data available to the Titanium Metallurgical Laboratory on the physical properties of titanium and titanium alloys. It is a revision and an extension of TML Report No. 39 entitled "Survey of Physical-Property Data for Titanium and Titanium Alloys", dated March 30, 1956.

Wherever possible, reference is given only to the original source covering specific data determined for a given physical property.

Attempts were made to compare the data of various investigators and to suggest best values when sufficient background information was available to permit formulation of an opinion. Usually, data in the titanium producers' trade literature are not in themselves referenced; therefore, there was no basis for evaluation. These data are tabulated without comment.

The composition of the commercial titanium alloys available from the four major producers is given in Table 1. The alloys are identified in subsequent tables of the report under the column headed "Alloy Designation".

SUMMARY

The most probable values for the physical properties of unalloyed titanium are summarized in Table 2. These values apply to iodide titanium or to relatively pure commercial titanium having a minimum yield strength of about 40,000 to 55,000 psi. Values for the various grades of commercially pure titanium are listed separately in the subsequent tables on individual physical properties.

The data on physical properties of titanium alloys most sought by aircraft producers are summarized in Table 3. The properties contained in Table 3 are density, electrical resistivity, thermal conductivity, coefficient of thermal expansion, and specific heat. Except for the coefficient of thermal expansion, the properties apply to room temperature. Other available physical properties, as well as their dependence upon temperature and composition, are covered in subsequent tables in the report.

TABLE 1. COMPOSITION OF COMMERCIAL ALLOYS

Producer and Alloy Designation	Nominal Composition (Balance Titanium), weight per cent						
	Al	Cr	Fe	Mn	Mo	Sn	V
<u>Mallory-Sharon Titanium Corporation</u>							
MST-Grade III	--	--	--	--	--	--	--
MST-2Al-2Fe	2	--	2	--	--	--	--
MST-3Al-5Cr	3	5	--	--	--	--	--
MST-6Al-4V	6	--	--	--	--	--	4
MST-2Fe	--	--	2	--	--	--	--
MST-2.5Fe-2.5V	--	--	2.5	--	--	--	2.5
MST-4Mn-4Al	4	--	--	4	--	--	--
MST-8Mn	--	--	--	8	--	--	--
3Mn complex	--	1	1	3	1	--	1
<u>Rem-Cru Titanium, Inc.</u>							
A-55 (was RC-55)	--	--	--	--	--	--	--
A-70 (was RC-70)	--	--	--	--	--	--	--
A-110AT	5	--	--	--	--	2.5	--
C-110M (was RC-130A)	--	--	--	8	--	--	--
C-110M modified	--	--	--	5	--	5	2
C-120AV	6	--	--	--	--	--	4
C-130AM (was RC-130B)	4	--	--	4	--	--	--
<u>Republic Steel Corporation</u>							
RS-55	--	--	--	--	--	--	--
RS-70 (A)	--	--	--	--	--	--	--
RS-110	--	3	1.5	--	--	--	--
RS-110A	--	--	--	8	--	--	--
RS-110BX	1	--	--	3	--	--	--
RS-120	--	--	--	7	--	--	--
RS-130	4	--	--	4	--	--	--
RS-140X	5	2	2	--	--	--	--
<u>Titanium Metals Corporation of America</u>							
Ti-75A	--	--	--	--	--	--	--
Ti-100A	--	--	--	--	--	--	--
Ti-125A	--	--	--	--	--	--	--
Ti-130A	--	--	--	--	--	--	--
Ti-140A	--	2.1	2.2	--	2.0	--	--
Ti-150A	--	2.8	1.5	--	--	--	--
Ti-150B	--	3	1.5	--	--	--	--
Ti-155A	5	2	2	--	2	--	--
Ti-155AX	5	1.4	1.3	--	1.4	--	--
Ti-175A	--	--	--	--	--	--	--
Ti-6Al-4V	6	--	--	--	--	--	4

TABLE 2. SUMMARY OF PHYSICAL PROPERTIES
OF UNALLOYED TITANIUM

Property	Value
Atomic number	22
Atomic weight	47.90 g/mole
Absorption cross section for thermal neutrons	5.6 ± 0.4 barns
Crystal structure	
Alpha, hexagonal, close-packed	$c = 4.6832 \pm 0.0004$ A $a = 2.9504 \pm 0.0004$ A $c/a = 1.5873$
Beta, cubic, body-centered	$a = 3.28 \pm 0.003$ A
Compressibility	$0.80 \times 10^{-6} \text{ cm}^2/\text{kgm}$
Surface tension	1200 dynes/cm
Velocity of sound	16,320 ft/sec
Coefficient of thermal expansion, alpha, at 68 F	$4.67 \times 10^{-6} \text{ in/in/F}$
Thermal conductivity	$\sim 10 \text{ BTU/hr/ft}^2/\text{ft/F}$
Specific heat	0.125 cal/C/gm
Transformation temperature	1620 F (882.5 C)
Latent heat of transformation	1050 cal/mole
Heat of fusion	~ 5 kcal
Melting temperature	3035 F (1668 C)
Heat of vaporization	112,500 cal/mole
Boiling temperature, estimated	5900 F (3260 C)
Electrical resistivity	
High purity	42 microhm-cm
Commercial purity	55 microhm-cm
Superconductivity, critical temperature	~ 0.38 K
Hall coefficient	$+ 1.82 \pm 0.2 \times 10^{-13}$ volt-cm/amp/oersted
Magneto-resistance coefficient, B_t	$6.6 \times 10^{-13}/\text{oersted}^2$
Magnetic susceptibility	$3.17 \times 10^{-6} (\pm 0.03 \times 10^{-6}) \text{ emu/g}$
Magnetic permeability	1.00005
Emissivity	
Alpha (1490-1598 F)	0.459
Beta (2550 F)	0.42
Work function	4.17 ev
Band width (from soft X-ray spectra)	6.0 ± 0.5 ev
Electronic specific heat	$8.00 \times 10^{-4} \text{ cal/C/mole}$

TABLE 3. SOME PHYSICAL PROPERTIES OF TITANIUM ALLOYS

Nominal Composition	Alloy Designation	AMS Designation	Density, lb/in. ³	Electrical Resistivity, microhm-cm, at Room Temperature	Thermal Conductivity, Btu/hr/ft ² /ft/F, at Room Temperature	Coefficient of Thermal Expansion, x 10 ⁶ /F (68-1000 F)	Specific Heat, Btu/lb /F., at Room Temperature
99+% Ti	A-40	4902	0.163	—	—	—	—
99+% Ti	A-55	4900,4900A	0.163	48.6	11.5	5.6	0.125
99+% Ti	A-70	4901	0.163	54.8	10.1	5.6	0.125
99+% Ti	MST Grade III	4900,4900A	0.162	55	—	—	—
99+% Ti	MST Grade III	4901	—	—	—	—	—
99+% Ti	RS-40	—	0.163	—	—	—	—
99+% Ti	RS-55	4900,4900A	0.163	61	9.1	5	—
99+% Ti	RS-70	4901	0.163	—	—	—	—
99+% Ti	Ti-55A	4902	0.163	—	—	—	—
99+% Ti	Ti-65A	4900,4900A	0.163	—	—	—	—
99+% Ti	Ti-75A	4901	0.163	—	9.84	—	0.125
99+% Ti	Ti-100A	4921	0.164	—	—	—	—
2Al-2Fe	MST 2Al-2Fe	—	0.165	118 to 125	—	—	—
3Al-5Cr	MST 3Al-5Cr	4927	0.166	150	—	5.9	—
4Al-4Mn	C-130AM	4925	0.163	146.1	4.0	5.4	0.130
4Al-4Mn	MST-4Al-4Mn	4925	0.163	—	—	6.3 (70-1830 F)	—
4Al-4Mn	RS-130	4925	0.165	—	—	—	—
5Al-2Cr-2Fe	RS-140X	—	0.163	—	—	—	—
5Al-1.5Fe-1.4Cr-1.2Mo	Ti-155A	—	—	—	—	4.9	—
5Al-2.5Sn	A-110AT	—	0.161	157.3	4.52	5.4	0.127
5Al-2.5Sn	MST-5Al-2.5Sn	—	—	—	—	—	—
5Al-2.5Sn	RS-110C	—	—	—	—	—	—
5Al-2.5Sn	Ti-5Al-2.5Sn	—	—	—	—	—	—
6Al-4V	C-120AV	49AA	0.160	—	—	—	—
6Al-4V	MST-6Al-4V	49AA	0.160	—	—	5.2 (90-932 F)	—
6Al-4V	RS-120A	49AA	—	—	—	—	—
6Al-4V	Ti-6Al-4V	49AA	0.161	176	3.8	5.5	0.135
2.8Cr-1.5Fe	Ti-150A	—	0.167	60	—	—	0.120
3Cr-1.5Fe	RS-110	—	0.168	—	—	—	—
3Cr-1.5Fe	Ti-150B	—	0.168	153	—	—	0.124
2.2Fe-2.1Cr-2.0Mo	Ti-140A	4923	0.169	79	—	4.5	—
2.5Fe-2.5V	MST-2.5Fe-2.5V	—	0.167	78 to 85	—	—	—
7Mn	RS-120	—	0.170	—	—	5.5 (0-1200 F)	—
8Mn	C-110M	4908	0.171	90.7	6.3	6.0	0.118
8Mn	MST-8Mn	4908	0.172	—	—	—	—
8Mn	RS-110A	4908	0.171	—	—	—	—
3Mn-1.5Al	RS-110BX	—	0.165	—	—	—	—
3.25Mn-2.25Al	RS-110B	—	—	—	—	—	—

CONCLUSIONS AND RECOMMENDATIONS

The basic physical properties of unalloyed titanium are known but with varying degrees of accuracy. There are, however, certain areas where additional work is needed. These areas where information is lacking are discussed in the following paragraphs.

Data on the physical properties of titanium alloys are considerably more incomplete than for unalloyed titanium. Inspection of the data in Table 3, which summarizes the physical properties of commercial alloys, shows that, except for density, even the common properties that would be most useful to aircraft producers are known only sketchily. Emissivity could not be included in Table 3 because no information was available.

For unalloyed titanium, more accurate data on purer material would be scientifically pleasing, but not urgently needed. The properties which require more investigation so that definite values can be established are the following:

- (1) Emissivity - More study is required of the emissivity for unalloyed titanium between room temperature and 1200 F (650 C), and just below and above the transformation temperature. The only data on alloyed titanium consist of some values of the emissivity of a few Ti-V alloys. Obviously, the entire alloy field requires more attention.
- (2) Electrical Resistivity - The resistivity of high-purity titanium is well established. This property of commercially pure material is known to depend upon the purity and the condition of the individual sample. The resistivities above room temperature are known only for a few of the commercial alloys. Fewer data are available at low temperatures. Because resistivity measurements are useful for studying the electronic structure of titanium, more data would aid in formulating an alloying theory.
- (3) Thermal Conductivity - To date, there has been only one investigation on the thermal conductivity of unalloyed titanium at low temperatures. The data appear to be unsatisfactory and need verification.

Above room temperature, the minimum in the curve for conductivity versus temperature for

unalloyed commercial titanium also needs to be verified, and the temperature range for study should be extended to cover higher temperatures.

Data are available for most commercial compositions, but not for every alloy designation. Below room temperature, data are available on only one or two alloys.

- (4) Coefficient of Thermal Expansion - Next to density, more data are available on the thermal expansion of alloys than any other physical property. The temperature range covered by these data is from room temperature to about 1400 F (760 C). Information on thermal expansion at low temperatures, however, is lacking for both unalloyed and alloyed titanium.

- (5) Specific Heat - The value for specific heat of unalloyed titanium needs to be verified in the temperature range from 900 F (485 C) up to and just above the transformation temperature, 1620 F (882.5 C). In addition to providing accurate data for this temperature range, an accurate value for the latent heat of transformation could be derived.

The specific heat of alloys at low temperatures has not been thoroughly investigated.

There are a number of other physical properties, of no immediate concern to the titanium users, that have not been investigated experimentally. These include:

- (1) Heat of Fusion - Only estimated values are available.
- (2) Boiling Temperature - Only estimated values are available.
- (3) Electronic Structure - Little is known about the electronic structure upon which the physical properties of solid titanium are based. Exact measurements of physical properties, such as magnetic susceptibility, soft X-ray spectra, intensity measurements of X-ray diffraction, precision lattice constants, Hall coefficients, coefficients of magneto-resistance, and measurements of thermoelectric power at low and high temperature, would be useful in understanding the basic physical character of titanium.

PROPERTIES OF THE TITANIUM ATOM

Atomic Number

The atomic number of titanium is 22. It is in the First Long Period and in Group IV A of the Periodic Table.

Isotopic Constitution and Atomic Weight

There are five naturally occurring isotopes of titanium. The mass^{(1)*} and relative abundance⁽²⁾ of each are as follows:

<u>Mass Number</u>	<u>Mass (Physical Scale)</u>	<u>Relative Abundance, per cent</u>
46	45.96612 ± 0.00095	7.95
47	46.96473 ± 0.00095	7.75
48	47.96332 ± 0.00048	73.45
49	48.96479 ± 0.00053	5.51
50	49.96229 ± 0.00038	5.34

Based on these values, the atomic weight of titanium on the physical scale is 47.867. The chemical atomic weight, as determined by Okuda and Ogata,⁽¹⁾ is 47.88 ± 0.04 . Except when individual isotopic values are important, the international value of 47.90 grams per mole should be used as the atomic weight of titanium.

Cross Section for Thermal Neutrons

The scattering cross section for thermal neutrons⁽³⁾ for the naturally occurring isotopes is as follows:

<u>Isotope</u>	<u>Cross Section, barns</u>
46	0.6 ± 0.2
47	1.6 ± 0.3
48	8.0 ± 0.6
49	1.8 ± 0.5
50	0.2

*Numbers give references found at the end of the report.

The thermal-neutron absorption cross section⁽³⁾ for the normally occurring isotopic mixture in metallic titanium is 5.6 ± 0.4 barns ($0.070 \text{ cm}^2/\text{g}$). This value for titanium is about equal to that for steel but is higher than the values for aluminum, beryllium, magnesium, or zirconium.

Nuclear Spin and Nuclear Magnetic Moment

The nuclear spin and nuclear magnetic moment for two stable isotopes⁽⁴⁾ are as follows:

Isotope, Mass Number	Nuclear Spin	Nuclear Magnetic Moment, mm units
47	5/2	-0.78706 ± 0.0001
49	7/2	-1.1022 ± 0.0002

Electronic Structure

The 22 electrons in the free un-ionized atom are arranged as follows:

$$1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^2, 4s^2.$$

With 4 electrons in the 3d and 4s states outside the argon-like core, titanium can form four ions. The ionization potential of the four states, as listed by Moore,⁽⁵⁾ are as follows:

	Ti	Ti ⁺	Ti ⁺⁺	Ti ⁺⁺⁺	Ti ⁺⁺⁺⁺
Outer electron configuration	$3d^2 4s^2$	$3d^2 4s$	$3d^2$	3d	--
Ionization potential, V	--	6.83	13.63	28.14	43.24

The ionization potential of higher ions can be obtained from the work of Finkelnburg.⁽⁶⁾ The higher ionization potentials are of no practical importance, therefore, they are not listed here.

Crystal Structure

Two allotropic forms of metallic titanium exist. Below 1620 F (882.5 C), the stable phase, called alpha, has a hexagonal close-packed structure. The c/a ratio is slightly less than the ideal value, 1.633, for close packing. The high-temperature phase above 1620 F is called beta and exhibits a body-centered cubic structure.

Lattice Parameter of Alpha Titanium

The lattice parameter measurements of Clark⁽⁷⁾ and of Denney⁽⁸⁾ on high-purity titanium are probably the most accurate made to date. Other values reported in the literature were affected by the higher impurity contents and, therefore, are not representative. Lattice parameter values are presented in Table 4.

The Effect of Carbon, Oxygen, and Nitrogen on the Lattice Parameters of Alpha Titanium

When in solution, carbon, oxygen, and nitrogen expand the unit cell of alpha titanium. Carbon produces the greatest change and oxygen the least. In all cases, the lattice constant, c , is affected to a greater extent than is the atomic diameter, a . Thus, the c/a ratio is increased and workability is decreased when these impurities are present. The c/a ratio for commercial titanium is about 1.590. Table 5 presents lattice parameters of titanium with different amounts of carbon, oxygen, or nitrogen.

The Effect of Added Metals on the Lattice Parameters of Alpha Titanium

Silver and tin increase the value of the lattice constant, c . Gallium, in small amounts, also increases the c value. Beyond about 2 weight per cent, gallium decreases the c value. Aluminum also decreases the c parameter.

Of these elements, only tin increases the atomic diameter, a , and does so only to a small extent. The a value decreases linearly with increasing quantities of the other elements mentioned.

Carlson,⁽¹⁶⁾ et al., found that 10 and 20 weight per cent additions of thorium to titanium decreased the c value and had little effect on the a parameter. Because thorium has little solubility in titanium, the effect was attributed to the removal of oxygen by the thorium from the hexagonal lattice.

Brotzen, et al.,⁽¹⁷⁾ showed that vanadium decreased both the c and a parameters of the alpha prime phase. The c value decreased, according to Vergard's law, as the vanadium content was increased up to 10 weight per cent, and the a value decreased as the content was increased to 7.5 per cent vanadium. At 10 per cent vanadium, the a parameter was higher than expected.

TABLE 4. LATTICE PARAMETERS OF ALPHA TITANIUM AT ROOM TEMPERATURE

Author	Reference	c, A	a, A	c/a
Clark	7	4.6833	2.9504	1.5873
Denney	8	4.68312	2.95030	1.5873
Berry and Raynor	9	4.6822	2.9496	1.587
Finlay and Snyder	10	4.6834	2.9504	1.587
Greiner and Ellis	11	4.6904	2.9509	1.5907
Fast	12	4.68	2.951	1.59
Burger and Jacobs	13	4.730	2.953	1.602
Litton and Gonser	14	4.695	2.952	1.591
Rostoker	15	4.679	2.945	1.588

TABLE 5. LATTICE PARAMETER VALUES FOR TITANIUM WITH EITHER CARBON, OXYGEN, OR NITROGEN⁽¹⁰⁾

Solute	Weight Per Cent	c, A	a, A	c/a
Titanium	--	4.6834	2.9504	1.5873
Carbon	0.1	4.6883	2.9517	1.5884
Carbon	0.2	4.6932	2.9530	1.5894
Oxygen	0.055	4.6843	2.9504	1.5876
Oxygen	0.105	4.6852	2.9504	1.5879
Oxygen	0.19	4.6868	2.9504	1.5884
Nitrogen	0.05	4.6845	2.9505	1.5876
Nitrogen	0.10	4.6856	2.9506	1.5880
Nitrogen	0.15	4.6867	2.9507	1.5883

Data from the various investigators on the lattice parameters of the alpha phase are given in Table 6.

Lattice Parameter of Beta Titanium

Burgers and Jacobs⁽¹³⁾ found the parameter of beta titanium at 1650 F (900 C) to be 3.32 Å. Their parameters of the alpha phase were larger than those of other investigators, so it is possible that their parameter for beta titanium may be slightly high also.

Levinger⁽²²⁾ calculated a value for the lattice parameter of unalloyed beta titanium at room temperature by extrapolating the parameters of a number of retained-beta alloys to zero alloy composition. In practically all cases, the value obtained was 3.282 ± 0.003 Å.

The lattice parameter of beta titanium decreases with increasing amounts of the beta stabilizing elements. Values of the beta lattice parameters have been obtained in alloys quenched from elevated temperatures. The changes in the parameters with alloy content are linear; the slope of the line depends upon the particular alloy system.

MASS PROPERTIES

Density

Fast⁽¹²⁾ obtained an average value of 0.163 lb/in.^3 ($4.507 \pm 0.005 \text{ g/cm}^3$) for the density of high-purity titanium from a number of pycnometric determinations. Calculations based on the lattice parameter values reported by Clark yield a value of 0.163 lb/in.^3 (4.505 g/cm^3). Consequently, 0.163 lb/in.^3 can be accepted as the density of high-purity titanium. All of the usual alloying elements except aluminum will increase the density. The density of commercial titanium may be slightly higher.

Table 7 lists the room-temperature density of titanium of commercial purity and its alloys.

Elyutin and Marirakh⁽²³⁾ determined the density of liquid titanium just above the melting point. A mean value of 0.148 lb/in.^3 ($4.11 \pm 0.08 \text{ g/cm}^3$) was obtained for material of 98.7 per cent purity. The chief impurity was 0.6 to 0.8 per cent carbon.

TABLE 6. LATTICE PARAMETERS OF THE ALPHA PHASE OF VARIOUS TITANIUM ALLOYS

Alloy Content, weight per cent	c, Å	a, Å	Reference
0	4.68312	2.95030	8
1.18Ag	4.68459	2.94882	8
2.42Ag	4.68602	2.94771	8
3.42Ag	4.68724	2.94673	8
4.31Ag	4.68838	2.94597	8
5.65Ag	4.69002	2.94478	8
6.10Ag	4.69110	2.94390	8
7.80Ag	4.69252	2.94302	8
8.75Ag	4.69371	2.94223	8
11.00Ag	4.69640	2.94070	8
12.68Ag	4.69842	2.93933	8
0	4.685(a)	2.951(a)	18
5.6Ag(a)	4.692(a)	2.945(a)	18
13.4Ag(a)	4.701(a)	2.941(a)	18
0	4.68312	2.95030	8
0.83Al	4.68318	2.94758	8
1.08Al	4.68313	2.94680	8
1.25Al	4.68316	2.94629	8
1.51Al	4.68314	2.94552	8
1.77Al	4.68278	2.94441	8
1.97Al	4.68211	2.94370	8
2.48Al	4.68096	2.94161	8
3.12Al	4.67912	2.93664	8
3.76Al	4.67742	2.93435	8
4.67Al	4.67575	2.93431	8
5.32Al	4.67448	2.93215	8
5.83Al	4.67385	2.93055	8
6.96Al	4.67334	2.92690	8
7.58Al	4.67017	2.92512	8
8.58Al	4.66802	2.92211	8
0	4.679	2.943	19
4Al	4.668	2.929	19
7Al	4.670	2.923	19
9Al	4.661	2.924	19
10Al	4.661	2.912	19
16Al	4.633	2.892	19
22Al	4.619	2.882	19
25Al	4.619	2.881	19
29Al	4.617	2.878	19

TABLE 6. (Continued)

Alloy Content, weight per cent	c, Å	a, Å	Reference
0	4.693(a)	2.951(a)	20
2.5Al(a)	4.692(a)	2.942(a)	20
5.0Al(a)	4.690(a)	2.933(a)	20
7.0Al(a)	4.687(a)	2.923(a)	20
10.0Al(a)	4.677(a)	2.915(a)	20
12.0Al(a)	4.663(a)	2.907(a)	20
0	4.68312	2.95030	8
0.70Ga	4.68721	2.94910	8
1.58Ga	4.68808	2.94763	8
1.64Ga	4.68796	2.94750	8
2.63Ga	4.68715	2.94604	8
2.66Ga	4.68706	2.94600	8
3.73Ga	4.68261	2.94430	8
3.90Ga	4.68163	2.94400	8
4.07Ga	4.68097	2.94361	8
4.56Ga	4.67990	2.94282	8
5.07Ga	4.67901	2.94208	8
5.49Ga	4.67838	2.94170	8
0	4.685(a)	2.951(a)	21
8.2Sn	4.706(a)	2.952(a)	21
14.4Sn	4.719(a)	2.954(a)	21
18.9Sn	4.728(a)	2.955(a)	21
0	4.702	2.952	16
10Th	4.696	2.952	16
20Th	4.693	2.953	16
0	4.689(a)	2.953(a)	17
2V(a)(b)	4.683(a)	2.950(a)	17
4V(a)(b)	4.677(a)	2.947(a)	17
6V(a)(b)	4.671(a)	2.943(a)	17
8V(a)(b)	4.661(a)	2.940(a)	17

(a) Data derived from graphs in referenced work.

(b) Alpha prime phase.

TABLE 7. THE DENSITY OF COMMERCIALY PURE TITANIUM AND TITANIUM ALLOYS

Nominal Composition	Alloy Designation	Density, lb/in. ³	Remarks	Reference
99.2Ti	A-40, A-55, Ti-55A, Ti-65A, RS-40, RS-55	0.163	--	25, 26, 27
99.2Ti	MST Grade III	0.162	--	28
99.0Ti	A-70, Ti-75A, RS-70	0.163	--	25, 26, 27
99.0Ti	Ti-100A	0.164	--	29
99.0Ti	Ti-175A	0.168	--	30
Ti powder compact	--	0.112 to 0.126	Compacted at 30 to 50 tons/in ²	31
Ti sintered compact	--	0.161	Sintered 1 hr at 1650 to 2100 F	31
1.9Al	--	0.167	--	32
2Al	--	0.162	--	33
4Al	--	0.160	--	33
4.1Al	--	0.162	--	32
5.9Al	--	0.161	--	32
6Al	--	0.159	--	33
7.5Al	--	0.157	--	34
7.9Al	--	0.158	--	32
8Al	--	0.157	--	33
36Al	--	0.130	--	35
37Al	--	0.137	γ phase	36
2Al-2Fe	MST-2Al-2Fe	0.165	--	30
3Al-5Cr	MST-3Al-5Cr	0.166	--	30, 37
4Al-4Mn	C-130AM, MST-4Al-4Mn	0.163	--	25, 28
4Al-4Mn	RS-130	0.165	--	27
5Al-2Cr-2Fe	RS-140X	0.163	--	37
5Al-2.5Sn	A-110AT	0.161	--	25
6Al-1Si	--	0.158	--	33
6Al-4V	C-120AV, MST-6Al-4V	0.160	--	25, 28
6Al-4V	Ti-6Al-4V	0.161	--	38
8Al-2Cb-1Ta	MST-8Al-2Cb-1Ta	0.1587	--	39
8Al-4Mo	--	0.163	--	33
8Al-1Si	--	0.157	--	33
0.40C	--	0.166	--	32
0.66C	--	0.164	--	32
0.85C	--	0.164	--	32
38Co	--	0.206	CoTi ₂	40
38Co	--	0.210	CoTi ₂ , sintered, hot pressed	40
38Co	--	0.202	CoTi ₂ , heat treated	40
2.8Cr-1.5Fe	Ti-150A	0.167	--	37
3Cr-1.5Fe	Ti-150B	0.168	--	30
3Cr-1.5Fe	RS-110	0.168	--	37
4.5Cr-4.5Fe-4.5Mo	--	0.175	--	34
3.02Cu	--	0.167	--	32
6.36Cu	--	0.170	--	32
11.5Cu	--	0.173	--	32
2.2Fe-2.1Cr-2.0Mo	Ti-140A	0.169	--	38
2.5Fe-7.5V	MST-2.5Fe-2.5V	0.167	--	30
37Fe	--	0.201	FeTi ₂	40
37Fe	--	0.210	FeTi ₂ , sintered and hot pressed	40

TABLE 7. (Continued)

Nominal Composition	Alloy Designation	Density, lb/in ³	Remarks	Reference
0.002H ₂	--	0.164	--	41
0.004H ₂	--	0.165	--	41
0.50H ₂	--	0.162	--	41
1.11H ₂	--	0.160	--	41
1.94H ₂	--	0.157	--	41
2.73H ₂	--	0.154	--	41
3Mn-1.5Al	RS-110BX	0.163	--	26
5Mn-5Sn-2V	C-110M(modified)	0.171	--	25
7Mn	RS-120	0.170	--	37
8Mn	C-110M	0.171	--	25
8Mn	MST-8Mn	0.172	--	38
8Mn	RS-110A	0.171	--	26
30Mo	--	0.199	--	34
30Mo	--	0.195	--	33
38Ni	--	0.203	NiTi ₂	40
38Ni	--	0.206	NiTi ₂ , sintered and hot pressed	40
38Ni	--	0.208	NiTi ₂ , heat treated	40
1.20V	--	0.1636	(a)	42
1.20V	--	0.1635	(b)	42
2.475V	--	0.1646	(a)	42
2.475V	--	0.1647	(b)	42
3.14V	--	0.1645	(a)	42
3.14V	--	0.1645	(b)	42
4.22V	--	0.1652	(a)	42
4.22V	--	0.1650	(b)	42
5.31V	--	0.1656	(a)	42
5.31V	--	0.1655	(b)	42
5.96V	--	0.166	(c)	43
7.55V	--	0.1665	(a)	43
7.55V	--	0.1666	(b)	43
10.6V	--	0.170	--	32
10.9V	--	0.1683	(a)	43
14.1V	--	0.170	(c)	43
14.73V	--	0.1709	(a)	43
14.73V	--	0.1687	(b)	43
15.3V	--	0.1734	--	32
21.0V	--	0.1728	(a)	43
21.0V	--	0.1716	(b)	43
21.5V	--	0.173	--	32
25.2V	--	0.176	--	32
26.1V	--	0.1754	(a)	43
26.1V	--	0.1750	(b)	43
31.27V	--	0.1781	(a)	43
31.27V	--	0.1782	(b)	43
31.3V	--	0.179	--	32
51.4V	--	0.184	(c)	43
16V-2.5Al	--	0.168	--	39

- (a) Du Pont, arc melted.
(b) Du Pont, hot rolled.
(c) National Lead material.

No accurate values for the density of unalloyed beta titanium has been reported. The density can be calculated from the value of the lattice parameter determined by Burgers and Jacobs⁽¹³⁾ at 1650 F (900 C) which is just within the beta range. A density of 0.155 lb/in.³ (4.32 g/cm²) is obtained. The material, however, was probably contaminated during the testing. Blocher and Campbell⁽²⁴⁾ obtained a value of 0.156 lb/in.³ (4.35 g/cm³) by observation of the amount of sag in a titanium filament. If the lattice parameter calculated by Levinger⁽²²⁾ for beta titanium at room temperature is used, a value of 0.161 lb/in.³ (4.47 g/cm³) is obtained for the density of beta titanium.

Compressibility

The only value available on the compressibility of titanium was that determined by Bridgman⁽⁴⁴⁾ in 1929. A value of 0.80×10^{-6} cm²/kg was obtained for sodium-reduced titanium.

Surface Tension

The surface tension of titanium and a number of Ti-V alloys was determined by Powers and Wilhelm⁽⁴²⁾ by the sessile drop method. Their data are presented in Table 8.

Sound Transmission

A limited amount of research has been conducted on determining the speed of sound in titanium. Fusfeld and Gilbert⁽⁴⁵⁾ determined the velocity of sound in unalloyed titanium at room temperature by the resonance technique. Their values are given in Table 9. For comparison, the velocities derived from data obtained with ultrasonic pulse techniques are also included in the table. The agreement between the two methods is fair.

THERMAL PROPERTIES

The thermal properties of titanium are interesting when compared to other structural metals. Titanium has the highest melting point of structural materials now in tonnage use. The thermal conductivity is much lower than the thermal conductivity of aluminum, carbon steel, magnesium, or copper. It is comparable with austenitic stainless steel. The electrical

TABLE 8. SURFACE TENSION OF TITANIUM
AND Ti-V ALLOYS

Alloy Composition (Balance Ti), weight per cent	Surface Tension, dynes/cm
DuPont Ti	1200
1.2V	1097
2.5V	1240
3.1V	1071
4.2V	1064
5.3V	1168
7.6V	940
10.9V	1174
14.8V	1217
20.0V	1189
21.0V	1116
26.1V	1148
31.0V	1138
51.7V	1204
69.5V	1436
75.5V	1358(a)
84.5V	1725(a)
100V	1511

(a) Rough surface on specimen.

TABLE 9. VELOCITY OF SOUND IN TITANIUM AT
ROOM TEMPERATURE

Investigator	Reference	Technique	Velocity of Sound, ft/sec
(1) Fusfeld and Gilbert	45	Resonance	16,350 16,349 16,273 16,299 16,318(a)
(2) Reynolds	46	Pulse	15,908
(3) Laquer	47	Pulse	16,826

(a) Average.

resistivity of titanium is exceedingly high for a pure metal; whereas, the specific heat and coefficient of thermal expansion are about normal, in comparison with the other commercial metals. The heat of vaporization is high, thus indicating strong bonding forces within the metal lattice.

Thermal Expansion

The coefficient of thermal expansion of polycrystalline alpha titanium is about 4.67×10^{-6} in./in./F at 68 F. Very little work has been done on the thermal expansion of iodide titanium above room temperature.

Altman, et al.,⁽⁴³⁾ determined the coefficient of expansion for iodide titanium between room temperature and about -400 F. Figure 1 shows the data from this work and the data of other investigations on less pure titanium at elevated temperatures. The data by Altman, et al., appear to be representative of the thermal expansion of pure titanium. From their work the value of 4.67×10^{-6} in./in./F was obtained.

Table 10 lists values of the coefficient of thermal expansion for titanium and some alloys for various ranges of temperature. For titanium of commercial purity, the coefficient of thermal expansion at room temperature is between 4.8 and 5.2×10^{-6} in./in./F.

Because alpha titanium has a hexagonal crystal lattice, it is anisotropic and the coefficient of thermal expansion should vary depending upon the direction of measurement. The mean coefficient of thermal expansion along the c and a direction of the lattice can be derived from the X-ray lattice parameters of Berry and Raynor.⁽⁹⁾ Their results are:

Temperature Range, F	Direction	Coefficient of Thermal Expansion, $\times 10^6$
68 - 750	Perpendicular to c axis	5.66
68 - 1290	Perpendicular to c axis	6.13
68 - 1290	Parallel to c axis	7.14

Consequently, expansion along the c axis is about 20 per cent greater than along the a axis.

The coefficient of expansion for beta titanium over the range from room temperature to 1830 F (1000 C) was estimated by Levinger⁽²²⁾ to be 5.6×10^{-6} in./in./F. Levinger compared this value for beta titanium to 6.1×10^{-6} in./in./F for alpha titanium for the same temperature range. Beta thus shows less expansion than alpha titanium.

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FIGURE 1. THE RELATIONSHIP BETWEEN THE MEAN LINEAR COEFFICIENT OF THERMAL EXPANSION OF TITANIUM AND TEMPERATURE

TABLE 10. THE MEAN LINEAR COEFFICIENT OF THERMAL EXPANSION OF TITANIUM AND TITANIUM ALLOYS

Nominal Composition	Alloy Designation	Mean Linear Coefficient of Thermal Expansion Between 68 F and Indicated Temperature, in./in./F x 10 ⁶															Remarks	Reference
		-400 F	-300 F	-200 F	-100 F	0 F	68 F	200 F	400 F	600 F	800 F	1000 F	1200 F	1400 F	1600 F	1800 F		
Iodide Ti	—	—	—	—	—	—	—	—	4.80	4.95	5.16	5.29	5.41	5.53	5.67	—	—	34
Ti	—	3.2	3.8	4.2	4.5	4.5 ^(a)	4.6 ^(b)	—	—	—	—	—	—	—	—	—	As deposited, cold swaged, unannealed	43
Ti	—	—	—	—	—	—	—	—	4.45	4.70	5.01	5.32	5.48	5.54	—	—	—	49
Ti	—	—	—	—	—	—	—	—	4.21	4.39	4.61	4.80	5.02	5.22	5.41	—	—	50
Ti	—	—	—	—	—	—	—	5.1	5.2	5.3	5.5	5.6	5.8	—	—	—	—	51
Ti	—	—	—	—	—	—	—	—	4.87	4.94	5.11	5.29	5.41	5.69	5.60	—	—	34
Commercial Ti	A-55	—	—	—	4.4	4.8	—	4.7	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.8 ^(c)	—	25
Commercial Ti	RS-55	—	—	—	—	—	—	—	—	—	—	5.0	—	—	—	—	—	27
Commercial Ti	A-70	—	—	—	3.9	4.3	—	4.8	5.2	5.2	5.3	5.4	5.6	5.6	5.7	6.0 ^(c)	—	25
Commercial Ti	Ti-75A	0.7	1.3	3.3	4.7	6.0	—	—	—	—	—	—	—	—	—	—	—	26
2Al-2Fe	MST-2Al-2Fe	—	—	—	—	—	6.4 ^(d)	—	—	—	—	—	—	—	—	—	—	52
2Al-2Fe	MST-2Al-2Fe	—	—	—	—	—	5.4 ^(d)	—	—	—	—	—	—	—	—	—	—	29, 30
3Al-5Cr	MST-3Al-5Cr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	6.1 ^(e)	28
3Al-5Cr	MST-3Al-5Cr	—	—	—	—	—	—	5.0	5.0	5.1	5.2	5.5	5.9	—	—	—	—	53
4Al-4Mn	C-130AM	—	5.6	6.4	7.0	—	—	—	—	—	—	—	—	—	—	—	—	54
4Al-4Mn	C-130AM	—	—	—	—	—	—	4.9	4.9	5.1	5.3	5.4	5.6	5.8	5.7 ^(c)	5.3 ^(c)	—	25
4Al-4Mn	—	—	—	—	—	—	—	4.6	4.9	4.9	5.0	4.9	4.9	4.7	—	—	—	53
4Al-4Mn	MST-4Al-4Mn	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	6.3 ^(f)	28
5Al-2.75Cr-1.25Fe	RS-140X	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	5.2 ^(g)	55
5Al-1.5Fe-1.4Cr-1.2Mo	Ti-155A	—	—	—	—	—	—	4.6	4.9	4.9	5.1	5.1	4.9	4.7	—	—	—	53
5Al-2.5Sn	A-110AT	—	—	—	—	—	—	5.2	5.2	5.3	5.3	5.4	5.5	5.6	5.7	5.7 ^(c)	—	25
5Al-2.5Sn	—	—	—	—	—	—	—	5.7	5.4	5.3	5.4	5.2	5.3	5.6	—	—	—	53
6Al-4V	MST-6Al-4V	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	5.2 ^(h) , 5.8 ⁽ⁱ⁾	28
6Al-4V	Ti-6Al-4V	—	—	—	—	—	—	4.8	5.0	5.1	5.2	5.3	5.5	5.7	—	—	—	56
6Al-4V	—	—	—	—	—	—	—	—	—	—	—	4.7	—	—	—	—	—	57
6Al-4V	—	—	—	—	—	—	—	4.6	4.8	5.0	5.1	5.0	5.0	5.1	—	—	5.1 ^(j)	53
6Al-4V	—	—	—	—	—	—	—	4.6	5.0	5.0	5.1	5.2	5.3	5.6	—	—	5.6 ^(j)	53
6Al-4V	—	—	—	—	—	—	—	4.2	4.1	4.3	4.7	5.2	5.4	5.3	—	—	5.7 ^(j)	53
6Al-4V	—	—	—	—	—	—	—	4.6	4.9	4.9	5.0	5.1	5.3	5.4	—	—	5.4 ^(j)	53
6Al-4V	—	—	—	—	—	—	—	5.1	5.2	5.3	5.5	5.6	5.8	—	—	—	As received, second run	51
0.04C	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	51
10Cb	—	—	—	—	—	—	—	4.67	4.78	5.01	5.26	5.29	5.28	5.25 ^(c)	—	—	—	34
5Cr	—	—	—	—	—	—	—	—	4.83	5.08	5.34	5.52	5.48 ^(c)	5.62 ^(c)	5.58 ^(c)	—	—	34
10Cr	—	—	—	—	—	—	—	—	5.07	5.27	5.56	5.74	6.40 ^(c)	5.73 ^(c)	—	—	—	34
15Cr	—	—	—	—	—	—	—	—	5.15	5.09 ^(c)	5.90 ^(c)	6.22 ^(c)	6.87 ^(c)	6.38 ^(c)	6.40 ^(c)	—	—	34
40Cr	—	—	—	—	—	—	—	—	4.64	4.79	5.38	5.47	6.24 ^(c)	5.85 ^(c)	5.83 ^(c)	—	—	34
2.6Cr-1.3Fe	—	—	—	—	—	—	—	—	4.93	4.98	5.06	5.14	5.33	4.97 ^(c)	—	—	—	34
2.8Cr-1.5Fe	Ti-150A	—	4.4	5.0	5.4	—	—	—	—	—	—	—	—	—	—	—	—	54
3Cr-1.5Fe	Ti-150B	—	—	—	—	—	5.0 ^(d)	—	—	—	—	—	—	—	—	—	—	30
5Cu	—	—	—	—	—	—	—	—	5.06	5.13	5.26	5.45	5.58	5.78	5.82 ^(c)	—	—	34

TABLE 10. (Continued)

Nominal Composition	Alloy Designation	Mean Linear Coefficient of Thermal Expansion Between 68 F and Indicated Temperature, in./in./F x 10 ⁶																Remarks	Reference
		-400 F	-300 F	-200 F	-100 F	0 F	68 F	200 F	400 F	600 F	800 F	1000 F	1200 F	1400 F	1600 F	1800 F	Other		
2Fe-2Cr-2Mo	Ti-140A	-	-	-	-	-	-	4.6	4.5	4.5	4.5	5.0	4.5	4.4	-	-	-	-	53
2Fe-2Cr-2Mo	Ti-140A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.9 ^(k)	-	58
2.2Fe-2.1Cr-2.0Mo	Ti-140A	-	-	-	-	-	4.9 to 5.1 ^(d)	-	-	-	-	-	-	-	-	-	5.0 ^(b)	Completely stabilized	29
2.5Fe-2.5V	MST-2.5Fe-2.5V	-	-	-	-	-	5.1 ^(d)	-	-	-	-	-	-	-	-	-	-	-	29, 30
2.5Fe-2.5V	MST-2.5Fe-2.5V	-	-	-	-	-	5.3 ^(d)	-	-	-	-	-	-	-	-	-	-	-	52
2.5Mn	-	-	-	-	-	-	-	-	4.95	5.12	5.32	5.50	5.67	5.76	5.54 ^(c)	-	-	Completely stabilized	34
3Mn-1Cr-1Fe-1Mo-1V	MST 3Mn complex	-	-	-	-	-	-	4.5	4.7	4.8	5.0	5.1	6.6	9.0	-	-	-	Annealed bar stock	53
3Mn-1Cr-1Fe-1Mo-1V	-	-	-	-	-	-	-	4.6	3.6	3.9	12.9	11.8	12.5	12.0	11.4	-	-	Heated at 1600 F, 10 min., water quenched	59
3Mn-1Cr-1Fe-1Mo-1V	-	-	-	-	-	-	-	-	4.7	4.8	5.1	5.2	4.8	5.2	5.4	5.7	-	Heated at 1600 F, 10 min., water quenched, 1000 F., 26 hours, air cool	59
7Mn	RS-120	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.5 ^(k)	-	27
8Mn	C-110M	-	-	-	-	-	-	4.8	5.1	5.4	5.7	6.0	6.5	6.9 ^(c)	7.1 ^(c)	7.4 ^(c)	-	-	25
8Mn	C-110M	-	-	-	-	-	-	-	5.5	6.2	6.7	7.8	8.7	9.2	9.4	-	-	-	58
5Mo	-	-	-	-	-	-	-	-	4.77	4.93	5.09	5.25	5.34	5.40	5.32 ^(c)	-	-	Completely stabilized	34
2.5Ni	-	-	-	-	-	-	-	-	4.60	4.82	5.04	5.23	5.45	5.48 ^(c)	5.65 ^(c)	-	-	Completely stabilized	34
7.5Ni	-	-	-	-	-	-	-	-	4.82	5.01	5.21	5.45	5.79 ^(a)	5.85 ^(c)	5.39 ^(c)	-	-	Completely stabilized	34
10Ni	-	-	-	-	-	-	-	-	4.92	5.08	5.23	5.38	5.49 ^(c)	5.43 ^(c)	5.08 ^(c)	-	-	Completely stabilized	34
1Si	-	-	-	-	-	-	-	-	4.99	5.04	5.27	5.40	5.51	5.64	5.72	-	-	Completely stabilized	34
3Si	-	-	-	-	-	-	-	-	4.81	4.97	5.16	5.34	5.50	5.69	5.79	-	-	Completely stabilized	34
10Zr	-	-	-	-	-	-	-	-	4.71	4.88	5.07	5.24	5.40	5.56	5.65	-	-	Completely stabilized	34

(a) 9 F.

(b) 63 F.

(c) In α - β transformation range.

(d) Temperature not given, assumed to be room temperature.

(e) 70-1650 F.

(f) 70-1830 F.

(g) 70-900 F.

(h) 90-932 F.

(i) 932-1652 F.

(j) At 1500 F.

(k) 0-1200 F.

The addition of alloying elements, as represented by the commercial alloys, does not change greatly the expansivity of titanium. Likewise, neither temperatures above room temperature nor heat treatments greatly affect the coefficient of expansion.

Thermal Conductivity

The thermal conductivity of titanium is low for a pure metal. This low thermal conductivity is in agreement with titanium's high electrical resistivity in indicating a low number of conduction electrons.

Thermal conductivity is affected by impurities. The value obtained by Mendelssohn and Rosenberg⁽⁶⁰⁾ for their high-purity specimen, 99.99 per cent Ti, is about double the value for a 99.9 per cent Ti specimen at a temperature of about -400 F (-240 C). Measurements on alloys at low temperatures, about -400 F (-240 C), show also that aluminum and manganese in C-130AM and iron and chromium in Ti-150A greatly reduce the conductivity.

Data on the thermal conductivity contained in Table 11 are plotted in Figure 2 for unalloyed titanium and in Figure 3 for alloys. More data are needed on unalloyed titanium in the temperature range from room temperature to liquid helium temperature, -455 F (-270 C). A part of the present data indicates a possible maximum in the conductivity at about -100 F (-73 C) and a minimum at about +400 F (205 C). Other data, however, show a linear decrease in conductivity at about +200 F (93 C). As shown in Figure 3, the conductivity of titanium alloys increases with increasing temperature from the lowest to the highest measured temperatures.

Diffusivity

The diffusivity of titanium, as given by McIntosh, et al.,⁽⁶⁸⁾ is as follows:

<u>Temperature, F</u>	<u>Diffusivity, ft²/hr</u>
1057	0.24
1300	0.23
1542	0.19, 0.21

TABLE 11. THERMAL CONDUCTIVITY OF TITANIUM AND TITANIUM ALLOYS

Nominal Composition	Alloy Designation	Thermal Conductivity, Btu per hour per ft ² per ft per F														Reference
		-400	-300	-200	-100	32	68	200	400	600	800	1000	1200	1400	Other	
Ti (99.99)	-	11.2	-	-	-	-	-	-	-	-	-	-	-	-	-	60
Ti- (99.9)	-	6.6	-	-	-	-	-	-	-	-	-	-	-	-	-	60
Commercially Pure Ti	-	7.5	10.2	11.6	12.1	11.5	-	-	-	-	-	-	-	-	-	61, 62
Commercially Pure Ti	-	-	-	-	-	-	-	8.80	8.53	8.28	8.04	7.81	7.6	-	-	63
Commercially Pure Ti	A-55	-	-	-	11.8	-	11.5	10.9	10.4	10.5	10.5	10.7	11.3	12.1	12.5 ^(a)	25
Commercially Pure Ti	A-55	-	-	-	-	-	-	11.2	10.9	10.6	10.3	9.9	-	-	-	64
Commercially Pure Ti	RS-55	-	-	-	-	-	9.1	-	-	-	-	-	-	-	-	27
Commercially Pure Ti	A-70	-	-	-	10.3	-	10.1	9.8	9.8	9.8	10.0	10.5	11.1	11.9	12.4 ^(a)	25
Commercially Pure Ti	Ti-75A	-	-	-	-	-	9.84	-	-	-	-	-	-	-	-	26
Commercially Pure Ti	Ti-75A	-	-	-	-	-	-	13.4	13.2	13.0	12.8	12.7	12.6	-	-	64
Commercially Pure Ti	Ti-75A	-	-	-	-	-	-	11.7	11.5	11.3	11.3	11.1	11.0	-	-	64
36Al	-	-	-	-	-	-	-	11.4 ^(b)	-	-	-	-	-	-	-	65
4Al-4Mn	C-130AM	1.64	2.76	3.48	4.09	4.77	-	-	-	-	-	-	-	-	-	66, 67
4Al-4Mn	C-130AM	-	-	3.5 ^(c)	-	-	4.0	4.5	5.25	6.25	7.25	8.25	9.25	10.5	11.25 ^(d)	25
5Al-2.5Sn	A-110AT	-	-	-	3.89	4.31	-	4.85	5.55	6.30	7.11	8.01	8.96	9.97	10.48 ^(a)	25
6Al-4V	Ti-6Al-4V	-	-	-	-	-	3.8	4.3	5.1	5.9	6.8	7.6	8.5	9.5	10.5 ^(e)	56
2.8Cr-1Fe	Ti-150A	-	3.6	4.7	5.8	7.5	-	-	-	-	-	-	-	-	-	61
2.8Cr-1.5Fe	Ti-150A	-	-	-	-	-	-	9.8	9.8	9.8	9.8	9.8	9.8	-	-	64
2.8Cr-1.5Fe	Ti-150A	-	-	-	-	-	-	8.5	8.6	8.7	8.9	9.1	-	-	-	64
3.38Cr-2.1Mo	-	-	-	-	-	-	-	9.7	9.7	9.6	9.6	9.6	-	-	-	64
6.50Mn	Ti-130A	-	-	-	-	-	-	8.3	8.7	9.0	9.3	9.6	-	-	-	64
8Mn	C-110M	-	-	-	-	-	6.3	6.7	7.4	8.1	8.8	9.8	10.3	11.3	-	25

(a) At 1500 F. (b) At 140 F. (c) At -180 F. (d) At 1550 F. (e) At 1600 F.

FIGURE 2. THERMAL CONDUCTIVITY OF COMMERCIALLY PURE TITANIUM AT VARIOUS TEMPERATURES

FIGURE 3. THERMAL CONDUCTIVITY OF TITANIUM ALLOYS AT VARIOUS TEMPERATURES

Specific Heat

Until recently the only available data on heat capacity for titanium was based on the low-temperature measurements, 50 to 300 K (-370 F to +80 F), by Kelley⁽⁶⁹⁾ and on the high-temperature measurements by Jaeger, Rosenbohm, and Fonteyne.⁽⁷⁰⁾ Specific heat data in the ASM Handbook⁽⁷¹⁾ and Kelley's compilations⁽⁷²⁾ were derived from these sources. Kelley's material contained only 98.75 per cent titanium and Jaeger, et al., probably also had impure material. According to Jaeger, et al., the specific heat progressively increases from about 800 K (980 F) up to the alpha-beta transformation temperature. This behavior is not expected theoretically and indicates severe contamination of the titanium. These early data are believed to be not very reliable.

Recently, the specific heat of titanium, approximately 99 per cent pure, was determined for the temperature range of 1.8 to 4.2 K (-455 to -450 F) by Estermann, Friedberg, and Goldman.⁽⁷³⁾ Later work by Aven, Craig, Waite, and Wallace⁽⁷⁴⁾ covered the temperature range of 4 and 15 K (-451 to -431 F) on iodide titanium, 99.95 to 99.99 per cent Ti. Their results are summarized for temperatures below 13 K (-435 F) by the following equation: $C_p(\text{cal/mole/degK}) = 8.08 \times 10^{-4} + 0.621 \times 10^{-5}T^3$, where T is in degrees Kelvin. Similarly, the specific heat of TiH is given by the following equation: $C(\text{cal/mole/degK}) = 5.35 \times 10^{-4}T + 0.930 \times 10^{-5}T^3$, again T is in degrees Kelvin.

Kothen and Johnston⁽⁷⁵⁾ measured the specific heat of high-purity titanium, 99.96 per cent, over the temperature range covered by Kelley. Their values between the temperatures of 15 and 300 K (-431 to +80 F) are listed in Table 12. These data are considered to be the best now available. Friedberg⁽⁷⁶⁾ measured the specific heat from 15 to 200 K (-431 to -98 F). Within the temperature range of overlap, good agreement was obtained with Kothen and Johnston. Therefore, these data are not included.

Mah, Kelley, et al.,⁽⁷⁷⁾ measured the specific heat of high-purity titanium containing additions of oxygen. Below about 165 K (-160 F), titanium containing oxygen has a lower specific heat than pure titanium when compared with Kothen and Johnston's data. However, above about 165 K (-160 F), the titanium-oxygen alloys had higher specific heats than pure titanium. Consequently, specific heat measurements made on impure material will give values higher than the true specific heats at, or above, room temperature.

The specific heat of two alloys containing 1.90 and 9.95 per cent oxygen is included in Table 12 for comparison with Kothen and Johnston's values for high-purity titanium.

TABLE 12. HEAT CAPACITY OF HIGH-PURITY TITANIUM AND
TITANIUM-OXYGEN ALLOYS AT LOW TEMPER-
ATURES⁽⁷⁷⁾

Temperature, K	Heat Capacity, C_p , cal/mole/deg K		
	Titanium	Ti-1.90 Weight Per Cent O	Ti-9.95 Weight Per Cent O
50	1.136	1.031	0.683
75	2.402	2.271	1.750
100	3.434	3.310	2.831
125	4.155	4.074	3.780
150	4.684	4.650	4.564
175	5.043	5.067	5.141
200	5.321	5.380	5.697
225	5.539	5.627	6.101
250	5.713	5.822	6.429
275	5.864	5.991	6.703
298.15	5.976	6.130	6.930

TABLE 13. SPECIFIC HEAT OF ALPHA
TITANIUM AT ELEVATED
TEMPERATURES

Temperature, K	Specific Heat, C_p , cal/mole/deg K
300	6.153
350	6.496
400	6.711
450	6.852
500	6.947
550	7.011
600	7.055
650	7.085
700	7.104
750	7.115
800	7.121
850	7.121
900	7.119
950	7.113
1000	7.105
1050	7.095
1100	7.084
1150	7.071

The need for data on the specific heat of high-purity titanium at elevated temperature to supplement the work by Jaeger, et al.,⁽⁷⁰⁾ was partially satisfied by Staskiewicz.⁽⁷⁸⁾ The progressive increase in specific heat between 800 K (980 F) and 1150 K (1610 F) found by Jaeger, et al., was absent as expected, but an anomalous maximum occurred in the curve for specific heat versus temperature at 800 K (980 F). Consequently, additional research is still needed in this temperature range.

Values for the specific heat of alpha titanium between room temperature and the transformation temperature are presented in Table 13. The specific heat at other temperatures can be calculated with the aid of the following equation:

$$C_p(\text{cal/mole/degK}) = 7.654 - 4.2546 \times 10^{-4}T - 1.236 \times 10^{-5}T^2 \quad .$$

Based on the data of Jaeger, et al., Kelley⁽⁷²⁾ selected a constant value of 7.5 cal/mole/degK for the specific heat of beta titanium. Staskiewicz⁽⁷⁸⁾ obtained 8.00 cal/mole/degK for the temperature range 1150 to 1300 K (1610 to 1880 F). Schofield⁽⁷⁹⁾ reported unpublished work by I. Backhurst that gave a specific heat of 7.90 cal/mole/degK at 1184 K (1675 F), which was at the beginning of the beta range. Therefore, the higher value of 8.0 cal/mole/degK is probably more reliable than Kelley's value of 7.5 cal/mole/degK.

Specific heat data on commercially pure titanium and titanium alloys are collected in Table 14.

Kolsky and Giles⁽⁸⁰⁾ have calculated the specific heat for gaseous titanium for the temperature range from 10 to 8000 K (-440 to 13,940 F). Their data are presented in Table 15.

Transformation Temperature

The hexagonal, close-pack structure of alpha titanium transforms to the body-centered cubic form at about 1620 F (882.5 C). This value is the result of studies on high-purity grades of titanium. The data of various investigators are presented in Table 16.

Aluminum, carbon, oxygen, and nitrogen raise the transition temperature while the common alloying elements, iron, manganese, molybdenum, chromium, and vanadium lower it. All of the elements cause the transformation to occur over a range of temperature. Table 17 presents the transformation temperatures of some of the commercial alloys.

TABLE 14. SPECIFIC HEAT OF TITANIUM AND TITANIUM ALLOYS

Nominal Composition	Alloy Designation	Specific Heat, Btu/F/lb, at the Indicated Temperatures											Ref.
		32 F	68 F	200 F	400 F	600 F	800 F	1000 F	1200 F	1400 F	1550 F	1600 F	
Commercial Ti	A-55, A-70	—	0.125 ^(a)	0.130	0.136	0.143	0.151	0.160	0.171	0.183	0.193	—	25
Commercial Ti	Ti-75A	—	0.125 ^(b)	0.126	0.130	0.138	0.150	0.166	0.186	0.186	0.209	—	64
Commercial Ti	Ti-175A	—	0.129	—	—	—	—	—	—	—	—	—	30
4Al-4Mn	C-130AM	0.128	0.130 ^(c)	0.133	0.139	0.148	0.157	0.168	0.181	0.195	0.207	—	25
5Al-2.5Sn	A-110AT	0.126	0.128 ^(c)	0.131	0.137	0.145	0.153	0.161	0.170	0.180	0.188	—	25
6Al-4V	Ti-6Al-4V	—	0.135	0.135	0.137	0.144	0.154	0.167	0.184	0.205	—	0.229	56
2.8Cr-1.5Fe	Ti-150A	—	0.120 ^(b)	0.121	0.125	0.133	0.145	0.161	0.181	0.204	—	—	64
3Cr-1.5Fe	Ti-150B	—	0.129	—	—	—	—	—	—	—	—	—	64
8Mn	C-110M	0.112	0.120 ^(c)	0.130	0.141	0.147	0.153	0.166	0.192	0.236	0.286	—	34
8Mn	C-110M	—	0.118	—	—	—	—	—	—	—	—	—	25

(a) At 77 F.

(b) At 70 F.

(c) At 100 F.

TABLE 15. SPECIFIC HEAT OF GASEOUS TITANIUM
CALCULATED FROM SPECTROGRAPHIC
DATA

Temperature, K	C_p^0 , cal/deg/mole	Temperature, K	C_p^0 , cal/deg/mole
10	4.96798	1300	5.17630
20	4.97000	1350	5.20457
30	5.02099	1400	5.23687
40	5.19654	1450	5.27304
50	5.46304	1500	5.31289
60	5.74307	1550	5.35620
70	5.98968	1600	5.40273
80	6.18802	1650	5.45225
90	6.33868	1700	5.50453
100	6.44708	1750	5.55930
110	6.51938	1800	5.61636
120	6.56135	1850	5.67546
130	6.57826	1900	5.73641
140	6.57488	2000	5.86303
150	6.55548	2100	5.99481
160	6.52378	2200	6.13059
170	6.48299	2300	6.26943
180	6.43575	2400	6.41057
190	6.38425	2500	6.55346
200	6.33023	2600	6.69761
225	6.19224	2700	6.84266
250	6.05972	2800	6.98829
275	5.93872	2900	7.13418
298.16	5.83861	3000	7.28006
300	5.83116	3200	7.57056
325	5.73689	3400	7.85720
350	5.65484	3600	8.13723
375	5.58361	3800	8.40776
400	5.52176	4000	8.66606
425	5.46798	4200	8.90968
450	5.42108	4400	9.13666
475	5.38006	4600	9.34556
500	5.34406	4800	9.53549
550	5.28431	5000	9.70608
600	5.23733	5200	9.85746
650	5.19998	5400	9.99008
700	5.17011	5600	10.1047
750	5.14629	5800	10.2022
800	4.12758	6000	10.2838
850	5.11344	6200	10.3505
900	5.10356	6400	10.4033
950	5.09783	6600	10.4435
1000	5.09625	6800	10.4720
1050	5.09886	7000	10.4898
1100	5.10572	7200	10.4977
1150	5.11689	7400	10.4967
1200	5.13239	7600	10.4873
1250	5.15221	7800	10.4703
		8000	10.4464

TABLE 16. TRANSFORMATION TEMPERATURE OF
HIGH-PURITY TITANIUM

Author	Purity of Titanium, per cent	Transformation Temperature	Reference
McQuillan	99.92	1620 ± 2 F (882 ± 1.0 C)	81
Worner	99.95	1621 to 1630 F (883 to 887 C)	82
Duwez	99.95	1620 ± 7 F (882 ± 4 C)	83
Edwards, et al.	99.88	1623 ± 7 F (884 ± 3.5 C)	84
McQuillan	99.92	1620 ± 1 F (882.5 ± 0.5)	85
Greiner and Ellis	99.88	1625 ± 4 F (885 ± 2 C)	11

TABLE 17. TRANSFORMATION TEMPERATURES OF TITANIUM AND TITANIUM ALLOYS

Nominal Composition	Alloy Designation	Transformation Temperature, F				Reference
		$\alpha/\alpha + \beta$	All β	$\beta/\alpha + \beta$	All α	
Commercial Ti	--	1580	1760	--	--	81
Commercial Ti	Ti-75A	--	1575 to 1625	--	--	26
5Al	--	--	1767	--	--	19
6Al	--	--	--	1965 $\pm$ 77	--	86
8Al	--	--	1924	--	--	19
2Al-4Cr	--	--	--	1640	--	87
2Al-2Mn	--	--	--	1697 $\pm$ 45	--	88
2Al-4Mn	--	--	--	1652 $\pm$ 45	--	88
2Al-6Mn	--	--	--	1562 $\pm$ 45	--	88
2Al-0.3Si	--	1652 $\pm$ 45	--	--	--	89
2Al-0.3Si	--	--	--	1742 $\pm$ 45	--	88
2Al-0.6Si	--	1652 $\pm$ 45	--	--	--	89
2Al-0.6Si	--	--	--	1742 $\pm$ 45	--	88
2Al-0.9Si	--	1652 $\pm$ 45	--	--	--	89
2Al-0.9Si	--	--	--	1742 $\pm$ 45	--	88
3Al-5Cr	MST-3Al-5Cr	1250	1625	--	--	90
3Al-5Cr	--	--	--	1598 $\pm$ 45	--	88
4Al-2Cr	--	--	--	1780	--	87
4Al-4Cr	--	--	--	1750	--	87
4Al-2Mn	--	--	--	1787 $\pm$ 45	--	88
4Al-4Mn	--	--	--	1697 $\pm$ 45	--	88
4Al-4Mn	C-130AM	--	--	1760	--	91
4Al-6Mn	--	--	--	1652 $\pm$ 45	--	88
4Al-0.3Si	--	1742 $\pm$ 45	--	--	--	89
4Al-0.3Si	--	--	--	1832 $\pm$ 45	--	88
4Al-0.6Si	--	1742 $\pm$ 45	--	--	--	89
4Al-0.6Si	--	--	--	1832 $\pm$ 45	--	88
4Al-0.9Si	--	1742 $\pm$ 45	--	--	--	89
4Al-0.9Si	--	--	--	1832 $\pm$ 45	--	88
4Al-2V	--	--	--	1740 $\pm$ 77	--	86
4Al-4V	--	--	--	1740 $\pm$ 77	--	86
5Al-2Cr-2Fe	RS-140X	--	--	1875	1800	92
5Al-2.5Sn	A-110AT	1900	2000	--	--	91
6Al-0.3Si	--	1787 $\pm$ 45	--	--	--	89
6Al-0.3Si	--	--	--	1922 $\pm$ 45	--	88
6Al-0.6Si	--	1787 $\pm$ 45	--	--	--	89
6Al-0.6Si	--	--	--	1922 $\pm$ 45	--	88
6Al-0.4Si	--	1787 $\pm$ 45	--	--	--	89
6Al-0.9Si	--	--	--	1922 $\pm$ 45	--	88
6Al-2V	--	--	--	1875 $\pm$ 77	--	86
6Al-4V	--	--	--	1830 $\pm$ 77	--	86
6Al-4V	Ti-6Al-4V	--	--	1825	--	93
7Al-4V	--	--	--	1830 $\pm$ 77	--	86
2.8Cr-1.5Fe	Ti-150A	1400	1700	--	--	94
8Mn	C-110M	--	--	1450	--	91
15V-2.5Al	--	--	1480	--	--	94

Latent Heat of Transformation

The alpha-to-beta transformation in titanium at 1620 F (882.5 C) is a first order transformation and is accompanied by a latent heat of transformation. This latent heat has now been determined by direct calorimetric measurements, from cooling curves, and from a thermodynamic treatment of measurements on the hydrogen-equilibrium-pressure/temperature/hydrogen-concentration relationships in the titanium-hydrogen system. Results by the various methods are presented in Table 18. The agreement among the various investigators is not good. The cooling curve method is the least accurate; however, the calorimetric values do not agree either. Tentatively, 1050 cal/mole is suggested as the most probable value for the latent heat of transformation. The hydrogen-pressure data agree with one of the calorimetric values for which published information is available. The hydrogen-pressure method involves a large number of independent measurements that are not likely to be in error by more than ± 10 per cent⁽⁹⁹⁾. Even if the true value were lower by a few hundred calories, the latent heat of transformation for titanium is extremely high for a solid-state transformation in a pure metal.

Heat of Fusion

The latent heat of fusion for titanium has not been determined experimentally. Ogden and Gonser⁽⁹⁸⁾ and McQuillan and McQuillan⁽⁹⁹⁾ have estimated a value of 5 kcal/mole.

Melting Point

The supposedly very high melting point of titanium was the property that first attracted attention to titanium. In 1910, Hunter⁽¹⁰⁰⁾ obtained a melting temperature of about 3270 F (1800 C). This value has been used throughout the years as the melting temperature and still appears in some uncritical tabulations. It is much too high and represents the value for highly contaminated titanium. In 1939, Fast⁽¹⁰¹⁾ reported 3140 ± 18 F (1727 ± 10 C) as the melting point of iodide titanium. This value has persisted and is still often listed as the melting point of titanium. This temperature, however, is still too high. All recent work done with high accuracy shows that the melting point of high-purity titanium is about 3035 ± 18 F (1668 ± 10 C). There are indications that the uncertainty may even be less than 18 F (10 C). Experimental values for the melting point of high-purity titanium are presented in Table 19.

TABLE 18. LATENT HEAT OF TRANSFORMATION OF TITANIUM

Type of Measurement	Latent Heat of Transformation, cal/mole	Investigator	Reference
Hydrogen-equilibrium-pressure/ temperature/hydrogen-concen- tration curves	1050 ^(a)	McQuillan	95
Calorimetric	1046.6	Staskiewicz	78
Calorimetric	880 $\pm$ 5%	Backhurst	96
Calorimetric	950 ^(b)	Kelley	72
Time-temperature cooling curves	1135	Jet Propulsion Laboratory	97
Time-temperature cooling curves	811 $\pm$ 10%	Schofield	79
Time-temperature cooling curves	814 $\pm$ 10%	Schofield	79

(a) This value of 1050 cal/mole has been corrected⁽⁹⁵⁾ for a numerical error in McQuillan's⁽⁸⁶⁾ previous reported value of 678 cal/mole.

(b) Kelley⁽⁷²⁾ estimated this value from the specific-heat measurements of Jaeger, Rosenbohm, and Fonteyne.⁽⁷⁰⁾

TABLE 19. THE MELTING POINT OF HIGH-PURITY TITANIUM

Source	Melting Point	Reference
Oriani and Jones	3041 $\pm$ 9 F (1672 $\pm$ 4 C)	102
Schofield	3029 $\pm$ 9 F (1665 $\pm$ 5 C)	103
Bickerdike and Hughes	3040 $\pm$ 14 F (1671 $\pm$ 8 C)	104
Deardorff and Hayes	3034 $\pm$ 18 F (1668 $\pm$ 10 C)	105
Carlson, et al.	3029 $\pm$ 18 F (1665 $\pm$ 10 C)	106
Farrar and Margolin	3029 $\pm$ 18 F (1665 $\pm$ 10 C)	107

Confusion over the melting point arises because the interstitial elements, oxygen, nitrogen, and carbon, and some high-melting-point metals such as tungsten, tantalum, niobium, etc., raise the melting temperature of titanium. Most other metallic impurities lower the melting point. Consequently, the high melting points reported previously are the result of contamination by interstitials or, perhaps, from tungsten or tantalum support wires used during the determination of the melting point. On the other hand, melting points considerably below 3035 F (1668 C) occur in commercial sponge that is reasonably low in interstitials but that contains metallic impurities. Consequently, the melting temperature of commercial titanium depends upon the type of impurity and the amounts present. Melting temperatures for commercially pure material may range from about 3000 to 3300 F (1650 to 1815 C).

In Table 20 are presented the melting temperatures of some titanium alloys.

Heat of Vaporization and Vapor Pressure

Heat of vaporization of titanium was determined by Carpenter and Mair;⁽¹¹¹⁾ Edwards, Ditmars; and Johnston;⁽⁸⁴⁾ and Blocher and Campbell.⁽²⁴⁾ Mean values of 111,680; 112,715; and 111,186 cal/mole, respectively, were obtained. Differences in the values are due to the various emissivity values used in determining the temperature of the specimen. Carpenter and Mair used the emissivity of beta titanium of Bradshaw⁽¹¹²⁾ and extrapolated it to 2800 F. Because the temperature dependence of Bradshaw's emissivity appears to be incorrect, this extrapolation probably results in an emissivity that is too high. If the Carpenter and Mair data and the Blocher and Campbell data are corrected to a lower and probably more correct emissivity, their results come into better agreement with those of Edwards, et al. The heat of vaporization determined by Edwards, et al., does not depend upon the emissivity chosen. Consequently, the vapor pressures and heat of vaporization of Edwards, et al., appear to be the most accurate. Their value, rounded to 112,500 cal/mole, is recommended for the heat of vaporization.

Table 21 presents the data of each of the investigators. Included in the table are the measured vapor pressures from which the heat of vaporization was calculated. Vapor pressures are summarized by the equations on page 38.

TABLE 20. MELTING POINT OF TITANIUM ALLOYS

Nominal Composition	Alloy Designation	Melting Point, F	Reference
Commercially Pure Titanium	A-40, A-55, A-70	3135	25
Commercially Pure Titanium	Ti-75A	3020 ± 18	65
5Al	--	3074	108
5Al	--	3110	20
10Al	--	3020	108
10Al	--	3092	20
15Al	--	2966	108
20Al	--	2930	108
20Al	--	3074	20
30Al	--	2750	108
30Al	--	2912	20
36Al	--	2600	35
40Al	--	2624	108
40Al	--	2696	20
50Al	--	2588	108
3Al-5Cr	MST-3Al-5Cr	3000-3045	37
4Al-4Mn	C-130AM	2820-3000	25
4Al-4Mn	C-130AM	2910-3090	30, 52
5Al-2.5Sn	A-110AT	2820-3000	25
6Al-4V	MST-6Al-4V	2786-2976	56
2.8Cr-1.5Fe	Ti-150A	2950	109
2.2Fe-2.1Cr-2.0Mo	Ti-140A	3002	37
8Mn	C-110M	2730-2970	25
8Mn	C-110M	2730-2910	37
8Mn	C-110M	2550-2740	52
2Fe-3.8Mn	--	3072	110
4Fe-13.2Mn	--	2592	110
4Fe-28.5Mn	--	2444	110
8Fe-9.6Mn	--	2661	110
8Fe-21.7Mn	--	2160	110
12Fe-13.8Mn	--	2079	110
14Fe-11.8Mn	--	2530	110
14Fe-13.1Mn	--	2352	110
14Fe-18.9Mn	--	2277	110
18Fe-15.7Mn	--	2138	110
20Fe-4.9Mn	--	2066	110
20Fe-8.2Mn	--	2194	110
20Fe-13.2Mn	--	1918	110
20Fe-17.8Mn	--	2032	110
20Fe-23.0Mn	--	2253	110
20Fe-31.5Mn	--	2286	110
30Fe-2.0Mn	--	1900	110
30Fe-6.0Mn	--	2044	110
30Fe-13.4Mn	--	2350	110
30Fe-20Mn	--	2007	110
30Fe-25.6Mn	--	2183	110
10Mo-1 O	--	3290	110
10Mo-4 O	--	3360	110
10Mo-7 O	--	3261	110
10Mo-10 O	--	3281	110
19Mo-1 O	--	3301	110
19Mo-4 O	--	>3990	110
19Mo-7 O	--	3211	110
19Mo-10 O	--	3340	110
31Mo-1 O	--	2581-2750	110
31Mo-4 O	--	3191	110
31Mo-7 O	--	>3990	110
3.14V	--	2966	42
14.8V	--	2921	42
20.0V	--	2894	42
21.0V	--	2876	42
26.1V	--	2863	42
31.0V	--	2870	42

TABLE 21. HEATS OF VAPORIZATION OF TITANIUM

Temperature ^(a) , F	P(atm), x 10 ⁸	-log P	-R ln P, cal/deg/mole	$\Delta(F^\circ - H^\circ)/T$, cal/deg/mole	ΔH° , cal/mole	Average ΔH°
<u>Carpenter and Mair⁽¹¹¹⁾</u>						
2525.0	4.91	7.3089	33.44	33.92	111,680	
2528.6	5.18	7.2857	33.34	33.92	111,650	
2611.4	14.16	6.8489	31.34	33.87	111,250	
2652.8	14.51	6.8383	31.29	33.84	112,610	
2773.8	70.6	6.1512	28.15	33.78	111,230	
2788.8	83.0	6.0809	27.82	33.77	111,110	
2795.0	66.9	6.1847	28.30	33.76	112,200	111,680
<u>Edwards, Ditmars, and Johnston⁽⁸⁴⁾</u>						
2397.2	0.773	8.113	37.124	34.000	112,874	
2463.8	1.864	7.731	35.374	33.956	112,592	
2512.4	3.23	7.492	34.283	33.926	112,613	
2541.2	4.25	7.373	33.736	33.909	112,764	
2553.6	5.05	7.298	33.395	33.905	112,728	
2597.0	7.91	7.103	32.500	33.876	112,706	
2645.6	13.24	6.879	31.476	33.848	112,684	
2715.8	26.3	6.582	30.116	33.808	112,762	112,715
<u>Blocher and Campbell⁽²⁴⁾</u>						
2258.6	0.205	8.688	39.753	34.092	111,506	
	0.228	8.642	39.543	34.092	111,189	
2444.0	2.08	7.682	35.150	33.970	111,491	
	2.42	7.616	34.848	33.970	111,003	
2485.4	3.8	7.420	33.952	33.943	111,076	
	4.1	7.387	33.801	33.943	110,829	
2649.2	17.9	6.747	30.872	33.846	111,768	
	18.6	6.730	30.794	33.846	111,633	
2838.2	128	5.893	26.964	33.750	110,621	
	124	5.907	27.029	33.750	110,734	111,186

(a) Temperature converted from absolute scale, K.

<u>Investigators</u>	<u>Reference</u>	<u>Vapor Pressure, atmospheres</u>	<u>Temperature Range, K</u>
Edwards, Johnston and Ditmars	84	$\log P \approx 7.7960 - \frac{24,644}{T} - 0.000227 T$	1587 - 1698
Blocher and Campbell	24	$\log P \approx 7.782 - \frac{24,215}{T} - 0.000230 T$	1500 - 1800
Carpenter and Mair	111	$\log P \approx 7.30 - \frac{24,200}{T}$	1650 - 1810

Boiling Temperature

The boiling temperature of titanium has never been determined experimentally. McQuillan and McQuillan⁽⁹⁹⁾ and Blocher, et al.,⁽²⁴⁾ have calculated values from the heat of fusion and vapor pressure of titanium, respectively. Assuming a heat of fusion of 5 kcal/mole, McQuillan calculated 5840 F (3230 C). Blocher, et al., estimated a value of 5900 F (3260 C).

ELECTRICAL PROPERTIES

The electrical properties of titanium are interesting. Titanium has a very high electrical resistance for a pure metal. At very low temperatures, it is a superconductor. In addition, it has a positive Hall coefficient, which is unusual for metals.

Electrical Resistivity

The electrical resistivity of titanium is about 42 to 48 microhm-cm. This is very high for a metal, although the resistivity of the other members of the IV A sub-group, zirconium and hafnium, are comparable.⁽¹¹³⁾ Other structural metals such as iron and aluminum have a resistivity of about 9.8 and 2.82 microhm-cm, respectively. Stainless steel has a resistivity of about 80 microhm-cm.⁽¹¹⁴⁾

Impurities increase the resistivity of titanium rapidly. Values as low as 42 microhm-cm have been obtained on iodide titanium,^(12, 81) although values of 46 to 48 microhm-cm are usually obtained. The true resistivity of titanium is probably the lowest value, 42 microhm-cm. Results are summarized in Table 22. Resistivity for commercially pure titanium is also included. Recent commercial grades of titanium have a resistivity in the

TABLE 22. ELECTRICAL RESISTIVITY OF UNALLOYED TITANIUM
AT ROOM TEMPERATURE

Material	Alloy Designation	Resistivity, microhm-cm,	Temperature, F	Reference
Iodide	--	42.0	--	12
Iodide	--	46.2	--	115
Iodide	--	46.7	--	113
Iodide 99.96%Ti	--	54.98	77	116
Iodide 99.96%Ti	--	52.7	73	8
Iodide 99.8 to 99.95%Ti	--	46.7	68	117
Iodide 99.99%Ti	--	49.6	68	118
Iodide	--	42.1	68	82
Sponge ^(a)	--	60	--	119
Sponge ^(a)	--	53.9	68	11
Sponge 99.2%Ti	A-55	48.6	68	25
Sponge 99.0%Ti	A-70	54.8	68	25
Sponge 99.2%Ti	RS-55	61	68	27
Sponge 99.2%Ti	MST Grade III	55	68	28

(a) Purity not known.

range of 48 to 61 microhm-cm. About 55 microhm-cm would be typical for commercially pure titanium.

The temperature dependence of the resistivity of titanium is unusual. The resistivity increases linearly from room temperature up to about 750 F (400 C). Above 750 F (400 C), the change in resistivity with increasing temperature begins to decrease and becomes very low as the transformation temperature of 1620 F (882.5 C) is reached. At the transformation temperature, the resistivity drops below the value for alpha titanium. Above the transformation temperature, the curve for beta titanium shows that the resistivity increases with increasing temperature but the slope of the curve is not steep. These features are illustrated in Figure 4.

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FIGURE 4. THE ELECTRICAL RESISTIVITY OF HIGH-PURITY TITANIUM AT VARIOUS TEMPERATURES

The low temperature coefficient of beta titanium suggests unusual behavior for a metal. In a normal pure metal, the resistivity approaches zero at a temperature of absolute zero. However, if the resistivity curve for beta titanium is extrapolated to below the transformation temperature where pure beta titanium is not stable, it appears that the resistivity would not extrapolate to zero at a temperature of absolute zero. Ames and McQuillan⁽¹¹⁵⁾ examined beta alloys stabilized with niobium and the data tended to support this conclusion. Later work by Ames and McQuillan⁽¹²⁰⁾ on beta-stabilized Ti-H alloys showed that the resistivity of beta titanium decreases from the transition temperature of 1620 F (882.5 C) to a minimum

of about 140 microhm-cm at 1290 F (700 C), and then increased again as the temperature was lowered to 750 F (400 C). The unusual electrical behavior of beta titanium is further demonstrated by the fact that, within certain composition ranges, the temperature coefficient of resistivity is negative in the Ti-Mo,⁽¹²¹⁾ Ti-V,⁽¹²²⁾ and Ti-Nb⁽¹¹⁵⁾ alloy systems. It has recently been shown also that alpha titanium alloys containing aluminum above about 8 weight per cent also have a negative temperature coefficient of resistivity.⁽¹²³⁾

Data on the resistivity of commercial titanium alloys and other binary alloys are presented in Table 23. Resistivity at various temperatures for unalloyed and alloyed titanium is listed in Table 24. Figure 5 shows the data for resistivity as a function of temperature for commercially pure titanium and for the commercial alloys 6Al-4V, C-130AM, A-110AT, and C-110M.

The resistivity of an alloy is determined by its electronic structure, but the effect of alloying additions on the electronic structure of titanium is not known at present. However, it has been found experimentally that in solid solutions of alpha titanium the rate of increase in resistivity with increasing alloying addition is very large compared with that for dilute solutions in such metal-base systems as copper and aluminum.⁽¹¹³⁾ Data additional^(113, 120) to those in Table 23 are presented in Figures 6 to 11, inclusive, for titanium binary alloys. Figure 6 summarizes these data for various compositions at room temperature; whereas, Figures 7, 8, 9, 10, and 11 show how resistivity varies with temperature.

McQuillan and Ames⁽¹¹³⁾ did not find the change in the slope of the resistivity-composition curve observed by Denney⁽⁸⁾ as occurring at 1.8 weight per cent aluminum at room temperature. The data of Munster, et al.,⁽¹²³⁾ indicate that there may be a break in the curve at about this composition.

Thermoelectric Force

Measurements of the thermoelectric force have been made on couples of Ti-Pt^(11, 82, 127, and 128) and Ti-Au.^(70, 129) For titanium alloys, the thermoelectric power of a couple consisting of copper and C-130 AM was determined at low temperatures, 20 to 300 K,⁽⁶⁶⁾ (-420 to 80 F).

Figure 12 shows the emf developed in a titanium-platinum couple as determined by Worner.⁽⁸²⁾ Iodide titanium was used. The measurements were made during both heating and cooling in the range 78 to 1725 F (25 to 940 C) and are shown by curve A in Figure 12. Inflections in the curve occur at approximately 390 and 930 F (200 and 500 C).

TABLE 23. ELECTRICAL RESISTIVITY OF TITANIUM ALLOYS AT ROOM TEMPERATURE

Nominal Composition	Alloy Designation	Resistivity, microhm-cm.	Remarks	Reference
1.186Ag	--	55.3	--	8
2.422Ag	--	60.6	--	8
3.381Ag	--	64.1	--	8
4.266Ag	--	63.9	--	8
5.545Ag	--	71.0	--	8
6.450Ag	--	75.9	--	65
7.573Ag	--	73.4	--	65
8.457Ag	--	79.1	--	30
0.186Al	--	78.0	--	119
0.260Al	--	56.2	--	8
0.486Al	--	61.8	--	8
0.833Al	--	69.4	--	8
0.964Al	--	72.2	--	8
1.073Al	--	81.3	--	8
1.245Al	--	80.8	--	8
1.515Al	--	88.9	--	8
1.798Al	--	89.6	--	8
1.990Al	--	92.0	--	8
2.514Al	--	96.3	--	8
2.64Al	--	128.0	--	119
2Al-2Fe	MST-2Al-2Fe	118	--	30
2Al-2Fe	MST-2Al-2Fe	120	--	52
2Al-2Fe	MST-2Al-2Fe	120-125	--	29
2Al-4V	--	108	As received	30
3Al-5Cr	MST-3Al-5Cr	150	--	28
4Al-4Mn	C-130AM	146.1	--	25
5Al-2.5Sn	A-110AT	157.3	--	25
6Al-4V	Ti-6Al-4V	176	--	56
0.1B	--	58	--	119
0.5B	--	58	--	119
0.37Be	--	66	--	119
0.5Be	--	66	--	119
1.07Be	--	65	--	119
1.28C	--	61	--	119
38Co	--	110	Pressed	40
38Co	--	51.4	Heat Treated	40
2.8Cr-1.5Fe	Ti-150A	60	--	30, 37, 52, 93, 124
2.2Fe-2.1Cr-2.0Mo	Ti-140A	79	--	29, 52, 65
2.5Fe-2.5V	MST-2.5Fe-2.5V	78	--	30
2.5Fe-2.5V	MST-2.5Fe-2.5V	80	--	52
2.5Fe-2.5V	MST-2.5Fe-2.5V	80-85	--	29
0.402Ga	--	57.6	--	8
0.914Ga	--	63.6	--	8
0.947Ga	--	67.1	--	8
1.519Ga	--	77.0	--	8
1.536Ga	--	81.6	--	8

TABLE 23. (Continued)

Nominal Composition	Alloy Designation	Resistivity, microhm-cm.	Remarks	Reference
2.160Ga	--	95.5	--	8
2.261Ga	--	94.3	--	8
2.354Ga	--	95.1	--	8
2.641Ga	--	92.9	--	8
2.937Ga	--	96.7	--	8
3.132Ga	--	96.5	--	8
0.98In	--	92	--	119
3.53Mn	--	88	--	119
4.30Mn	--	93	--	119
4.74Mn	--	102	--	125
5.62Mn	--	116	--	119
6.02Mn	--	105	--	119
7.22Mn	--	118	--	119
8Mn	C-110M	90.7	--	25
8Mn	--	95	As received	30
8Mn	--	94	As received	30
10.21Mo	--	80	--	119
12.52Mo	--	98	--	119
38Ni	--	165	Pressed	40
38Ni	--	160	Heat treated	40
0.5Si	--	63	--	119
1.06Si	--	95	--	119
0.5V	--	73	--	119
1.20V	--	72.5	86.9%H. R. (a)	42
2.5V	--	87.8	85.5%H. R.	42
4.2V	--	107.3	90.6%H. R.	42
7.6V	--	121.2	85.1%H. R.	42
14.8V	--	182.6	77.4%H. R.	42
20.0V	--	196.6	92.2%H. R.	42
21.0V	--	172.4	77.8%H. R.	42
21.0V	--	173.4	77.8%H. R.	42
21.0V	--	175.5	77.8%H. R.	42
26.1V	--	158.6	87.3%H. R.	42
26.1V	--	157.4	87.3%H. R.	42
31.0V	--	153.8	89.0%H. R.	42
1.20V	--	68.6	800C anneal	42
2.5V	--	86.1	800C anneal	42
4.2V	--	81.0	800C anneal	42
5.0V	--	87.0	--	119
7.6V	--	87.8	800C anneal	42
7.6V	--	102.0	800C anneal	42
14.8V	--	111.1	800C anneal	42
21.0V	--	171.2	800C anneal	42
10.0Zr	--	76.0	--	119
20.0Zr	--	80.0	--	119
30.0Zr	--	94.0	--	119
40.0Zr	--	115.0	--	119

(a) H. R. = hot rolled.

TABLE 24. ELECTRICAL RESISTIVITY OF TITANIUM AND TITANIUM ALLOYS AT VARIOUS TEMPERATURES

Alloy Composition, weight per cent	Designation	Resistivity, microhm-cm, at Indicated Temperature, F																Remarks	References
		-400	-300	-200	-100	32	68	200	400	600	800	1000	1200	1400	1600	1800	2000		
Iodide Ti	—		12.3	23.0	35.6	52.3	56.7	73.4	98.6	123.6	145.0	161.8	175.2	185.0	189.2	172.9	173.7	—	116
Commercial Ti	—		15.2	25.3	35.5	48.8	52.2	65.7	85.9	105.8	125.4	140.3	152.2	161.0	169.5	152.6	154.5	—	116
Commercial Ti i	A-55						48.6	62.6	82.5	101.4	117.7	132.6	145.3					—	25
Commercial Ti i	A-70						54.8	67.2	86.8	105.4	122.3	136.9	148.8	159.2				—	25
Commercial Ti	—		18.1	27.0	36.8	50.0	53.3	67.9											11
Commercial Ti	—		18.7	28.7	38.5	51.8	55.2	68.5	88.5	106.9	124.2	140.0	152.3	162.0					11
Commercial Ti	—						78.5	92.2	111.2	128.9	144.5	157.2	168.1	177.8	181.8	178.2	175.0	Wire	126
Commercial Ti	—						49.0	62.3	82.4	102.8	121.9	137.5	150.8	161.3				Annealed 12 hr 1200- 1300 F, data on heating	118
Commercial Ti	—						49.9	63.1	82.9	102.3	121.8	138.0	151.1	161.4				Annealed 12 hr 1200- 1300 F, data on cooling	118
Commercial Ti	—						51.1	64.3	84.5	104.5	123.8	139.8	152.7	162.8				Annealed 10 hr 1247- 1292 F, data on heating	118
Commercial Ti	—						57.5	71.0	91.0	111.3	128.2	142.8	154.2	162.8				Annealed 8 hr 1300- 1337 F, data on heating	118
2Al-4V	—			85	100		115											Heat treated	30
2Al-4V	—			88	98		114											Heat treated	30
2Al-4V	—			84	98		115											Heat treated	30
4Al-4Mn	C-130AM	144	149	154	159		167												67
4Al-4Mn	C-130AM						146.1	151.4	158.4	162.2	168.1	170.0	159.3	157.8	152.6	148.3	151.0	—	25
5Al-2.5Sn	A-110AT						157.3	162.5	170.7	177.5	182.8	186.0	187.9	188.5					25
8Mn	C-110M						90.7	101.6	117.3	131.0	141.3	149.0	154.7	156.2	153.9	155.3	157.0	—	25
8Mn				166.0	178.0		174.0											Heat treated	30
8Mn					177.0		175.0												30
6Al-4V	Ti-6Al-4V						176	179	183	186	188	189	189	187	182				56

FIGURE 5. THE EFFECT OF TEMPERATURE ON THE ELECTRICAL RESISTIVITY OF SOME COMMERCIAL ALLOYS(25, 67)

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FIGURE 6. THE EFFECT OF VARIOUS ADDITION ELEMENTS ON THE RESISTIVITY OF α -TITANIUM AT ROOM TEMPERATURE⁽¹¹³⁾

FIGURE 7. THE EFFECT OF TEMPERATURE ON THE RESISTIVITY OF A SERIES OF α -PHASE TITANIUM-ALUMINUM ALLOYS⁽¹¹³⁾

FIGURE 8. THE EFFECT OF TEMPERATURE ON THE RESISTIVITY OF A SERIES OF α -PHASE TITANIUM-TIN ALLOYS⁽¹¹³⁾

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FIGURE 9. THE EFFECT OF TEMPERATURE ON THE RESISTIVITY OF A SERIES OF TITANIUM-ZIRCONIUM ALLOYS⁽¹¹³⁾

FIGURE 10. THE EFFECT OF TEMPERATURE ON THE RESISTIVITY OF α -PHASE TITANIUM-OXYGEN, TITANIUM-COPPER, AND TITANIUM-NIOBIUM ALLOYS⁽¹¹³⁾

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FIGURE 11. THE RESISTIVITY OF β -PHASE TITANIUM-HYDROGEN ALLOYS AT VARIOUS TEMPERATURES⁽¹²⁰⁾

Note: The broken lines represent linear extrapolation of the curves toward pure titanium and toward the hypothetical saturated alloy, showing a composition corresponding to TiH . The hydrogen concentration is expressed in terms of the ratio of the number of hydrogen atoms in solution per titanium atom.

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FIGURE 12. ELECTROMOTIVE FORCE OF TITANIUM-PLATINUM COUPLE ($\phi_{Ti/Pt}$) VERSUS TEMPERATURE⁽⁸²⁾

Cold junction temperature = 0 C.

Curve A: Results of direct measurement.

Curve B: Deduced from Figure 13 by graphical integration.

Details of curve A (see inset) in range 850 to 920 C.

Figure 13 presents the results of the thermoelectric power determinations. The slight inflections shown in Figure 12 are much more pronounced in Figure 13.

Figure 14, also derived by Worner⁽⁸²⁾ shows some thermoelectric functions of titanium in the range 32 to 1830 F (0 to 1000 C) and, also, clearly indicates the transformation temperature of titanium.

In Figure 15 and Table 25, Greiner and Ellis⁽¹¹⁾ show the thermoelectric force of a titanium-platinum couple from -330 to 1830 F (-200 to 1000 C). In this investigation, titanium sponge was used. A plot of these data would lie below those of Worner's.

Tyler and Wilson⁽⁶⁶⁾ measured the thermoelectric power of the C-130AM-Cu couple, and they were able to calculate the absolute thermoelectric power of C-130AM. Their results were obtained in the temperature range from 17 to 278 K (-425 to 40 F) and are presented in Table 26. These data indicate a low density of free carriers as do the high electrical resistivity and low thermal conductivity. The negative sign of the absolute thermoelectric power indicates that electric conduction is primarily by electrons rather than holes.

Superconductivity

Titanium becomes superconducting at a temperature below about 1 K (-457 F). The results of superconductivity measurements of high-purity titanium are given in Table 27. Complete agreement of the critical values has not been obtained. The disagreement in results can probably be attributed to differences in the preparation of the sample, because the critical temperature is apparently affected by residual strains.

Hall Coefficient

The Hall coefficient for pure titanium was found to be positive by several investigators.^(8, 53, 134) This would seem to indicate that electrical conduction in titanium is primarily by positive holes. However, the positive Hall coefficient may result from the anisotropic nature of the titanium because the thermoelectron data indicate conduction by electrons, at least for C-110AM.

Table 28 contains the values obtained for pure titanium. The agreement between the various workers is not good. Foner⁽¹³⁴⁾ found that non-metallic impurities greatly affect the value of the Hall coefficient. A specimen containing about 0.34 weight per cent oxygen had a negative Hall coefficient.

FIGURE 13. THERMOELECTRIC POWER OF TITANIUM-PLATINUM COUPLE ($P_{Ti/Pt}$) VERSUS TEMPERATURE⁽⁸²⁾

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FIGURE 14. THERMOELECTRIC COEFFICIENTS AND ABSOLUTE THERMOELECTRIC POWER VERSUS TEMPERATURE⁽⁸²⁾

- Curve A: Peltier coefficient, $\pi_{Ti/Pt}$.
 Curve B: Difference between Thomson coefficients of titanium and platinum ($\sigma_{Ti} - \sigma_{Pt}$).
 Curve C: Absolute thermoelectric power of titanium, S_{Ti} .

FIGURE 15. THERMOELECTRIC FORCE OF THE TITANIUM-PLATINUM COUPLE⁽¹¹⁾

Reference junction at 0 C.

TABLE 25. THERMOELECTRIC FORCE OF TITANIUM VERSUS PLATINUM
OBTAINED WITH COMMERCIALY PURE TITANIUM

Temperature		Thermoelectric Force, millivolts	Temperature		Thermoelectric Force, millivolts
F	C		F	C	
-300	-184	-0.5	600	316	3.9
-200	-139	-0.6	800	427	5.2
-100	-73	-0.4	1000	538	6.4
32 ^(a)	0	0	1200	649	7.6
68	20	0.2	1400	760	9.0
200	93	1.0	1600	871	10.6
400	204	2.5	1800	982	12.5

(a) Reference temperature.

TABLE 26. THERMOELECTRIC POWER OF TITANIUM ALLOY C-130AM-CU
COUPLE VERSUS TEMPERATURE

Temperature, K	Thermoelectric Power of C-130AM-Cu couple, microvolts/K	Absolute Thermoelectric Power of Cu	Absolute Thermoelectric Power of C-130AM
17.18	0.58	+0.35	-0.23
19.91	0.72	+0.45	-0.27
23.35	1.06	+0.55	-0.51
42.37	2.87	+1.05	-1.82
65.26	3.74	+1.40	-2.34
78.76	4.00	+1.40	-2.60
82.59	4.08	+1.40	-2.68
100.6	4.20	+1.30	-2.90
141.3	4.55	+1.10	-3.45
196.1	5.43	+1.40	-4.03
204.1	5.45	+1.40	-4.05
276.3	6.57	+1.70	-4.87
278.0	6.62	+1.70	-4.92

TABLE 27. SUPERCONDUCTIVITY OF TITANIUM

Material Purity, per cent Ti	Condition	Critical Temperature, T_C K	Temp. Coefficient of the Magnetic Field, $(\partial H/\partial T)_{T-T_C}$	Threshold Magnetic Field, H_0 , gauss	Reference
Iodide (99.95)	Crystal bar, unannealed	0.53	470	--	130
Iodide (99.95)	Crystal bar, annealed	0.558	450	--	131
Iodide (99.94)	Crystal bar, annealed	0.387	89.5	20	132
Iodide (99.98)	Cold swaged wire, unannealed	0.37	465	86	133
Iodide (99.99+)	Crystal bar, unannealed	0.49	400	--	133

TABLE 28. HALL COEFFICIENTS FOR TITANIUM AND TITANIUM ALLOYS

Composition	Hall Coefficient, volt-cm-amp ⁻¹ -oersted ⁻¹	Investigator	Reference
Iodide Ti	$+1.82 (\pm 0.2) \times 10^{-13}$	Denney	8
Ti	$+3.0 (\pm 0.1) \times 10^{-13}$	Scovil	135
Ti	$+0.95 \times 10^{-13}$	Foner	134
0.83 Al	$+1.90 \times 10^{-13}$	Denney	8
1.99 Al	$+1.73 \times 10^{-13}$	Denney	8
2.51 Al	$+1.51 \times 10^{-13}$	Denney	8
2.42 Ag	$+1.68 \times 10^{-13}$	Denney	8
7.57 Ag	$+1.44 \times 10^{-13}$	Denney	8

The Hall coefficients for alloys containing aluminum and silver are also presented in Table 28. The additions of aluminum and silver had little effect on the Hall coefficient of unalloyed titanium.

Magnetoresistance

The change in resistance of unalloyed titanium and of alloys containing aluminum, silver, and gallium in a magnetic field has been measured. The magnetoresistance coefficients, B_t , of titanium and titanium alloys for current normal to the magnetic field are presented in Table 29.

The value of 6.6×10^{-13} oersted⁻² for the B_t of pure titanium is larger than those for the alkali metals, lithium, sodium, etc., and the noble metals, copper, silver, and gold. It is less, however, than the values for the less metallic elements such as antimony, arsenic, bismuth, cadmium, and barium.

MAGNETIC PROPERTIES

Magnetic susceptibility data are useful in studying the electronic structure of metals. More data are needed for unalloyed titanium at low temperatures and for titanium alloys at both low and high temperatures.

Magnetic Susceptibility

Titanium is paramagnetic and the specific magnetic susceptibility at room temperature appears to be well established as

$$3.17 \times 10^{-6} (\pm 0.03 \times 10^{-6}) \text{ emu g}^{-1}.$$

Titanium is similar with respect to the other transition metals in that it has a positive temperature coefficient of susceptibility.⁽¹³⁶⁾ The susceptibility increases from $3.17 \times 10^{-6} \text{ emu g}^{-1}$ at room temperature to 5.2 emu g^{-1} at 2000 F.⁽¹³⁷⁾

Reekie and Yao⁽¹³⁸⁾ investigated the anisotropic nature of magnetic susceptibility. A cold reduction of 80 per cent produced titanium that was isotropic with respect to magnetic susceptibility. The results of Reekie and Yao⁽¹³⁸⁾ are summarized as follows:

TABLE 29. MAGNETORESISTANCE OF TITANIUM
AND TITANIUM ALLOYS⁽⁸⁾

Composition of Alloy, weight per cent	Magneto-Resistance Coefficient, $B_t \times 10^{13}$, oersted ⁻²
Pure Ti	6.6
0.26 Al	7.0
0.83 Al	8.6
1.07 Al	8.8
1.25 Al	9.2
1.52 Al	8.8
1.80 Al	3.9
1.99 Al	2.5
2.51 Al	1.4
3.97 Al	1.5
0.40 Ga	6.8
0.91 Ga	7.2
0.95 Ga	7.0
1.52 Ga	7.2
1.54 Ga	7.5
2.16 Ga	6.9
2.35 Ga	5.6
2.64 Ga	2.6
2.94 Ga	1.4
1.19 Ag	4.0
2.42 Ag	1.9
3.38 Ag	1.6
4.27 Ag	1.1
5.55 Ag	1.7
6.45 Ag	1.4
7.57 Ag	1.5
8.46 Ag	1.4

	Magnetic Susceptibility, emu g^{-1}		
	Iodide Ti, Single Crystal	Sponge Ti, (a) Cold Rolled	Sponge Ti, Compressed
χ_{11} parallel to c axis	$3.35_0 \times 10^{-6}$	$3.34_0 \times 10^{-6}$	$3.33_7 \times 10^{-6}$
χ_1 perpendicular to c axis	$3.07_0 \times 10^{-6}$	$3.08_7 \times 10^{-6}$	$3.08_2 \times 10^{-6}$
$d\chi/dt$ temperature coefficient	--	--	$0.0011_3 \times 10^{-6}$
$(\chi_{11} - \chi_1)$ anisotropy	$0.28_0 \times 10^{-6}$	$0.25_3 \times 10^{-6}$	0.25×10^{-6}
$\overline{\chi}$ average	$3.16_3 \times 10^{-6}$	$3.17_3 \times 10^{-6}$	$3.16_7 \times 10^{-6}$

(a) Composition of commercial titanium: C, 0.074; N, 0.057; Fe, 0.15; Cu, 0.005; Mg, 0.003; O, 0.087; and H, 0.007 weight per cent.

Reekie and Yao recommended $3.17 \times 10^{-6} (\pm 0.03 \times 10^{-6}) \text{ emu g}^{-1}$ for the magnetic susceptibility of titanium at room temperature. Most of their work was done on commercially pure titanium, but the results were checked closely with single crystals from an iodide titanium bar. Trzebiatowski and Stalinski,⁽¹³⁶⁾ working with sponge titanium, and Squire and Kaufmann,⁽¹³⁷⁾ working with impure material, found values that checked very well with the recommended value. However, Denney's⁽⁸⁾ value of $3.31 \times 10^{-6} \text{ emu g}^{-1}$ appears to be high. The values reported in the ASM Handbook⁽⁷¹⁾ are completely out of line with other values and should be disregarded. It may be concluded that the magnetic susceptibility of titanium is not greatly affected by nonmagnetic impurities.

Values for the magnetic susceptibility for titanium and for titanium alloys are presented in Table 30. Denney⁽⁸⁾ found that aluminum up to 2.5 weight per cent and silver up to 10.5 weight per cent had little effect on the susceptibility of titanium. However, Munster, et al.,⁽¹²³⁾ found a minimum at about 12 weight per cent aluminum, a maximum at about 22 weight per cent aluminum, and a decrease between 22 and 40 weight per cent aluminum.

Trzebiatowski and Stalinski⁽¹³⁶⁾ investigated the effect of hydrogen and deuterium on the susceptibility of titanium. Their results are presented in Figure 16. In the alpha solid-solution range and in the range of alpha plus TiH, the susceptibility is approximately proportional to the hydrogen concentration, but the temperature increment of susceptibility decreases slightly. The properties of the titanium deuterides do not differ appreciably from those of the corresponding hydrides.

TABLE 30. MAGNETIC SUSCEPTIBILITY OF TITANIUM AND TITANIUM ALLOYS

Composition, Weight Per Cent	Magnetic Susceptibility, cgs units x 10 ⁶ , at Indicated Temperature, F											Reference
	-300	-100	32	68	77	81	400	800	1200	1600	2000	
Iodide Ti	-	-	-	-	3.17	-	3.36	-	-	-	-	138
Iodide Ti	-	-	-	-	3.31	-	-	-	-	-	-	8
Sponge Ti (99.5%)	3.03	3.09	-	3.18	-	-	3.39	-	-	-	-	136
Ti	1.70	1.25	1.25	1.25	-	-	-	-	-	-	-	71
Ti-0.83Al	-	-	-	-	3.27	-	-	-	-	-	-	8
Ti-1.0Al	-	-	-	2.75	-	-	-	-	-	-	-	123
Ti-1.52Al	-	-	-	-	3.24	-	-	-	-	-	-	8
Ti-1.99Al	-	-	-	-	3.22	-	-	-	-	-	-	8
Ti-2.51Al	-	-	-	-	3.21	-	-	-	-	-	-	8
Ti-3Al	-	-	-	2.50	-	-	-	-	-	-	-	123
Ti-7Al	-	-	-	2.25	-	-	-	-	-	-	-	123
Ti-8Al	-	-	-	4.00	-	-	-	-	-	-	-	123
Ti-9Al	-	-	-	2.35	-	-	-	-	-	-	-	123
Ti-12Al	-	-	-	2.25	-	-	-	-	-	-	-	123
Ti-18Al	-	-	-	4.60	-	-	-	-	-	-	-	123
Ti-20Al	-	-	-	4.40	-	-	-	-	-	-	-	123
Ti-22Al	-	-	-	5.00	-	-	-	-	-	-	-	123
Ti-30Al	-	-	-	3.50	-	-	-	-	-	-	-	123
Ti-36Al	-	-	-	3.95	-	-	-	-	-	-	-	123
Ti-40Al	-	-	-	3.15	-	-	-	-	-	-	-	123
Ti-2.42Ag	-	-	-	-	3.11	-	-	-	-	-	-	8
Ti-7.57Ag	-	-	-	-	3.14	-	-	-	-	-	-	8
Ti-10.5Ag	-	-	-	-	3.02	-	-	-	-	-	-	8
Ti-2.5H-2Si	-	-	-	-	-	3.78	-	-	-	-	-	139
Ti-2Si	3.1	3.2	-	3.3	-	-	3.4	3.7	4.0	4.5	5.2	137
Ti-2Si	-	-	-	-	-	3.2	-	-	-	-	-	139

FIGURE 16. SUSCEPTIBILITY ISOTHERMS OF THE TITANIUM-HYDROGEN SYSTEM⁽¹³⁶⁾

The susceptibility measurements suggest that TiH_2 is antiferromagnetic with a transition temperature of 300 K (80 F).⁽¹¹⁴⁾ Wohlfarth⁽¹⁴⁰⁾ offered an explanation of the antiferromagnetism which was based on the superexchange between Ti atoms through the intermediary of molecular hydrogen.

Magnetic Permeability

Commercially pure titanium (such as Rem-Cru's A-70) has a magnetic permeability of 1.00005 at 20 oersteds.⁽²⁵⁾ Similar values are given for the alloys that are produced by Rem-Cru; these are included in Table 31.

OPTICAL PROPERTIES

Emissivity

There are very little data on the emissivity of titanium in the range from room temperature to about 1000 F (540 C). This temperature range is

TABLE 31. MAGNETIC PERMEABILITY OF TITANIUM
AND TITANIUM ALLOYS

Nominal Composition	Alloy Designation	Permeability	Reference
Ti	--	1.0001	141
Commercial Ti	A-70	1.00005(a)	25
Commercial Ti	Ti-75A	1.0001	26
4Al-4Mn	C-130AM	1.00005(a)	25
5Al-2.5Sn	A-110AT	1.00005(a)	25
8Mn	C-110M	1.00005(a)	25

(a) At 20 oersteds, hot rolled and annealed.

of potential interest to aircraft producers. Most of the data available are in the alpha titanium temperature region, near the transformation temperature, and in the beta titanium temperature range.

Figure 17 shows the emissivity of unalloyed titanium versus temperature in the range from about 100 to 1000 F (40 to 540 C). The emissivity increases from about 0.15 at 250 F (120 C) to about 0.30 at 1000 F (540 C). Although Bradshaw⁽¹¹²⁾ found a constant emissivity of 0.459 for alpha titanium in the temperature range from 1490 to 1598 F (810 to 870 C), a positive temperature coefficient is more probable.

Figure 17 also shows the effect of surface contamination on the emissivity of titanium. Emissivity is higher for oxidized surfaces than for clean surfaces. Blue oxidation may be less emissive above 1000 F (540 C). The higher emissivity of the oxidized surface explains the apparently high values obtained on impure material by Michels and Wilford.⁽¹²⁶⁾

Table 32 contains the spectral and total emissivity of unalloyed titanium, both for the alpha and beta phases.

Most of the data on emissivity are for beta titanium. Apparently the emissivity attains a maximum value at about the transformation temperature 1620 F (882.5 C). The emissivity decreases with increasing temperature within the beta temperature range. However, the emissivity appears to level off to about 0.40 at a temperature of about 2700 F (1485 C).

Figure 18 contains curves for emissivity versus temperature from data by various investigators. All of the data show the same trends with considerable variation near the transformation temperature. Above about 2000 F (1040 C), the values for iodide titanium determined by Went⁽¹⁴²⁾ and by Powers and Wilhelm⁽⁴²⁾ in their highest vacuum agree generally, although the slope of their curves is opposite. The average emissivity value found by Edwards, et al.,⁽⁸⁴⁾ is not shown in Figure 18, but this value agrees well with other iodide titanium values at about 2550 F (1400 C). Likewise, Blocher and Campbell's⁽²⁴⁾ single value of emissivity for commercially pure titanium agrees with Went's data for iodide titanium. The temperature dependence of Bradshaw's⁽¹¹²⁾ emissivities for magnesium-reduced titanium appears to be in error, although the standard deviation of his results is quite low (0.01).

The results of Powers and Wilhelm⁽⁴²⁾ in Figure 18 show that the oxidation of the surface that occurred in the poorer vacuum increased the emissivity of beta titanium similarly to that for alpha titanium in Figure 17. The less pure DuPont sponge titanium had higher emissivities than iodide titanium, even in better vacuum.

The only data available for titanium alloys are those of Powers and Wilhelm⁽⁴²⁾ for Ti-V alloys in the beta temperature range. These data are

FIGURE 17. EMISSIVITY OF UNALLOYED TITANIUM ⁽²⁵⁾

Courtesy of Rem-Cru Titanium, Inc.

TABLE 32. EMISSIVITY OF TITANIUM

Material	Emissivity	Temperature, F	Phase	Reference
	<u>Spectral Emissivity</u> ($\lambda = 0.65 \mu$)			
Iodide	0.533	1615	Alpha	142
	0.523	1635	Beta	
	0.502	1975	Beta	
	0.480	2155	Beta	
	0.450	2335	Beta	
	0.419	2515	Beta	
Iodide, 99.88 Ti	0.43	2397	Beta	84
	0.44	2464	Beta	
	0.42	2512	Beta	
	0.45	2541	Beta	
	0.43	2556	Beta	
	0.43	2597	Beta	
	0.41	2646	Beta	
	0.41	2716	Beta	
	Avg. 0.43	2397 - 2716	Beta	
Mg-reduced, 99.52 Ti	0.459	1490 - 1598	Alpha	112
	0.484	1742	Beta	
	0.482	1832	Beta	
	0.479	2012	Beta	
	0.476	2192	Beta	
	0.473	2372	Beta	
	0.471	2462	Beta	
Comm. pure Ti	0.63	1430 - 2060	--	126
Comm. pure Ti	0.49	2060	Beta	24
	<u>Total Emissivity</u>			
Comm. pure Ti	0.31	81	Alpha	62, 126
	0.33	1431	Alpha	
	0.40	1881	Beta	
Iodide	0.30	1316	Alpha	143
Iodide	0.32	1348	Alpha	111

FIGURE 18. EMISSIVITIES OF TITANIUM⁽⁴²⁾

Courtesy of Iowa State College.

presented in Figure 19. Like unalloyed titanium, the alloys show considerable variation at the lower and upper ends of the temperature range investigated. In general, the alloys show the same temperature dependence of emissivity as unalloyed titanium. The emissivity is changed very little by the addition of up to 26 weight per cent vanadium.

Optical Constants and Reflectance

The optical properties of a titanium film were determined by Hass and Bradford.⁽¹⁴⁴⁾ Data are presented in Table 33 for the refractive index, n ; absorption coefficient, k ; and the reflectance for normal incidence, R .

ELECTRONIC PROPERTIES

The physical, and other, properties of a metal are fundamentally determined by its electronic structure. The structure of the titanium atom is well known, but little is known about the electronic structure of solid titanium. Because not enough is known to calculate physical properties from the electronic structure of the solid, the physical properties should be determined more accurately on purer materials over greater temperature and composition ranges to help elucidate the electronic structure. As can be observed in the foregoing parts of this report, data are now available in some areas. However, considerably more work is needed.

Work Function

The work function is the energy necessary to remove an electron from the surface of a metal. At high temperatures, a metal can emit electrons into empty space by the thermionic effect. At ordinary temperatures, metals can also emit electrons if they are illuminated by the proper light. This is called the photoelectric effect.

The work function of titanium has been investigated by the photoelectric effect, by contact potential measurements, and by vapor pressure of electrons over heated titanium. Table 34 presents the observed values of the work function.

Jain and Krishan⁽¹⁴⁵⁾ measured the thermionic emission of electrons from titanium. They obtained values for the constants A and ϕ in the following equation for the saturation equilibrium current:

$$i = AT^2 e^{-\phi/kT} ,$$

FIGURE 19. EMISSIVITIES OF TITANIUM-VANADIUM ALLOYS⁽⁴²⁾

Courtesy of Iowa State College.

TABLE 33. OPTICAL CONSTANTS AND REFLECTANCE OF TITANIUM

$\lambda^{(a)}$, m μ	n ^(b)	k ^(c)	Per Cent R, ^(d) Calculated	Per Cent R, Measured	Per Cent R, Measured (Corrected for effect of oxide film)
436	2.04	2.85	53.0	51.3	53.4
546	2.53	3.33	57.0	55.8	57.0
578	2.64	3.42	57.0	56.5	57.5
650	3.03	3.65	59.0	58.5	59.3

(a) λ = wave length of the incident ray.

(b) n = refractive index.

(c) k = absorption coefficient.

(d) R = reflectance for normal incidence.

TABLE 34. WORK FUNCTION OF TITANIUM

Method of Determination	Work Function, ev	Investigator	Reference
Vapor pressure of electrons	3.95 $\pm$ 0.02	Jain and Krishan	145
Photoelectric	3.95	Schulze	146
Photoelectric	4.17	Rentschler and Henry	147
Photoelectric	4.45 $\pm$ 0.05	Malamud and Krumbein	148
Photoelectric	4.11	Dalle Mura, et al.	149
Contact potential	4.14	Klein and Lange	150

where

i = saturation current

A = Richardson constant

T = absolute temperature

ϕ = work function

K = Boltzmann constant.

Their values for A and for ϕ were 44 ± 2 amp/cm²/deg² and 3.95 ± 0.02 eV, respectively.

Soft X-Ray Spectrum

Studies of the soft X-ray spectrum have yielded a value of 6.0 ± 0.5 eV for the band width in titanium metal.⁽¹⁵¹⁾ These data indicate that the density of energy levels at the top of the filled portion of the band is low.

Electronic Specific Heat

At low temperature, electrons contribute to the heat capacity as well as lattice vibrations. The electronic specific heat can be deduced from heat capacity data at low temperatures. Two measurements of the electronic specific heat agree. Estermann, Friedberg, and Goldman⁽⁷³⁾ obtained 8.00×10^{-4} cal/C/mole. Aven, et al.,⁽⁷⁴⁾ obtained 8.08×10^{-4} cal/C/mole. Estermann, et al., calculated 0.711 electron levels/atom-eV for the density of states at the top of the free electron band. These data also yielded an effective mass of 3.15 m for electrons at the top of the band; m is the rest mass of the electron.

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APPENDIX

LIST OF CONTRACTS
ON
CURRENT RESEARCH ON
PHYSICAL PROPERTIES OF
TITANIUM AND TITANIUM ALLOYS

APPENDIX

LIST OF CONTRACTS ON CURRENT RESEARCH
ON PHYSICAL PROPERTIES OF TITANIUM
AND TITANIUM ALLOYS

Title: Investigation of the Photoelectric Work Function of Titanium
Contract: N6onr 27010-NR 074-333
Contractor: Princeton University
Sponsor: USN, ONR
Term: No term

Title: Dilatometric Studies
Contract: TB 4-15
Contractor: WAL internal project
Sponsor: USA, Ord Corps, WAL
Term: Work in progress November, 1954

Title: Research on the Electronic Specific Heats of Ti and Ti Hydride
Contract: NSF-G-1452
Contractor: University of Pittsburgh
Sponsor: National Science Foundation
Term: No term

Title: Thermodynamic Properties of Ti Alloys
Contract: NSF-MPE-G-1621
Contractor: Grantee
Sponsor: National Science Foundation
Term: April, 1955 - April, 1957

Title: The Preparation of Pure Compounds of Ti
Contract: NAonr 173-53
Contractor: Nat. Bur. of Stds., Wash., D. C.
Sponsor: USN, ONR
Term: December, 1952 - June, 1957

Title: Thermodynamic Properties of Ti Compounds
Contract: NAonr 174-53
Contractor: U. S. Bur. of Mines, Pacific Exp. St., Berkeley, California
Sponsor: USN, ONR
Term: January, 1953 - June, 1957