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PROPERTIES OF TUNGSTEN AND TUNGSTEN ALLOYS
FOR REACTOR SHIELDING APPLICATIONS

T. D. Watts

UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

operated for the **ATOMIC ENERGY COMMISSION** under **U. S. GOVERNMENT** Contract W-7405 eng 26

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UNION CARBIDE CORPORATION
Nuclear Division

Y-12 PLANT

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ABSTRACT

All of the chemical, physical, and mechanical properties of unalloyed tungsten and its nickel-iron alloys that pertain to using these materials for reactor shielding have been collected. The normal fabrication techniques and commercial availability are also set forth.

Since much of the data were obtained by an extensive literature search, the main references, from which this compilation was made, are included. Most of the information on the tungsten-nickel-iron alloys has come from heretofore unpublished work.

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SUMMARY

All of the chemical, physical, and mechanical properties of tungsten and its nickel-iron alloys have been accumulated as an aid to using these materials for reactor shielding. Normal fabrication techniques and their commercial availability are also given. Most of the information comes from a rather extensive list of publications on the subject.

INTRODUCTION

Tungsten and its alloys, although relatively expensive, possess desirable properties for reactor shielding material. These properties make some tungsten products economically feasible when the specific reactor systems require their unique advantages. Pure tungsten is of prime importance because of its ultra-high-temperature resistance and high density. Of the less expensive high-density tungsten alloys, the most readily made and fabricated are the "heavy-met" alloys. There are two very similar series of these alloys, the tungsten-copper-nickel and tungsten-nickel-iron series. Since the tungsten-nickel-iron alloys display more uniform density and mechanical properties and since the two series of alloys behave almost identically, the discussion presented here will be limited to pure tungsten and the tungsten-nickel-iron system. This system is considered to be the most promising of the tungsten alloys for reactor shielding.

TUNGSTEN AND ITS NICKEL-IRON ALLOYS

SOURCE (Preparation and/or Composition)

Tungsten is never found in nature in the uncombined form but occurs as various compounds and mixtures of compounds. The most common ores are tungsten trioxide combined with the oxides of iron, manganese, and/or calcium. The high melting point of tungsten, its reactivity, and the problems of containing molten tungsten preclude the use of conventional smelting techniques. Tungsten is therefore produced by chemical decomposition and refining of the ore, isolation of the purified trioxide, and reduction of the oxide to metal powder. A great variety of tungsten powders is readily available from many manufacturers. The characteristics of the tungsten powder greatly affect both the fabrication procedure and the final properties of the product being made. This fact is true not only for the production of pure tungsten parts but also for alloy parts, with powder properties being quite critical, for the production of some of the liquid-phase-sintered tungsten-nickel-iron alloy compositions.

Although all tungsten is produced in powder form, and at various degrees of purity and as alloys, nearly all of the tungsten manufacturers also produce the metal in a wide variety of shapes such as billets, ingots, plate, sheet, rod, and wire. The variety of wrought products commercially available in the tungsten-nickel-iron alloy series is limited since parts with optimum properties can readily be made using normal powder metallurgy techniques.

FABRICATION

The actual fabrication procedures used in making tungsten parts are always dependent upon the properties of the starting powder and the properties required of the final product. The size and shape of parts required also influence the fabrication techniques used. This relationship is more true for tungsten than for nearly any other material because tungsten is quite difficult to form and/or machine. Almost all tungsten parts are made from powder through powder metallurgy techniques. Sheet is made from forgings which are, in turn, made from pressed and sintered or extruded powder billets. Some arc-melted and/or electron-beam-melted ingots are produced, but the starting electrodes are usually made from powder. Nearly every powder metallurgy technique for producing parts has been used successfully in making tungsten products. Rolling, forming, punching, shearing, and forging of tungsten can be done using standard procedures if the tungsten is kept above the ductile-brittle transition temperature. This transition temperature is affected by prior cold work, impurity content, grain size, and strain rate. Cold work, smaller grain size, and lower strain rates all tend to decrease the transition temperature; impurities generally increase it.

Since a large grain size drastically reduces the low-temperature ductility of the metal, the fabricator must be careful during his forming operations not to heat the tungsten to too high a temperature or recrystallization can hinder subsequent operations. The minimum recrystallization temperature varies, depending on the microstructure and history of the metal. Since the same factors affect the recrystallization temperature and the ductile-brittle transition temperature in the same way, the working temperatures are usually lowered progressively as more and more work is put into the material. For example, when making fine tungsten wire, the initial swaging is done at 1,500 - 1,700° C, while the final size is drawn at 300 - 400° C. (1)

It must be remembered while working tungsten at elevated temperatures that it is very susceptible to oxidation. Therefore, heating should be done in a protective atmosphere, preferably containing hydrogen, and exposure to air should be kept to a minimum. If some oxidation does take place, the oxide on the surfaces can be removed in a bath of hot caustic soda or by firing in a hydrogen atmosphere above 400° C. (2)

The tungsten-nickel-iron alloys, like most forms of tungsten, always start as powder. Alloy parts are produced by blending the component powders, pressing the blended powders in a precalculated configuration, and densifying by liquid-phase sintering. Most of the actual alloying takes place during the liquid-phase sintering, which is much faster and more uniform than normal solid-state sintering. With close temperature control, very precise sintering to size can be performed with the higher-tungsten-content alloys since the solid, tungsten-rich phase maintains structural strength during liquid-phase sintering and holds the liquid phase by capillary action. This action can be lost if the temperature is raised too far above the liquidus point. For the 95 weight percent tungsten-3.5 weight percent nickel-1.5 weight percent iron alloy, the matrix phase melts at $1,465 \pm 5^\circ \text{C}$. The composition of this phase is approximately 30 weight percent tungsten, 45 weight percent nickel, and 25 weight percent iron at room temperature. While the matrix phase is liquid, more tungsten is dissolved and (this excess is) subsequently precipitated out on the tungsten-rich grains. The tungsten-rich phase has small amounts of nickel and iron dissolved in it. The maximum solubilities of nickel and iron in tungsten are about 0.3 and 0.8 weight percent, respectively, but this depends on the maximum sintering temperature. Some decrease in nickel and iron content could occur in the tungsten-rich phase during cooling. A hydrogen sintering atmosphere is generally employed as it reduces contamination of the parts and acts as a surface activator, helping to improve the sintering efficiency. Inert-atmosphere sintering has also been successful, although less consistently.

Some of the heavy-met alloys can be rolled and/or formed with difficulty by the techniques used for pure tungsten. These processes only increase the density minutely. Therefore, it is generally much more economical to produce the alloys in a configuration close to the desired part. One of the biggest advantages of the heavy-met alloys is their excellent machinability. These alloys can readily be single-point machined at room temperature. The machinability of the alloy is best described as being comparable to stainless steel.

HEAT TREATMENT

Neither tungsten or the heavy-met alloys are readily susceptible to heat treatment. Pure tungsten can be annealed for stress relieving, but care must be taken to prevent recrystallization. The minimum recrystallization temperature is reduced by the amount of impurities, degree of cold work, and reduction of grain size.⁽¹⁾ Fine grain size is essential for any but the most brittle tungsten products. Any heat treatments that are performed must also be done in an inert or reducing atmosphere to avoid oxidation.

Although the tungsten-nickel-iron alloys are not really heat treatable, they are somewhat susceptible to hydrogen embrittlement. Since maximum sinterability is usually obtained in hydrogen atmospheres, it is sometimes desirable to heat treat the parts in either vacuum or an inert atmosphere to remove the adsorbed and/or absorbed hydrogen. Air annealing has also been successful for hydrogen degassing if the parts are not very thick. Approximately 1/2 hour per quarter inch of thickness is required at 1,100° C to remove the hydrogen. Thick parts, therefore, tend to lose considerable material due to oxidation during air annealing.

JOINING

Welding tungsten and tungsten-nickel-iron alloys is most difficult. Both systems have been joined by arc welding, electron-beam welding, resistance welding, or other standard welding techniques.⁽³⁾ The welds that have been made in pure tungsten have always shown complete recrystallization not only in the weld metal but also in the heat-affected zone.⁽⁴⁾ This factor leads to extremely brittle welds which often crack during welding. Welding of the tungsten-nickel-iron alloys either results in vaporized matrix material or matrix melting only. In the former instance no joint is made; in the latter, the joint is much less dense than the rest of the material and has completely different properties.

Brazing of tungsten can be accomplished, but the temperature resistance of the parts is reduced. The amount of reduction depends upon the braze material used. The tungsten-nickel-iron alloys can be joined by diffusion bonding, resulting in almost indiscernible interfaces. This, however, requires extremely close-tolerance fits and very accurate temperature control. Brazing of the tungsten-nickel-iron alloys has been successful with a variety of brazing alloys. Tungsten-nickel-iron alloys have also been brazed to a large variety of other materials.

PHYSICAL PROPERTIES

The most outstanding physical properties of pure tungsten are its high melting point (3,410° C) and high modulus of elasticity (59×10^6 psi) which are the highest of all

metallic elements. ⁽⁵⁾ Conversely, its vapor pressure and compressibility are the lowest of all metallic elements. The density of tungsten (19.3 gms/cc) is exceeded only by platinum, iridium, osmium, and rhenium. Its high density plus the substantial thermal neutron absorption cross section which it possesses (19 barns) ⁽⁶⁾ make tungsten a very effective shielding material. In addition to a fairly high thermal neutron cross section, the average neutron cross section, taken over the maxwell distribution of neutron energies, is 5 ± 1 barns, depending on its grain size. Although the density of tungsten is 2.5 times that of iron, a one-Mev gamma ray is shielded by tungsten 3.5 times better than iron. The shielding advantage of tungsten over iron becomes even greater at lower gamma ray energies. ⁽⁷⁾ At energies of 2.5 to 3.5 Mev the effective shielding is almost proportional to the weight of material. ⁽⁸⁾ For most reactors planned today, the gamma ray energy distribution will be within the 0.5 to 3.5-Mev range.

The thermal and electrical conductivities of tungsten, although only about one-half and one-third, respectively, that of annealed copper, are high when compared to most other metals. Neither iron or nickel have conductivities as high as tungsten. Table 1 lists some of the physical constants of tungsten.

The physical-property data on the tungsten-nickel-iron alloy are somewhat limited, as only those properties of particular interest to the users of this series of alloys have been determined. The most important are the high density (18.27 ± 0.12 gms/cc) and high modulus (54.37×10^6 psi) (Elastomat), which approximate that of pure tungsten. The density may, however, have local variations up to ± 1 percent, based on observations of small portions of the same part (ie, cc to cc small voids in the sintered product can affect density). Radiographic examination of tungsten-nickel-iron alloy parts show the density to be slightly less than theoretical with many evenly distributed small voids (up to 0.010 inch in diameter). A few voids and/or low-density spots up to 0.060 inch in diameter have also been observed.

Although the liquid-phase temperature is $1,465 \pm 5^\circ \text{C}$ for the 95 weight percent tungsten-3.5 weight percent nickel-1.5 weight percent iron alloy, it can withstand up to $1,375^\circ \text{C}$ for long periods of time in reducing or inert atmospheres with no deleterious effects. Even at the liquid-phase temperature, these high-tungsten-content parts will maintain their shape and have some strength. If the liquid-phase temperature is exceeded by 20°C or more, the parts will sag and/or matrix phase runout will occur, resulting in considerable nonuniformity of density and strength. Table 2 summarizes the physical constants of the 95 weight percent tungsten-3.5 weight percent nickel-1.5 weight percent iron alloy.

MECHANICAL PROPERTIES

Unalloyed tungsten displays high strength and high hardness at both room and elevated temperatures. Even with its high density, tungsten has the highest strength-to-weight ratio, at elevated temperature, of any known metal or alloy. ⁽¹⁾ Even at room

Table 1
PHYSICAL CONSTANTS OF UNALLOYED TUNGSTEN

Physical Property ⁽¹⁾	Value
Atomic Number	74
Atomic Weight	
Based on the O-16 Isotope = 16	183.92
Based on Natural Oxygen = 16	183.86
Based on the C-12 Isotope = 12	183.85
Natural Isotopes	180, 182, 183, 184, 186
Crystal Structure	Body-Centered Cubic (no transformation)
Lattice Constant (A)	3.16 ± 0.005
Density	
At 20° C (gms/cc)	19.3 (0.697 lb/in ³)
Calculated from Lattice Constant	19.26
Melting Point (°C)	3,410 ± 20 (6,170° F)
Boiling Point (°C)	5,900 (10,652° F)
Vapor Pressure (mm Hg)	
At 1,527° C (2,780° F)	1.93 × 10 ⁻¹⁹
At 2,127° C (3,860° F)	7.9 × 10 ⁻⁹
At 2,204° C (4,000° F)	4 × 10 ⁻⁸
At 2,537° C (4,600° F)	4 × 10 ⁻⁶
At 2,727° C (4,940° F)	6.5 × 10 ⁻⁵
At 3,204° C (5,800° F)	1 × 10 ⁻²
At 3,727° C (5,840° F)	4.68 × 10 ⁻³
At 3,548° C (6,420° F)	1 × 10 ⁻¹
At 3,948° C (7,140° F)	1
At 4,448° C (8,040° F)	10
At 5,082° C (9,180° F)	100
At 5,932° C (10,710° F)	760
$\log P = -\frac{A}{T} + B + C \log T + DT \text{ from room temperature to the melting point,}$ where A = 44,000; B = 8.76; C = 0.50; D = 0.	
Specific Heat (cal/gm-°C)	
At 20° C (68° F)	0.032
At 982° C (1,800° F)	0.039
At 1,982° C (3,600° F)	0.047
$C_p = a + bT + CT^{-2} \text{ from 298 to 2,000° K, where } a = 5.74; b = 0.76; C = 0.$	

(1) The data in this table are combined from many references^(1,2,5,9) with the best values used.

Table 1 (continued)

Physical Property	Value
Thermal Conductivity (cal/sec-cm-°C)	
At 20° C (68° F)	0.31
At 927° C (1,701° F)	0.275
At 1,127° C (2,061° F)	0.268
At 1,327° C (2,421° F)	0.260
At 1,527° C (2,781° F)	0.253
At 1,727° C (3,141° F)	0.245
At 1,982° C (3,600° F)	0.233
Linear Coefficient of Thermal Expansion (in/in)	
At 20° C (68° F)	2.47×10^{-6}
At 100° C (212° F)	4.5×10^{-6}
At 500° C (932° F)	4.6×10^{-6}
At 1,000° C (1,832° F)	4.6×10^{-6}
At 2,000° C (3,632° F)	5.4×10^{-6}
At 3,000° C (5,432° F)	6.6×10^{-6}
Atomic Volume (cc/gm-atom)	9.53
Heat of Fusion (cal/gm)	44
Heat of Vaporization (cal/gm)	1,183
Electrical Resistivity (μhm-cm)	
At 20° C (68° F)	5.5
At 100° C (212° F)	7.2
At 227° C (441° F)	10.5
At 500° C (932° F)	18
At 727° C (1,341° F)	24.3
At 1,000° C (1,832° F)	33
At 1,727° C (3,141° F)	55.7
At 2,000° C (3,632° F)	65
At 2,727° C (4,941° F)	90.4
At 3,000° C (5,432° F)	100
At 3,227° C (5,841° F)	108.5
Total Emissivity in Relation to Black Body	
At 732° C (1,350° F)	0.015
At 1,238° C (2,260° F)	0.192
At 1,727° C (3,140° F)	0.259
At 2,737° C (4,960° F)	0.334
At 3,237° C (5,860° F)	0.354

Table 1 (continued)

Physical Property ⁽¹⁾	Value
Thermionic Data	
Apparent Electron Work Function (ev)	4.55
Apparent Positive Ion Emission (ev)	11.93
Radiation Emission Coefficient	0.43
First Ionization Potential	7.60
Magnetic Susceptibility (gm-atom)	40×10^{-6}
Thermal Neutron Absorption Cross Section (barns/atom)	19.2 ± 1
Compressibility, per megabar at 20°C (in/in)	0.28×10^{-6}
Young's Modulus of Elasticity, at 20°C (psi)	59×10^6

temperature, highly worked tungsten (like fine wire) has greater tensile strength than that reported for any material made by standard production techniques. Part of tungsten's strength advantage at elevated temperature can be attributed to the fact that unlike most materials it does not exhibit a sharp decrease in hot tensile strength after it is heated above its recrystallization temperature.⁽¹⁰⁾

Table 2

PHYSICAL CONSTANTS OF A TUNGSTEN-NICKEL-IRON ALLOY
(95 wt % W-3.5 wt % Ni-1.5 wt % Fe)

Property ⁽¹⁾	Value
Structure	Two-phase alloy. One phase is 98-99 wt % W, the other ~ 30 wt % W-50 wt % Ni-20 wt % Fe.
Density (gms/cc)	18.27 ± 0.12
Melting Point, of Matrix Phase (°C)	$1,465 \pm 5$
Coefficient of Thermal Expansion	
Range (°C)	Coefficient (in/in/°C)
25 - 50	3.78×10^{-6}
25 - 100	4.73×10^{-6}
25 - 200	5.09×10^{-6}
25 - 300	5.19×10^{-6}
25 - 400	5.20×10^{-6}
25 - 500	5.23×10^{-6}
Young's Modulus (psi)	54.37×10^6 (Elastomat)
	57.5×10^6 (compression)

(1) From work done by the author.

The ductile-brittle transition temperature for most forms of tungsten is substantially above room temperature. This transition temperature depends on several things: (1) purity, especially interstitial concentrations; (2) the fabrication process including such factors as working temperatures and degree of reduction; (3) the final structure, grain size, and surface conditions; (4) the kind and rate of stress applied.⁽⁵⁾ The effect of these variables on the transition temperature has not been fully established. Single-crystal tungsten is reported to have a ductile-to-brittle transition temperature from -196 to -107°C , while sintered or as-cast polycrystalline tungsten has this transition anywhere from 150 to 450°C .⁽¹⁾

The tensile properties and hardness, like the transition temperature, are highly dependent upon the fabrication process, grain structure, and purity level. Table 3 lists two typical room-temperature mechanical properties for some standard, commercially available tungsten products.

Table 3
TWO TYPICAL MECHANICAL PROPERTIES OF FABRICATED SINTERED
TUNGSTEN AT ROOM TEMPERATURE

Form	Ultimate Tensile Strength ⁽¹⁾ (psi)	Hardness ⁽¹⁾ (R_c)
Sintered Ingot	16,000	
Rod		
0.250 ⁽²⁾	70,000	37
0.100	150,000	40
0.050	200,000	44
Wire		
0.025 ⁽²⁾	285,000	41
0.010	350,000	
0.005	430,000	
0.001	610,000	
Sheet		
0.040 ⁽³⁾	200,000	44
0.020	250,000	45
0.010	300,000	47

(1) Taken from two sources. (1,5)

(2) Diameter in inches.

(3) Thickness in inches.

The elevated-temperature properties are also dependent upon grain size and processing cycle. Table 4 gives some typical properties at higher temperatures.

The mechanical properties of tungsten-nickel-iron alloys are less dependent on fabrication, although improved properties can be obtained by heating the tungsten-nickel-iron alloy in vacuum, air, or an inert atmosphere, to $1,000^{\circ}\text{C}$ for approximately one-half hour for each quarter inch of thickness. This operation acts more as a gas-removal step, particularly for hydrogen, than as a heat treatment in the normal sense of the word. The grain size is generally not affected by this treatment.

The tungsten content, for alloys with the same nickel-iron ratio, affects density and ductility much more than it affects ultimate tensile strength. This effect of tungsten content can be seen by the data of Table 5.

The so called heat-treated alloy shows improved properties, as seen in Table 6. Much the same improvement can be obtained by air cooling parts from $1,000^{\circ}\text{C}$ at the end of the sintering cycle.

Elevated-temperature testing of tungsten-nickel-iron alloys also indicates better ductility for the heat-treated or air-cooled material. The advantage becomes less for higher-temperature testing, as shown in Table 7. These data are not directly comparable to the usual elevated-temperature tensile test results because the strain rate was somewhat high (20 in/in/sec). However, ductility is only slightly less than at slower strain rates (0.5 in/in/sec). In general, test results are not dependent on the strain rate between 0.1 and 10 in/in/sec.

CORROSION RESISTANCE

Tungsten is not affected by air, water, or water vapor at room temperature except when it is in powder form. Very fine tungsten powder is sometimes pyrophoric. Many oxidizing agents attack tungsten depending on the temperature. At 400°C , tungsten begins to oxidize in air; at red heat it oxidizes rapidly, forming the trioxide which spalls easily. In addition, carbon, boron, silicon, and sulfur react with tungsten at various elevated temperatures. Tungsten has good resistance to attack by liquid metals, mild alkali solutions (in the absence of oxygen), and most acids. Solutions of copper(II) chloride or iron(III) chloride corrode tungsten, and caustic solutions dissolve it. Fluorine attacks it at room temperature and bromine and iodine attack it at red heat. Molten nitrates, nitrites, and peroxides react violently with it. Tungsten resists molten sodium or potassium hydroxide, but the presence of a strong oxidant (like KNO_3 or KNO_2) in these hydroxides will cause rapid tungsten corrosion. (1,10) Table 8 describes the reaction of tungsten with various substances. Of particular interest for reactor applications is the fact that tungsten is one of the least reactive materials with uranium. Even liquid uranium reacts very little with tungsten unless heated well above its melting point ($1,130^{\circ}\text{C}$, $2,066^{\circ}\text{F}$). At the melting point of uranium it will dissolve approximately one atom percent tungsten, and the solubility of uranium in tungsten is about 0.1 atom percent. (10,11)

Table 4
THREE TYPICAL MECHANICAL PROPERTIES OF TUNGSTEN
AT ELEVATED TEMPERATURES

Treatment	Yield Strength ⁽¹⁾⁽²⁾ (psi)	Ultimate Tensile Strength ⁽¹⁾ (psi)	Elongation ⁽¹⁾ (%)
Swaged Rod, Annealed			
At 27° C (80° F)		215,000	0.2
At 326° C (600° F)		103,000	24.5
At 649° C (1,200° F)		76,600	16.0
At 871° C (1,600° F)		66,200	13.5
At 1,093° C (2,000° F)		59,000	14.5
At 1,649° C (3,000° F)		25,000	
Swaged Rod, Recrystallized			
At 326° C (600° F)	28,800	59,700	16.4
At 649° C (1,200° F)	15,200	44,500	55.3
At 871° C (1,600° F)	14,500	36,600	57.9
At 1,093° C (2,000° F)	12,900	33,500	52.0
Wire, Annealed			
At 1,093° C (2,000° F)		100,000	
At 1,204° C (2,200° F)		70,000	
At 1,649° C (3,000° F)		40,000	
Sheet, Annealed			
At 1,093° C (2,000° F)	57,000	72,000	6
At 1,649° C (3,000° F)	14,000	21,000	30
At 2,204° C (4,000° F)	7,000	11,000	16
Sheet, Recrystallized			
At 1,093° C (2,000° F)	14,000	35,000	50
At 2,204° C (4,000° F)		18,000	50

(1) Data taken from two sources. (5,9)

(2) At 0.2 percent offset.

Table 5
ROOM-TEMPERATURE TENSILE PROPERTIES OF TUNGSTEN-NICKEL-IRON ALLOYS
(With a 7:3 Nickel-Iron Ratio)

Tungsten Content (%)	Density ⁽¹⁾ (gms/cc)	Yield Strength ⁽¹⁾⁽²⁾ (psi)	Ultimate Tensile Strength ⁽¹⁾ (psi)	Elongation ⁽¹⁾ (%)
90	16.8	80,000	122,000	25
92.5	17.4	85,000	120,000	12
95	18.27	87,000	115,000	6
97.5	18.5	88,000	108,000	5

(1) Data shown are for as-sintered parts with a section thickness of one inch. Tensile specimens machined from thicker as-sintered parts show less ductility and less strength.

(2) At 0.2 percent offset.

There are very little data available on the corrosion of the tungsten-nickel-iron alloys. In general, these alloys have quite similar corrosion properties to pure tungsten, especially when the tungsten content is 95 percent or greater. The oxidation resistance, however, is somewhat better for the alloys, in that there are wider temperature ranges in which tenacious oxide films are formed, protecting the base material from further oxidation. The resistance to acids is somewhat reduced as is resistance to carburization. Liquid metal attack is comparable; of course, the melting temperature of the matrix phase of the alloy cannot be approached too closely. The effects of hydrogen upon the alloy have been discussed under HEAT TREATMENT.

Table 6
ROOM-TEMPERATURE MECHANICAL PROPERTIES OF A TUNGSTEN-NICKEL-IRON ALLOY
(95 wt % W-3.5 wt % Ni-1.5 wt % Fe)

Property	As Sintered	Heat Treated ⁽¹⁾	Air Cooled
Ultimate Tensile Strength (psi)	103,000	132,700	133,200
Yield Strength ⁽²⁾ (psi)	86,500	87,300	85,100
Elongation (%)	1.5	22.0	20.8
Shear Strength (psi)	-	103,000	102,600
Compressive Yield Strength ₁ (psi)	-	98,400	95,200
Unnotched Impact, Charpy (ft lbs)	2 to 12	14 to 43	22.7
Notched Impact, Charpy (ft lbs)	0.5 to 1.0	1.4 to 1.8	1.6

(1) The heat treatment was 2 hours per inch of thickness at 1,000°C in vacuum.

(2) At 0.2 percent offset.

Table 7
TYPICAL ELEVATED-TEMPERATURE TENSILE PROPERTIES
OF A TUNGSTEN-NICKEL-IRON ALLOY
(95 wt % W-3.5 wt % Ni-1.5 wt % Fe)

Test Temperature	As Sintered		Heat Treated	
	Ultimate Tensile Strength (psi)	Elongation (%)	Ultimate Tensile Strength (psi)	Elongation (%)
93° C (200° F)	100,000	10	120,000	20
204° C (400° F)	98,000	18	108,000	37
316° C (600° F)	95,000	24	97,000	42
427° C (800° F)	88,000	21	90,000	40
538° C (1,000° F)	80,000	19	85,000	31
649° C (1,200° F)	65,000	17	80,000	20
760° C (1,400° F)	61,000	12	68,000	17
871° C (1,600° F)	58,000	12	60,000	12
982° C (1,800° F)	51,000	10	51,000	10
1,093° C (2,000° F)	42,000	9		
1,204° C (2,200° F)	30,000	9		
1,315° C (2,400° F)	28,000			

RADIATION DAMAGE

There has been very little work done on the effects of radiation on tungsten or the tungsten-nickel-iron alloys. After irradiation of 3.3×10^{19} nvt slow and 6×10^{19} nvt fast neutrons, no significant change in the hardness of unalloyed tungsten was observed. The density decreased 0.1 to 0.15 percent and the tensile strength decreased 18 percent. Post irradiation annealing at 825° C (1,515° F) brought full recovery.⁽¹⁰⁾ Some experiments in elevated temperature irradiation have shown very little, if any, effect on pure tungsten.

COMMERICAL DATA

A large variety of tungsten powders is readily available. Powders may be obtained with an average particle size anywhere between 0.75 and 20.0 microns with the intermediate sizes being the least expensive. The general range of prices for tungsten powder is \$4 to \$6 per pound (1967 prices), depending on such factors as powder type, quantity, and status of the market.

Tungsten rod is available in sizes up to one inch in diameter and in lengths up to 10 feet, depending on the diameter of the rod. For instance, 1.00-inch-diameter rod

Table 8
CHEMICAL BEHAVIOR OF TUNGSTEN

Substance	Reaction ⁽¹⁾
H ₂	Compatible at all temperatures.
N ₂	No reaction up to at least 1,500° C (2,732° F).
Air or O ₂	Oxidation begins at 400° C (752° F).
NH ₃	None; brittleness occurs above 982° C (1,800° F).
Water	None.
Water Vapor	Oxidation above 700° C (1,292° F).
C	Carburization above 1,400° C (2,552° F).
CO	Carburization above 1,700° C (3,092° F).
CO ₂	Oxidation above 1,200° C (2,192° F).
F	Forms fluoride above 0° C (-32° F).
Cl	Forms chloride above 250° C (482° F).
Br	Forms bromide above 750° C (1,382° F).
I	Forms iodide above 800° C (1,472° F).
S	Slow attack when molten (above 119° C).
HF	Slight attack at 100° C (212° F).
H ₂ S	Superficial attack at red heat.
HCl (conc)	Slight attack at 100° C (212° F).
Aqua Regia	Superficial oxidation forming WO ₃ .
HF + HNO ₃	Attack at room temperature (rapid solution).
HNO ₃ (conc)	Slight attack at 100° C (212° F).
H ₂ SO ₄ (conc)	Slight attack at room temperature.
H ₂ SO ₄ (dilute)	Slight attack at 100° C (212° F).
NaOH (aqueous)	None at room temperature.
KOH (aqueous)	None at room temperature.
NaOH (fused)	Slow attack, rapid solution with oxidizing agent.
KOH (fused)	Slow attack, rapid solution with oxidizing agent.
Nu (in absence of O ₂)	Good resistance up to 900° C (1,652° F).
K (in absence of O ₂)	Good resistance up to 900° C (1,652° F).
Bi	No reaction below 982° C (1,800° F).
Cs	Very good resistance up to 982° C (1,800° F).

(1) Information taken from two sources. (1,5)

Table 8 (continued)

Substance	Reaction ⁽¹⁾
Li	Good resistance at 815° C (1,500° F); limited resistance at 982° C (1,800° F) (progressively dissolves, mass transfer with iron).
Pb	No appreciable reaction up to the boiling point of 1,738° C (3,160° F).
Sn	Good resistance to 975° C (1,787° F), but considerable mass transfer with iron or nickel present above 800° C (1,472° F).
Hg	No reaction even in the vapor state.
Zn	Good resistance up to 700° C (1,292° F) in a reducing atmosphere.
MgO	Reaction starts at 2,000° C.
Al ₂ O ₃	Stable up to its melting point 2,015° C (3,659° F).
ThO ₂	Stable up to at least 2,200° C (3,995° F).
UO ₂	Stable up to 2,450° C (4,442° F).
ZrO ₂	Stable up to 1,600° C (2,912° F).
Be	No reaction after six days at 700° C (1,292° F).
Nb	
Fe	
Mo	
Zr	
347 Stainless Steel	
U	Very little reaction (even in liquid state) up to 1,250° C (2,282° F).

(1) Information taken from two sources. (1,5)

comes in maximum lengths of 2 feet and 0.50-inch-diameter rod comes in maximum lengths of 5 feet per standard products. Special orders at higher prices can be filled. The price range for standard tungsten rod is about \$8 to \$16 per pound.

Tungsten wire under 20 mils in diameter is commercially available in several types and sizes down to 0.3 mil. The prices range between \$5 and \$100 per 1,000 meters (1967 prices), depending on such variables as diameter tolerance and state of the wire (ie, as drawn and chemically etched). Larger wire (20 to 60 mils in diameter) ranges between \$30 to \$200 per kilogram, depending on the same variables.

As-rolled tungsten sheet is available in thicknesses from 0.005 inch up to 0.600 inch. The thicker sheet (over 0.050 inch) has a cost variation of \$25 to \$75 per kilogram. The very thin sheet sells up to several hundred dollars per kilogram.

Pressed and sintered tungsten billets are available in sizes up to 9 inches in diameter by 30 inches, with a price range of \$8 to \$15 per pound.

Most tungsten suppliers also fabricate special parts, either as pressed and sintered parts or as fabricated parts.

The heavy-metal alloys can also be obtained in a large variety of sizes and shapes. Standard sizes for these parts are less than 24 inches in diameter by 24 inches high, and/or parts that can be fabricated from sintered blocks of this maximum size. Prices depend entirely on the size and shape of the parts.

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