H. CROSS COMPANY

Precision Metal Rollers

General Catalog of Materials & Processing Capabilities

Established in 1939 and Serving the metals industry with “Tailor Made” Products for over 74 Years

MICROWAVES READER RECALL award

PRESENTED TO

H. CROSS COMPANY

~~Fabricated Materials~~ 4/68

ISSUE

As a metals fabricator, Cross makes a great tailor.

In fact, we spend every working day tailoring ribbon and strip metal production to our customers' needs. We've become known as the custom shop—the one you can hand any job to and expect to get it back perfect. Big, medium or small.

Naturally, we get some pretty tough assignments thrown at us, with that kind of reputation. But we've developed some pretty special techniques for handling them. Take tolerances. We'll roll tungsten or molybdenum down to ± .0001" and hold that tolerance. There's not another shop around that can do that. With rhenium tungsten, rhenium moly, columbium, zirconium, titanium, vanadium, copper, nickel, alloys and other metals, we'll hold a tolerance of ± 00005".

No wonder we're called the custom shop. Isn't it time you came to Cross and had your ribbon and strip metal requirements custom-manufactured, with zero defects? And we don't care how mean and ornery a job you hand us. After all, would a good tailor tell a customer he couldn't fit him?

For further information write H. Cross Co., 363 Park Avenue, Weehawken, New Jersey, or call (201) 863-1134.

H. Cross Co. "The Master Rollers"

Tungsten – for filaments, heaters, grids, etc. **Rhenium Tungsten** – Tungsten containing 3% Rhenium. Used in application where resistance to recrystallization, room temperature, elongation, and pliability, after heating, are needed. **Thoriated Tungsten** – Tungsten containing 1% or 2% thoria. Used where relatively high electron emission is required. **Molybdenum** – Used as support for lamps and electron tube mandrels, for tungsten coil winding, traveling wave tube helixes, furnace windings, tube grids, etc. **Molybdenum Rhenium** – 50% Molybdenum and 50% Rhenium used for grids, heaters, supports etc. where high electrical resistivity and low thermal conductivity, ductility, weldability are of importance. **Rhenium** – Used for filaments in mass spectrometers, ion gauges and other electronic components where electrical resistivity, electron emission weldability and ductility are important. **Tantalum** – Used for heat exchanges. Electron tube capacitors, filaments, grid wires and getters. **Columbium** – Used for getters in electron tubes and electrical rectifiers.

H. CROSS COMPANY

PRECISION METAL RIBBONS AND STRIPS FOR 70 YEARS

H. Cross Company was established in 1939. We were the first and only company capable of rolling tungsten and molybdenum ribbon. Throughout the years, due to our superior research, development and engineering staff, we have been consistently improving the state of the art in the field. We often accomplish what is considered to be the impossible.

Rhenium
Rhenium Alloys
Molybdenum
Tungsten
Tantalum
Columbium

Precision Rolled Ribbons Strips and Foils

H. Cross Company is proud of its skills and capabilities to roll metal down to extremely thin dimensions yet retain the tightest tolerances conceivable. Due to stringent quality control we can always produce and supply a superior product with positive repeatability. We enjoy a challenge and are willing to work with our customers to develop new and superior products.

H. Cross has grown into a specialty metal rolling House tailoring all products to our customers' requirements. Nothing is produced for stock. We manufacture to customer specifications only. No matter how difficult your needs H. Cross Company is the international source most likely solve your problems and manufacture the products necessary to fill your orders.

H. Cross Company's 31,500 sq foot manufacturing plant is thoroughly equipped with the finest machinery and most capable personnel to produce the highest quality precision rolled metals.

H Cross Company
150 W Commercial Ave
Moonachie, NJ USA
07074

Web: www.hcrosscompany.com
Phone: 1-201-964-9380
Fax: 1-201-964-9385

Zirconium
Copper
Nickel
Brass
Phosphor Bronze
Kovar
Titanium
Vanadium
Steels
Rhodium
Iridium
Palladium
Platinum
Gold
Silver

And Many More including Customer Materials

PERIODIC TABLE OF PROPERTIES OF THE ELEMENTS

KEY

	SULFUR	
DENSITY, G/CC†	2.07	113 MELTING POINT, °C
ATOMIC NUMBER	16	
SYMBOL	S	6/8/2 ELECTRON SHELLS
ATOMIC WEIGHT	32.066	
VALENCES	2,4,6	444 BOILING POINT, °C

†At room temperature; for gases, G/Liter at NTP.

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	INERT GASES
HYDROGEN 0.0899 -259 1 H 1 1.008 1 -252.8																	HELIUM 0.1785 -272.2 2 He 2 4.003 0 -268.9
LITHIUM 0.534 179 3 Li 1/2 6.940 1 1317	BERYLLIUM 1.845 1284 4 Be 2/2 9.013 2 2507											BORON 2.34 2300 5 B 3/2 10.82 3 2550	CARBON 1.88 (s)3550 6 C 4/2 12.011 2,4 4200	NITROGEN 1.25 -210 7 N 5/2 14.008 1,2,3,4,5 -196	OXYGEN 1.429 -218 8 O 6/2 16.00 2 -183	FLOURINE 1.69 -223 9 F 7/2 19.00 1 -187	NEON 0.900 -248.6 10 Ne 8/2 20.183 0 -246.1
SODIUM 0.97 97.9 11 Na 1/8/2 22.991 1 883	MAGNESIUM 1.74 651 12 Mg 2/8/2 24.32 2 1103											ALUMINUM 2.7 660 13 Al 3/8/2 26.98 3 2450	SILICON 2.33 1410 14 Si 4/8/2 28.09 4 2480	PHOSPHORUS 1.82 44 15 P 5/8/2 30.975 1,3,4,5 280	SULFUR 2.07 113 16 S 6/8/2 32.066 2,4,6 444	CHLORINE 3.214 -101 17 Cl 7/8/2 35.457 1,3,4,5,7 -34.6	ARGON 1.784 -189.3 18 A 8/8/2 39.944 0 -185.9
POTASSIUM 0.87 63.7 19 K 1/8/8/2 39.10 1 760	CALCIUM 1.54 851 20 Ca 2/8/8/2 40.08 2 1482	SCANDIUM 2.99 1539 21 Sc 2/9/8/2 44.96 3 2727	TITANIUM 4.54 1668 22 Ti 2/10/8/2 47.90 2,3,4 3260	VANADIUM 6.11 1890 23 V 2/11/8/2 50.95 2,3,4,5 3000	CHROMIUM 7.19 1875 24 Cr 1/13/8/2 52.01 2,3,6 2199	MANGANESE 7.44 1244 25 Mn 2/13/8/2 54.94 1,2,3,4,6,7 2097	IRON 7.87 1535 26 Fe 2/14/8/2 55.85 2,3 3000	COBALT 8.90 1493 27 Co 2/15/8/2 58.94 2,3 3100	NICKEL 8.9 1452 28 Ni 2/16/8/2 58.71 2,3 2900	COPPER 8.94 1083 29 Cu 1/18/8/2 63.54 1,2 2595	ZINC 7.133 419.5 30 Zn 2/18/8/2 65.38 2 906	GALLIUM 5.907 29.75 31 Ga 3/18/8/2 69.72 2,3 1983	GERMANIUM 5.32 936 32 Ge 4/18/8/2 72.60 2,4 2700	ARSENIC 5.727 814 33 As 5/18/8/2 74.91 2,3,5 (s)615	SELENIUM 4.79 217 34 Se 6/18/8/2 78.96 2,4,6 685	BROMINE 3.12 -7.2 35 Br 7/18/8/2 79.916 1,3,5,7 58.8	KRYPTON 3.74 -157.3 36 Kr 8/18/8/2 83.80 0 -153.4
RUBIDIUM 1.53 38.5 37 Rb 1/8/18/8/2 85.48 1 688	STRONTIUM 2.6 770 38 Sr 2/8/18/8/2 87.63 2 1380	YTTRIUM 4.472 1509 39 Y 2/9/18/8/2 38.92 3 3200	ZIRCONIUM 6.45 1852 40 Zr 2/10/18/8/2 91.22 2,3,4 3580	COLUMBIUM* 8.57 2468 41 Cb 1/12/18/8/2 92.91 2,3,4,5 4927	MOLYBDENUM 10.22 2610 42 Mo 1/13/18/8/2 95.95 2,3,4,5,6 5560	TECHNETIUM 11.49 2140 43 Tc 1/14/18/8/2 99 4,5,6,7	RUTHENIUM 12.4 2250 44 Ru 1/15/18/8/2 101.1 3,4,5,6,8 4900	RHODIUM 12.44 1960 45 Rh 1/16/18/8/2 102.91 3 4500	PALLADIUM 12.02 1552 46 Pd 0/18/18/8/2 106.4 2,3,4 3980	SILVER 10.49 960.5 47 Ag 1/18/18/8/2 107.873 1 2212	CADMIUM 8.65 321 48 Cd 2/18/18/8/2 112.41 2 767	INDIUM 7.31 156.6 49 In 3/18/18/8/2 114.82 1,3 2075	TIN 7.3 232 50 Sn 4/18/18/8/2 118.7 2,4 2270	ANTIMONY 6.68 630.5 51 Sb 5/18/18/8/2 121.76 3,4,5 1440	TELLURIUM 6.25 449.5 52 Te 6/18/18/8/2 127.61 2,4,6 990	IODINE 4.93 113.5 53 I 7/18/18/8/2 126.91 1,3,5,7 184.3	XENON 5.89 -111.8 54 Xe 8/18/18/8/2 131.3 0 -108.06
CESIUM 1.873 28.5 55 Cs 1/8/18/18/8/2 132.91 1 705	BARIUM 3.5 710 56 Ba 2/8/18/18/8/2 137.36 2 1500	LANTHANUM 6.174 920 57 La 2/9/18/18/8/2 138.92 3 3469	HAFNIUM 13.29 2150 72 Hf 2/10/32/18/8/2 178.50 2,3,4 5400	TANTALUM 16.6 2996 73 Ta 2/11/32/18/8/2 180.95 2,3,5 6100	TUNGSTEN 19.3 3410 74 W 2/12/32/18/8/2 183.86 2,4,5,6 5900	RHENIUM 21.02 3130 75 Re 2/13/32/18/8/2 186.22 1,2,3,4,5,6,7 5900	OSMIUM 22.5 3000 76 Os 2/14/32/18/8/2 190.2 2,3,4,6,8 5500	IRIDIUM 22.42 2410 77 Ir 2/15/32/18/8/2 192.2 1,2,3,4,6 5300	PLATINUM 21.4 1769 78 Pt 1/17/32/18/8/2 195.09 2,3,4 4530	GOLD 19.32 1063 79 Au 1/18/32/18/8/2 197 1,3 2966	MERCURY 13.55 38.87 80 Hg 2/18/32/18/8/2 200.61 1,2 357	THALLIUM 11.85 303 81 Tl 3/18/32/18/8/2 204.39 1,3 1457	LEAD 11.34 227.4 82 Pb 4/18/32/18/8/2 207.21 2,4 1737	BISMUTH 9.8 271.3 83 Bi 5/18/32/18/8/2 209.0 2,3,4 1627	POLONIUM 9.398 252 84 Po 6/18/32/18/8/2 210 2,4 962	ASTATINE 85 At 7/18/32/18/8/2 211 1,3	RADON 9.73 -71 86 Rn 8/18/32/18/8/2 222 0 -61.9
FRANCIUM 87 Fr 1/8/18/32/18/8/2 223 1	RADIUM 5 960 88 Ra 2/8/18/32/18/8/2 226.05 2 1140	ACTINIUM 1050 89 Ac 2/9/18/32/18/8/2 227 3															

*Also Called NIOBIUM (Nb)

(s) = Sublimes

Indicates elements available as pure metal.

Indicates elements available in pure or alloyed form.

Conditions of Sale

1. WARRANTY:

The Company warrants that each product to be delivered hereunder will conform to the applicable specifications and be free from defects in material or workmanship, and no other warranty, express, implied or statutory (except of title), shall be implied. *No warranty of merchantability or of fitness for purpose shall apply*. The conditions of any test shall mutually agreed upon, and the Company shall be notified of, and may be made. If any failure to conform to such specifications, or any defect in material or workmanship appears within six months from date of shipment (hereinafter referred to as the Liability Period), the Purchaser shall notify the Company thereof immediately and the Company shall thereupon correct the defect or defects by making a replacement of the product at the Purchaser's plant, or by issuance of an appropriate credit at the Company's option.

It is understood that any defective product will not be returned until authorized in advance by the Company. Returned products should be intact in form as shipped and must retain the Company's identity.

2. LIABILITY OF THE COMPANY:

The liability of the Company (except as to title) arising out of the supplying said product , or its use, whether on warrants or claim on negligence, or otherwise, shall not in any case exceed the cost of correcting defects in the products as herein provided. Upon the expiration of the Liability Period specified herein, all such liability shall terminate and foregoing shall constitute the sole remedy of the Purchaser. *In no event shall the company be liable for consequential or special damages*

PATENTS:

The purchaser shall hold the Company harmless against any expenses or loss resulting from infringement of patents or trademarks arising from compliance with Purchaser's designs or specifications or instructions.

Except as otherwise provided in the preceding sentence, the Company shall defend any suit or proceeding brought against the Purchaser so far as based on a claim that any product, or any part thereof, furnished under this contract constitutes an infringement of any patent of the United States, if notified promptly in writing and given authority, information and assistance (at the Company's expense) for the damages and costs awarded therein against the Purchaser. In case said product, or any part thereof, is in such suit held to constitute infringement and the use of said product or part is enjoined, the Company shall, at its option and own expense, either procure for the Purchaser the right to continue using said product or part; or replace same with non-infringing products; or modify it so it becomes non-infringing; or remove said product and refund the purchase price and the transportation costs thereof. The foregoing states the entire liability of the Company for patent infringement by the said products or any part thereof.

The sale of products by the Company does not convey any license, by implication, estoppel, or otherwise, under patent claims covering (a) combinations of said products with other devices or elements or (b) a process or machine in connection with which the may be used.

4. TRANSPORTATION:

Delivery of the products hereunder shall be made EXW. Point of shipment. Unless otherwise specified in the Company's pricing policies in effect at time of shipment, transportation expenses shall be paid by the Purchaser, and Company shall ship as it sees fit unless otherwise instructed in writing by Purchaser. Risk of loss or damages to products in transit shall fall upon the Purchaser, whose responsibility it shall be to file claims with the carrier.

H. CROSS COMPANY

How to Order

Please Specify

Material and temper

Size and tolerance (thickness & width or dia.)

Finish (when applicable)

Spooling Requirements (if any)

USA Contacts

Edward McClary	**Phone: 1-201-964-9380**
Diane McClary	**Fax: 1-201-964-9385**

In United Kingdom

Goodburn Engineering LTD	**Phone: 73-431-4062**
5 Darwin Close-Commercial Rd.	**Fax: 73-475-0057**
Reading-Berkshire	
RG2 OTB	
England	

Website: www.hcrosscompany.com

Sales and Customer Service: CustService@hcrosscompany.com

Quotes and Info: Info@hcrosscompany.com

TUNGSTEN AND TUNGSTEN ALLOYS

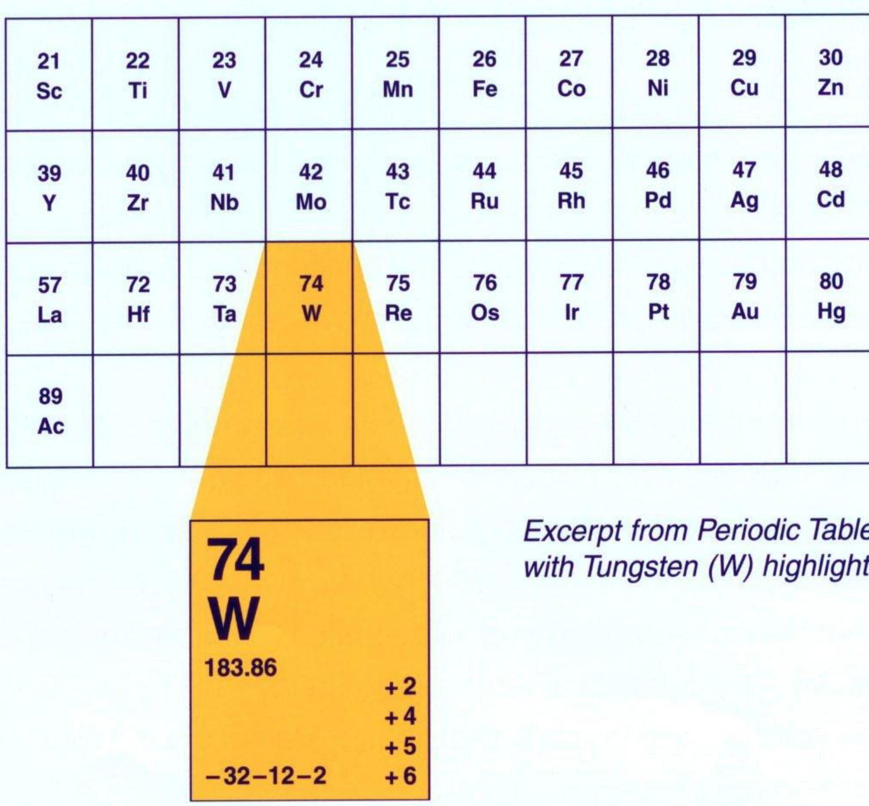
Rolling Your Way...

H. CROSS COMPANY

H. Cross Co. is the leading specialty metal rolling manufacturer of precision ribbons, sheets, foils and strips of tungsten and tungsten-base alloys. It also supplies wire, rod and cut pieces.

H. Cross Co. sells no product from stock; all its products are made to your exact specifications. The catalog is thus of necessity general in nature.

H. Cross Co. also supplies products in molybdenum and molybdenum-base alloys (catalog available), aluminum, copper, nickel, silver, gold, platinum, zirconium, titanium and others.



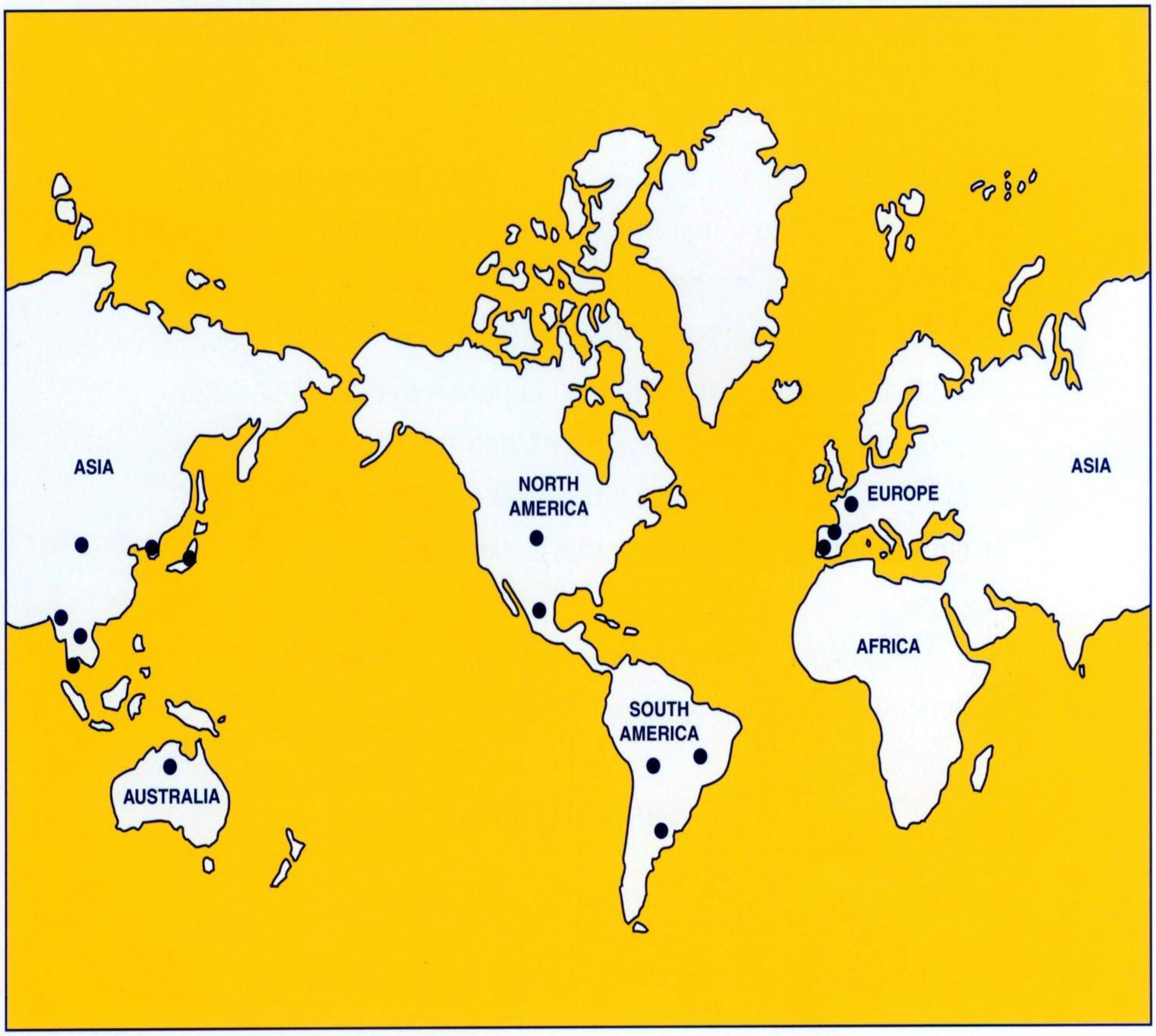
Excerpt from Periodic Table with Tungsten (W) highlighted

History

The word “tungsten” is an adaptation of the Swedish *tung sten* (heavy stone) and was first applied to the mineral scheelite about 1758. The element was first identified in 1781 by a Swedish chemist, K.W. Scheele, for whom the calcium tungstate mineral, scheelite was later named. Commercially tungsten is prepared from scheelite. The map identifies the major scheelite deposits.

Advantage is taken of their high specific gravity in concentrating tungsten minerals by means of jigs and tables. Flotation is extensively used in concentrating scheelite ores. The first concentrates are further concentrated by magnetic or electrostatic separation, floatation, roasting and leeching.

Further processing results in a yellow powder of tungsten trioxides which would be considered extremely pure by most commercial standards. However, the desired properties of tungsten wire are affected so aversely by minute quantities of unwanted impurities that another purication is added. This consists of re-dissolving the hydroxide, purifying the solution and crystallizing the tungsten out in the form of ammonium paratungstate.



● Major Scheelite Deposits

Fabrication and Applications

Tungsten has such a high melting temperature that is impractical to transform it into ingot form by conventional furnace melting techniques. Its manufacture by powder metallurgy consists of three distinct phases: the decomposition of the ore and its reduction to pure metal powder...the pressing of this powder into bars and the sintering of these bars into solid ingots...the swaging, rolling, or drawing of these ingots into desired forms and sizes.

Some of the applications of tungsten and tungsten-base alloys in their various forms are:

Strip and Ribbon

“Strip” is sheet or foil with width of 1/4 in. or more, while “ribbon” is sheet or foil with width of below 1/4 in.

H. Cross Company uses two basic techniques for manufacturing:

A. **Slit ribbon or strips**-Produced from sheet or foil to the desired finished thickness which is then precision slit to the desired width and tolerance. (End product has square edges, length is limited by length of starting sheet or foil.)

B. **Flattened-wire ribbons or strips**-Produced from wire of suitable diameter that is flattened to the desired thickness and width. Starting wire is specially processed and closely controlled in order to yield a quality finished product. (End product has round edges; length is limited by length of starting wire, which is generally available in longer lengths that sheet or foil.)

The dimensional tolerances and physical properties of the finished ribbons and strips are largely dependent on the sheet, foil or wire used as a starting point. Accordingly, Cross manufactures its own sheet, foil and wire under stringently controlled conditions. It is therefore in a position to also supply sheet, foil and wire to your needs.

Standard Tolerances

Thickness (in.)	Tolerance* (in.)	Width (in.)	Tolerance (in.)
0.0005 to 0.0019	± 0.00005	0.006 to 0.0109	± 0.0005
0.002 to 0.0029	± 0.0001	0.011 to 0.0209	± 0.001
0.003 to 0.0039	± 0.00015	0.021 to 0.309	± 0.0015
0.004 to 0.0049	± 0.0002	0.031 to 0.0609	± 0.002
0.005 to 0.0069	± 0.00025	0.061 to 0.0999	± 0.003
0.007 to 0.0109	± 0.00035	0.100 to 0.250	± 0.005
0.011 to 0.0309	± 0.0005		
0.031 to 0.040	± 0.001		

H. CROSS COMPANY

Sheet and Foil

"Sheet" is flat-rolled with thickness of .005" or more, while "foil" is flat-rolled with thickness below .005" to .0003".

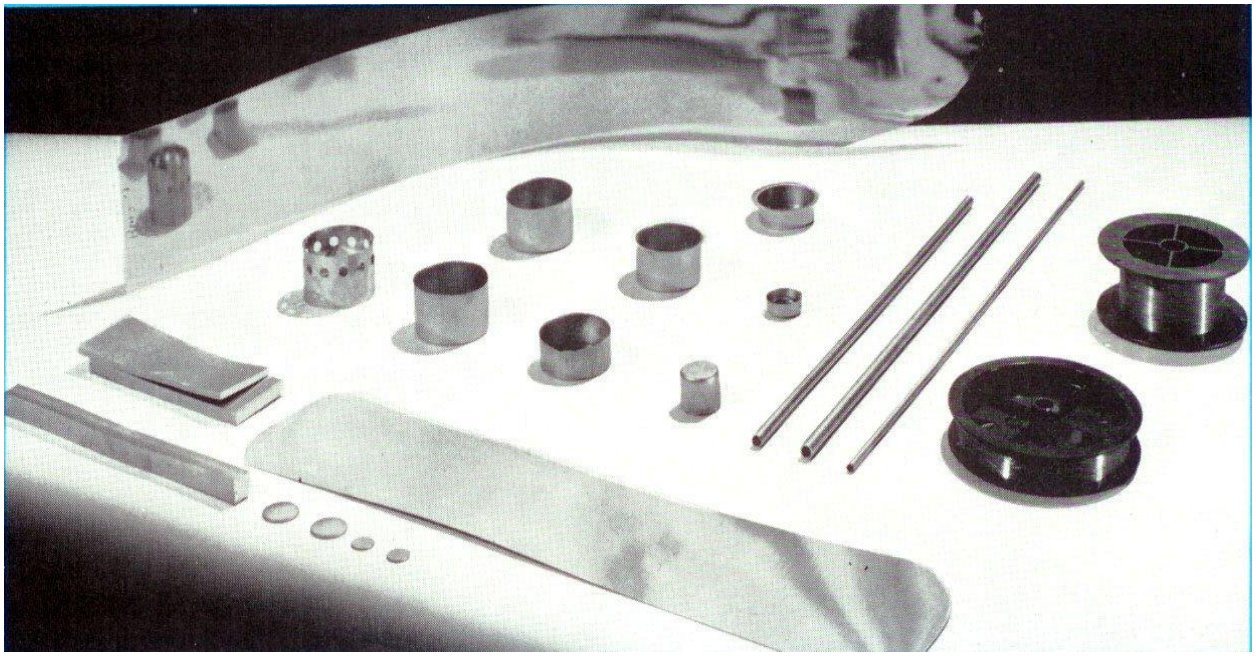
Tungsten and its alloys usually are hot-cold-worked, since true hot working (at 80% of the melting part) is not practicle. Specimens of tungsten are initially fabricated at 1485°C (2700° F) and subsequently at successively lower temperatures.

Tungsten sheet can be produced from arc-melted ingots but is often rolled from sintered slabs or bars. These are isostatically pressed from high-purity tungsten powder and sintered in hydrogen atmosphere furnaces to obtain a uniform density and grain size. (A uniform fine-grained cold-worked structure is obtained by reducing the thickness of sintered slabs at least 50% by rolling). The sheets are then stress-relieved and trimmed to the customer's requirements.

The original bar or slab is pressed into flat sections. These sections are highly heated and forged before rolling. As the metal is reduced to a very thin sheet rolling can be conducted at ordinary temperatures.

Sheets are normally supplied in a stress-relieved condition. Upon request they are supplied in the re-crystallized condition. Finally the sheets are cleaned and packaged.

The finished sheet has high polish and can be punched and stamped into various commercial forms.



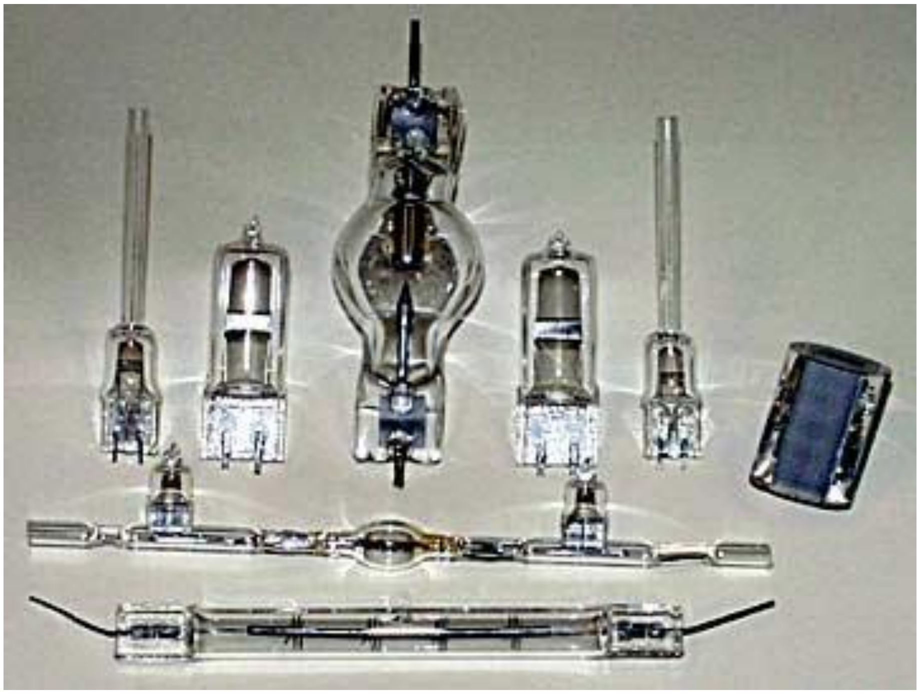
Machined Components

Wire and Rod

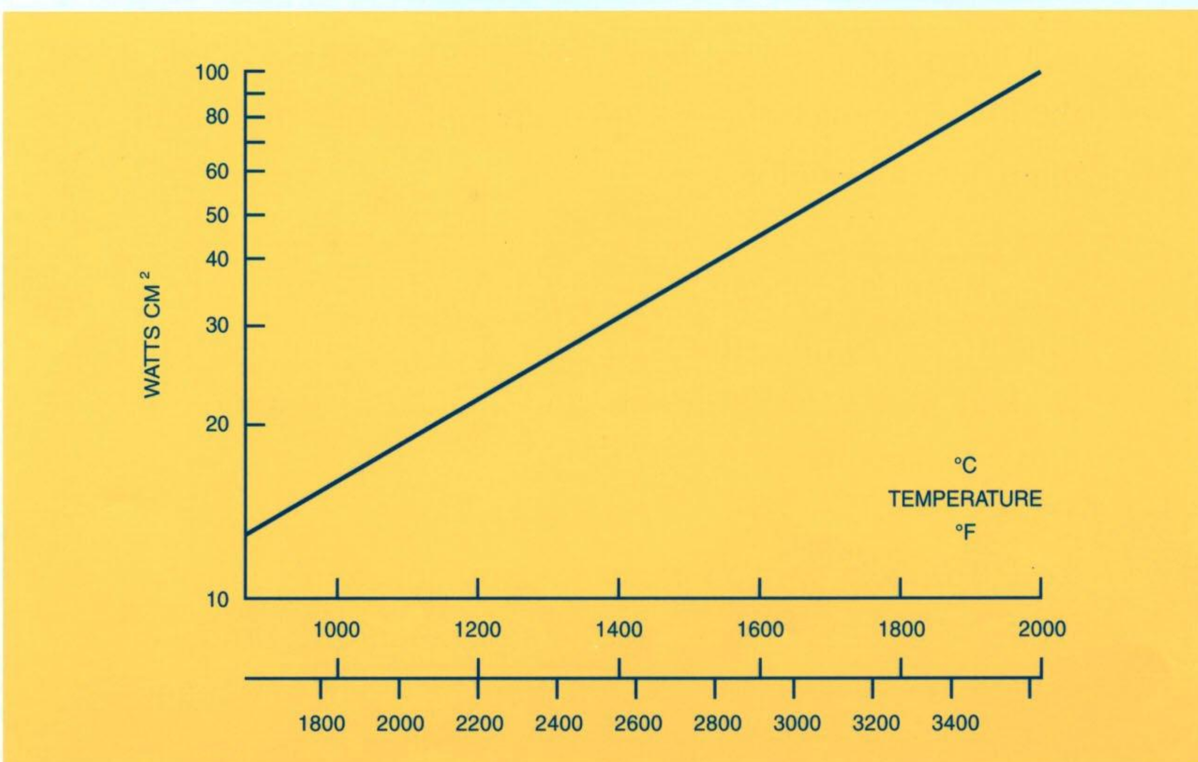
“Wire” is round material below 0.060 in. diameter usually furnished in coiled form while “rod” is round material 0.060 in. diameter and above, usually furnished in straightened and cut lengths.

Because tungsten wire is drawn below the recrystallization temperature (actually it is being “cold worked”) it work hardens and must be softened by stress-relieving anneals.

Through various drawing methods and annealing steps different physical characteristics can be produced in wire of a given size. Control of each step of wire manufacture assures our customer of wire meeting exact requirements with reliability and reproducibility.



Tungsten-halogen lamp-capsule in several high-intensity discharge arc-tubes

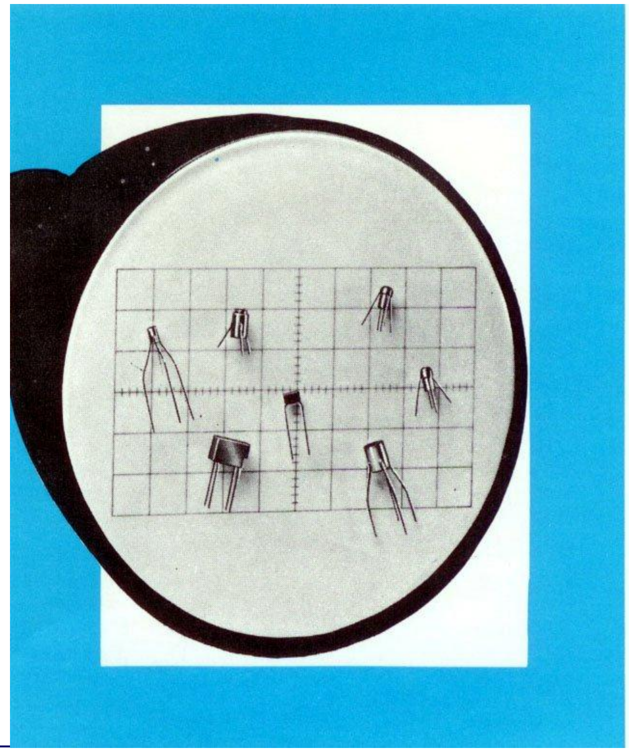


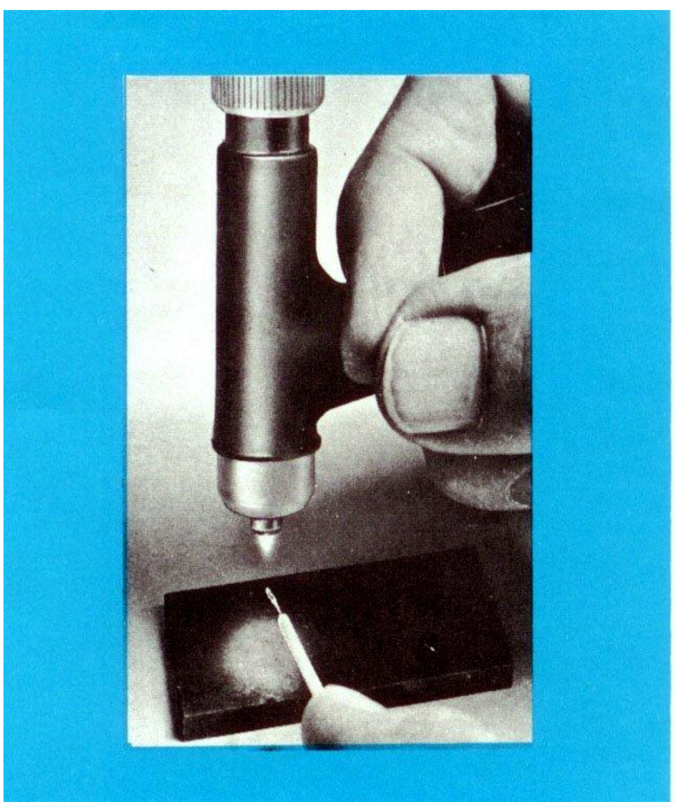
Wire Consumption (Watts) vs. Temperature

Wire Consumption (Watts) vs. Temperature

MESH FILAMENT

The desirable heat dissipation characteristics of W-25 Re wire and its great ductility are used to advantage in this mesh filament of a power grid vacuum tube.
In such applications involving high voltage coupled with high operating temperatures, the W-25 Re alloy has been displacing pure tungsten and molybdenum wire.





THERMOCOUPLE

A thermocouple for use above 2000°F can be prepared with W-25 Re wire as one lead and a tungsten wire containing 3% Rhenium (W-3 Re) as the other lead. The leads are plasma arc welded. (Tubing of Mo-50 Re is superior for thermocouple sheaths in many applications.)

Finishes

A colloidal graphite lubricant which imparts a black coating to “as drawn” tungsten wire is used to protect the wire from oxidation and to lubricate the wire as it passes through the die. Many applications require tungsten wire with characteristics other than those obtainable in “as drawn” wire. A variety of processes Produce wire with a cleaned surface or with a special finish.

After drawing operations have been completed the wire may be cleaned by exposure to elevated temperatures in a reducing atmosphere. It can also be cleaned by treating the surface chemically or etching it electrolytically. (The diameter of the wire may be further reduced after drawing by electrolytic etching.)

The cleaned wire can be electroplated with such elements as gold, silver, nickel and copper for use primarily in electronic tubes.

Packaging

All H. Cross Company products are delivered in packaging specifically designed for the product’s application. As an example wire is furnished on returnable plastic reels containing a single length of wire. If required H. Cross can adopt standard packaging methods or develop new ones for your special needs.

Made to Order

H. Cross Co. maintains two policies that are of great importance to you:

A. Nothing is sold from stock-everything is made to order.

B. A large inventory of in-process metals in all forms (e.g.; wire that can be rolled into special ribbons).

This two-fold approach means that you never have to settle for what we have but always get what you want. It also means that you usually get what you want quickly when you place your order. It also means that we can handle small orders as expeditiously as large ones and are anxious to supply your needs for research and development projects.

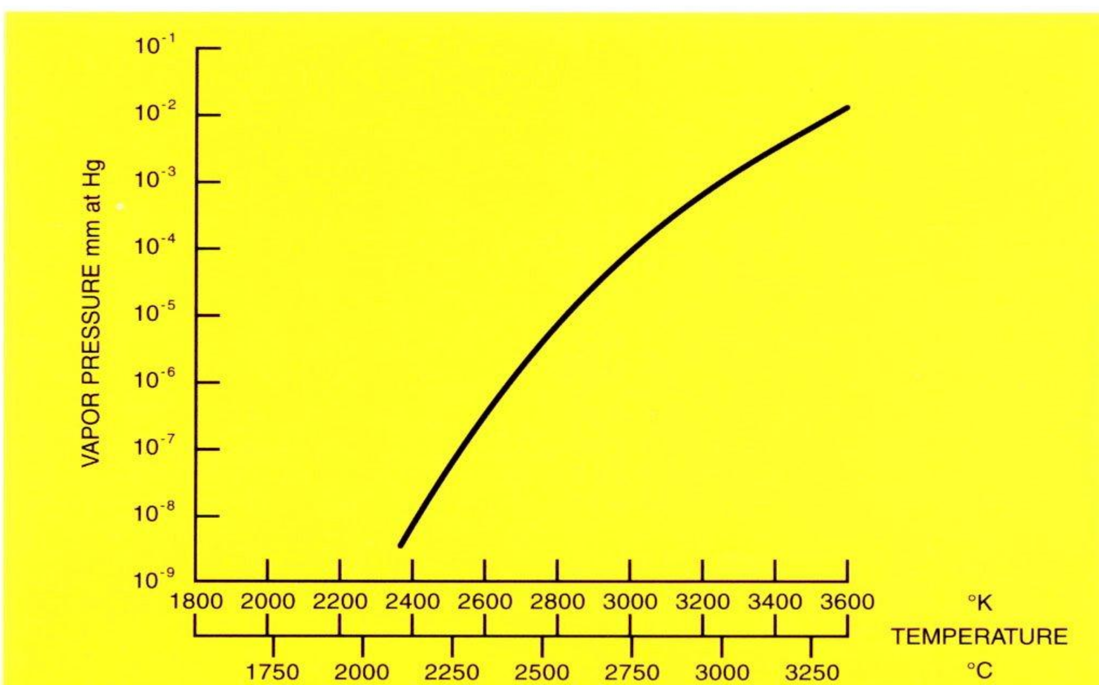
Properties Data

Typical tungsten purity specifications lie in the range (ppm by weight):

C, 30—200	H, 50 maximum	Fe, 50—200	Mo, 20—300
O, 150—3000	Al, 20—100	Ni, 10—200	Si, 10—100

Some of the disparities are governed by intended uses and methods. Tungsten powder of the higher purity levels usually is pre-sintered.

During purification by vacuum pre-sintering ample porosity (bulk and surface) provides exits for escaping gases whose pressure if they were trapped would cause swelling.



VAPOR PRESSURE–IN VACUUM VERSUS TEMPERATURE

Pure tungsten melts at approximately 3380°C (6100°F) which is the highest melting temperature of all the metallic elements. Good ductility in most cold-worked metals is not achieved until the metal's temperature is greater than 20% of the range from absolute zero to melting point. In the case of tungsten this means preheating to 675°C minimum before bending or shaping.

Diameter (Inches)		Tolerance (±Inches)	
Decimal	Fraction	Swaged & Drawn Products	Center-less Ground Products
0.500	1/2	0.0050	0.0020
0.438	7/16	0.0050	0.0010
0.375	3/8	0.0030	0.0010
0.312	5/16	0.0030	0.0010
0.250	1/4	0.0030	0.0010
0.188	3/16	0.0010	0.0010
0.125	1/8	0.0020	0.0010
0.100	-	0.0020	0.0010
0.090	-	0.0020	0.0010
0.080	-	0.0020	0.0010
0.070	-	0.0020	0.0010
0.060	-	0.0020	0.0010
0.050	-	0.0020	0.0010
0.040	-	0.0020	0.0010
0.035	-	0.0010	-
0.030	-	0.0010	-
0.025	-	0.0010	-
0.020	-	0.0010	-
0.015	-	0.0005	-
0.010	-	0.0005	-
0.009	-	0.0003	-
0.008	-	0.0003	-
0.007	-	0.0003	-
0.006	-	0.0003	-
0.005	-	0.0003	-
0.004	-	0.0003	-
0.003	-	0.0003	-

MOLYBDENUM
AND
MOLYBDENUM ALLOYS

H. CROSS COMPANY

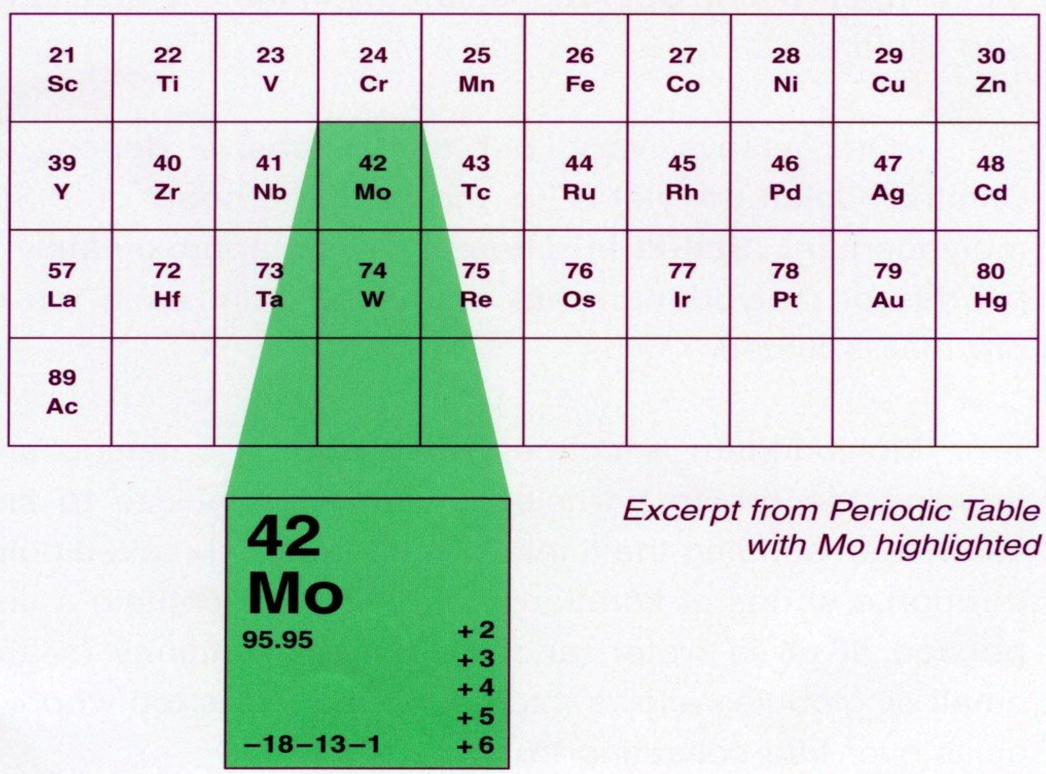
H. CROSS COMPANY

H. Cross Co. is the leading specialty metal rolling manufacturer of precision ribbons, sheets, foils and strips of molybdenum and molybdenum -base alloys. It also supplies wire, rod and a comprehensive line of customer products.

H. Cross Co. sells no product from stock all our products are made to your exact specifications. This catalog is thus of necessity general in nature.

H. Cross Co. produces many molybdenum products for the lamp industry. These include elliptically etched foil, platinum clad wire and ribbon. Our “Lamp Industry Products” section covers these products.

H. Cross Co. also supplies products in Metals from Aluminum thru Zirconium plus Customer Supplied metals and alloys.



Excerpt from Periodic Table with Mo highlighted

History

Molybdenum was discovered by C.W. Scheele in 1778 in a substance which he called molybdic ribbon. P.H. Hjelm isolated it as an element in 1790.

Between two-thirds and three-fourths of the free-world supply of molybdenum comes from mines where its recovery is the primary objective of the operation. (See map.) The remainder is recovered as a by-product of certain copper mining operations largely in the United States and Chile.

Ore assays vary but the extensive deposit at Climax, Colorado yields in the neighborhood of 0.3% molybdenum. Stated in different terms, approximately 6 pounds of molybdenum are recovered from each ton of ore that is mined.

Molybdenum is concentrated by first crushing and grinding that ore to particles comparable in size to fine sand then sending the finely ground material (called pulp) through a series of flotation cells. These cells contain a dispersion of oil in water and the material's affinity for the small oil globules allows it to be floated to the top where it spills over into collecting troughs.

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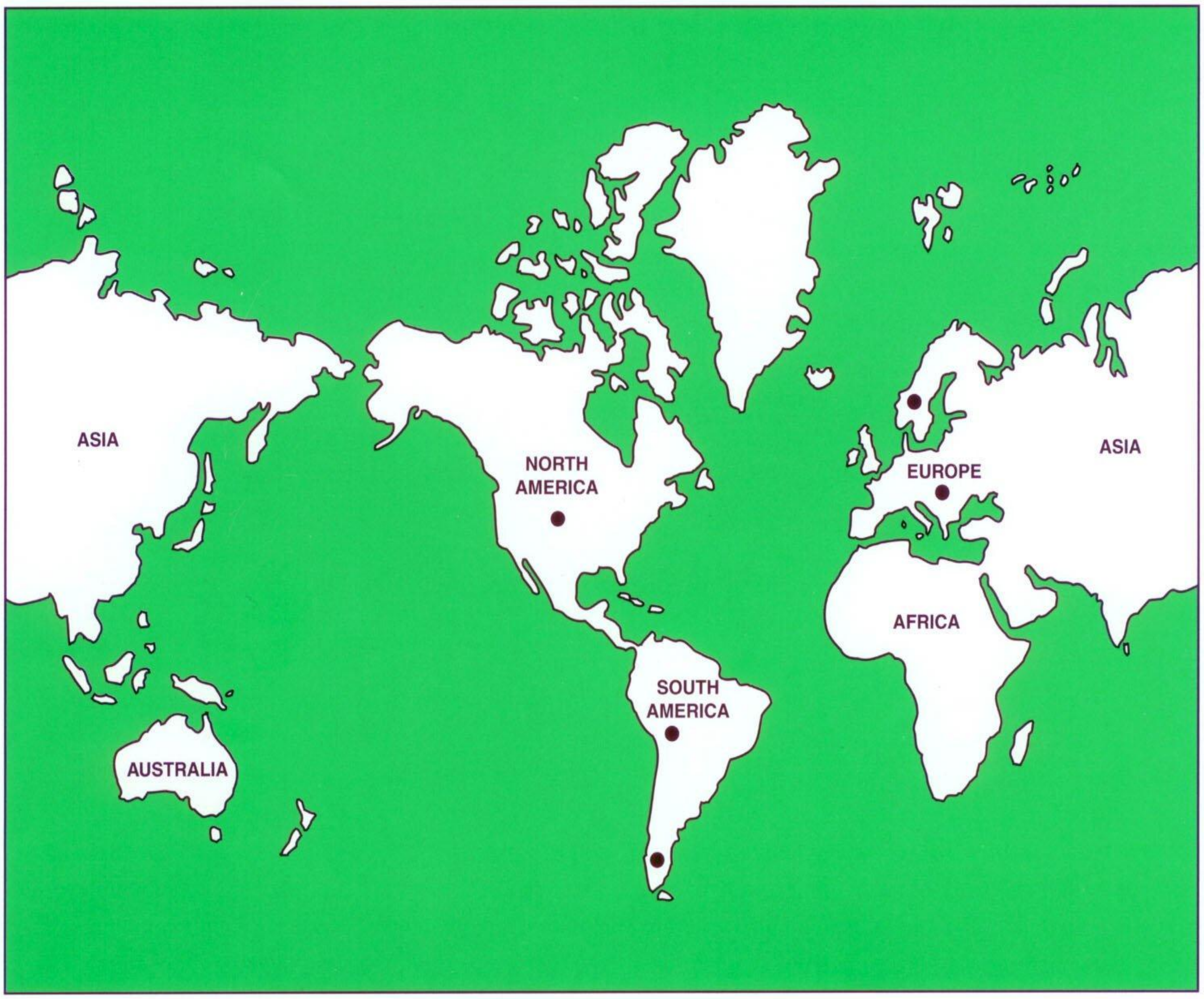

● Molybdenum Deposits

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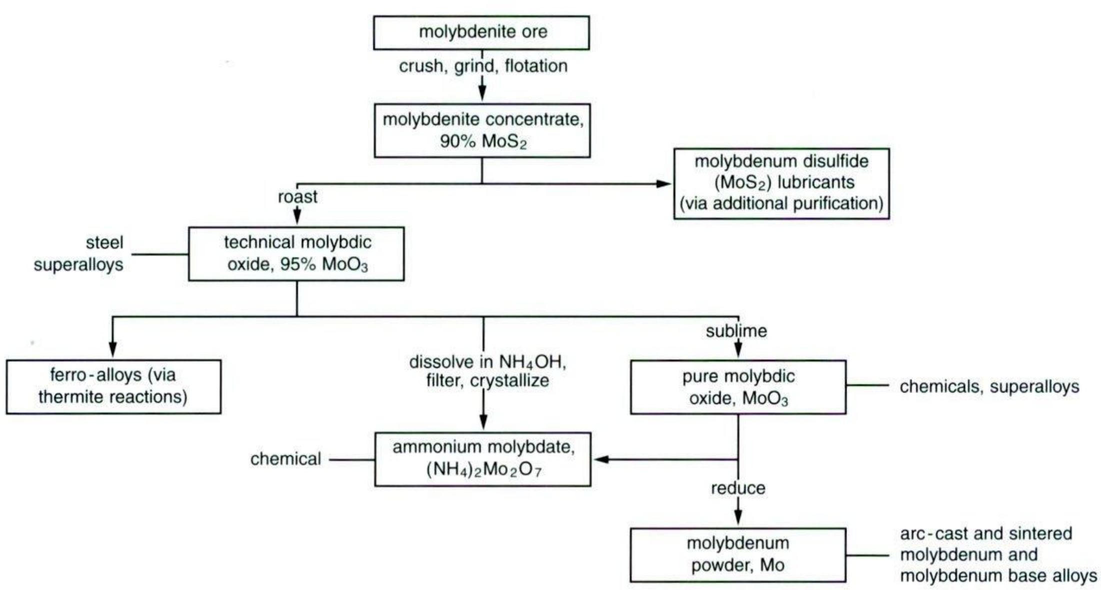
Fabrications and Applications

Molybdenum has such a high melting temperature that it is impractical to transform it into ingot forms by conventional furnace melting techniques. Its manufacture by powder metallurgy consists of three distinct phases: the decomposition of the ore and its reduction to puremetal powder...the pressing of this powder into bars and sintering of these bars into solid ingots...the swaging, rolling or drawing of these ingots into desired forms and sizes.

Some products are fabricated from arc-cast ingots. Prefabricated or continuously compacted and sintered electrodes made from metal powder are arc-melted in a water-cooled copper mold. The process is usually carried out in a vacuum, although in some instances inert-atmosphere melting is employed.



From Molybdenum Ore to Molybdenum Powder

Uses of Molybdenum and its Alloys

The first uses of molybdenum metal date from the late 19th century and were closely allied to the development of the incandescent light bulb. The increasing use of the metal in recent years has been spurred by improved methods of consolidating and by developments in the field of molybdenum-base alloys. The properties of metallic molybdenum that are responsible for increasing applications are high melting point, high strength at elevated temperatures, high modulus of elasticity, high thermal conductivity, good resistance to corrosion, low specific heat and low coefficient of expansion.

Electronic and Lamp Industries

The early light bulb application has been updated to include the use of molybdenum in a variety of electronic devices, comprising tubes, contacts, electrodes, transducers, transistors, and rectifiers.

Molybdenum wire is used in electronic tubes for grid lateral wire, lead-in wires, grid side rods, and supports. The properties of most importance to these applications are: high melting point, stability, retention of strength and stiffness at operating temperatures and thermal conductivity.

In the lamp industry quantities of molybdenum are used as structural supports, electrical leads and as the mandrel wire on which tungsten filaments are formed. (Refer to our “Lamp Industry Products” for details.)

Molybdenum is a preferred material for resistant element heaters in high-temperature electric furnaces which operate either under a high vacuum or with **non-oxidizing atmospheres.**

Molybdenum has been used for ladle-test molds for samples of molten iron and steel, where is lasts much longer than other mold materials. Here also resistance to heat checking and good thermal conductivity are the main benefits resulting from selection of molybdenum.

Molybdenum boats can be used for hydrogen-cleaning of electronic parts, high-temperature annealing of metals and high-temperature sintering of metal **powders or ceramics.**

Swaging Machine

Hydrogen Atmosphere Furnace for Pre-sintering and Annealing

Thermocouple

Various thermocouples based on molybdenum metal or molybdenum -base alloys have been suggested. Most extensively used is the molybdenum /tungsten couple, which is suitable for most temperatures above those that the platinum/platinum-rhodium couple can be used. Although the molybdenum/tungsten couple has a relatively low emf it is sufficiently accurate and reproducible for almost all uses up to at least 4500°F and has proved satisfactory for measuring the temperature of molten steel and slag.

Other thermocouples that have been used for special applications or on an experimental basis are molybdenum/nickel up to 2240°F; molybdenum/iron up to 22550°F; and tungsten/molybdenum—50% W up to 5250°F. (For thermocouples using molybdenum/rhenium alloys, refer to the rhenium data sheets.)

Refractory Use

The refractory nature of molybdenum makes it good for certain critical rocket and missile parts. The use of molybdenum that is melted and then spray coated on the surfaces of other materials is an established and growing field. The resulting composite structure often enhances the high temperature capabilities or the wear resistance of the base material. A spray coating of molybdenum is applied to automotive piston rings to improve resistance to galling.

Molybdenum as an intermediate layer between steel and some types of cladding, such as titanium and zirconium, offers the benefits of good bonding and prevention of brittle compounds that might be formed between the base metal and the cladding.

Molybdenum, with a melting point of 2622°C (4720°F) is one of the better known and most widely used of the refractory metals. In the form of wire it is used in many applications which require its special properties. These include strength at high temperatures, low thermal expansion and a high melting point. Molybdenum also has low vapor pressure, better than average electrical conductivity, and is relatively easy to machine and shape.

The chemical analyses of the most commonly supplied molybdenum and molybdenum-base alloys are given in the following chart. Since H. Cross Company sells no product from stock it can also produce other metals to your specifications.

Typical Analysis

99.95 % Purity

Na2	PPM
K	15 PPM
Al	< 8 PPM
Ca	6 PPM
Si	< 15 PPM
Fe	31 PPM
Cr	15 PPM
Ni	8 PPM
Cu	7 PPM
W	94 PPM
Mn	10 PPM
Mg	< 10 PPM
Sn	13 PPM
Co	< 8 PPM
Ti	< 10 PPM
Ag	< 1 PPM
Pb	< 10 PPM
Zr	< 10 PPM

Strip and Ribbon

“Strip” is sheet or foil with width of 1/2 in. or more while “ribbon” is sheet or foil with width of below 1/2 in. usually rolled from wire or rod.

H. Cross Company uses two basic techniques for manufacturing:

A. **Slit ribbons or strips**—Produced from sheet or foil of the desired finished thickness which is then precision slit to the desired width and tolerance. (End product has square edges; length is limited by length of starting sheet or foil.)

B. **Flattened-wire ribbons or strips**—Produced from wire of suitable diameter that is flattened to desired thickness and width. Starting wire is especially processed and closely controlled in order to yield a quality finished product. (End product has round edges; length is limited by length of starting wire, which is generally available in longer lengths than sheet or foil.)

The dimensional tolerances and physical properties of the finished ribbons and strips are largely dependent on the sheet, foil or wire used as a starting point. Accordingly, H. Cross Co. manufactures its own sheet, foil, and wire under stringently controlled conditions. It is therefore in a position to also supply sheet, foil and wire to your needs.

Sheet and Foil

“Sheet” is flat-rolled with thickness of 0.005 in. or more while “foil” is flat-rolled with thickness below 0.005 to 0.0003 in.

Flat-rolled molybdenum is manufactured by powder metallurgical techniques or arc-vacuum casting molybdenum content of 99.95%.

Purity of the molybdenum sheet (99.95%) is controlled from processing of molybdenum chemicals through reduction to metal powder, pressing, sintering and subsequent rolling.

Molybdenum foil is rolled to close thickness tolerance and uniformly bright finish. Precision slitting equipment designed specifically for foil produces the customer's specified width with square edges and tight width tolerances. Foil is processed to obtain maximum ductility for applications involving bending, spinning, drawing or stamping which in most applications can be performed at room temperature.

Wire and Rod

"Wire" is round material below .060 in. in diameter usually furnished in coiled form, while "rod" is round material .060 in. diameter and above, usually furnished in straightened and cut lengths.

Molybdenum metal powder is pressed into ingots, then sintered. The ingots are converted to rods by rolling or swaging or a combination of both. The metal is annealed or stress relieved between steps. Molybdenum work-hardens slowly in this process since each heating also serves to partially stress-relieve the energy absorbed from prior work. Therefore, relatively few anneals are required. The anneals which are used may be either full recrystallization or full stress-relief dependent upon the properties specified in the finished wire. Rods are drawn into wire through tungsten carbide or diamond dies.

Finishes

After wire drawing operations have been completed the wire may be cleaned by exposure to elevated temperatures in a reducing atmosphere. It can also be cleaned by treating the surface chemically or electrolytically.

The diameter of the wire may be further reduced after drawing by electrolytic etching. The cleaned wire can be electroplated with such elements as gold, silver, nickel, copper, for use primarily in electronic tubes. Platinum-clad wires are also available.

Packaging

Each H. Cross Company product is delivered in packaging specifically designed for the products application. As an example, wire is furnished on returnable plastic reels, each containing a single length of wire measuring 50 meters (197 feet) minimum. If required, H. Cross Company can adapt standard packaging methods or develop new ones for your special needs.

Services

H. Cross Co. maintains two policies that are of great importance to you:

A. Nothing is sold from stock—everything is made to order.

B. A large inventory of in-process metals all forms (e.g., wire that can be rolled into special ribbons).

This two-fold approach means that you never have to settle for what we have but always get what you want. It also means that you usually get what you want quickly when you place your order. It also means that we can handle small orders as expeditiously as large ones and are anxious to supply your needs for research and development projects.

LAMP INDUSTRY PRODUCTS

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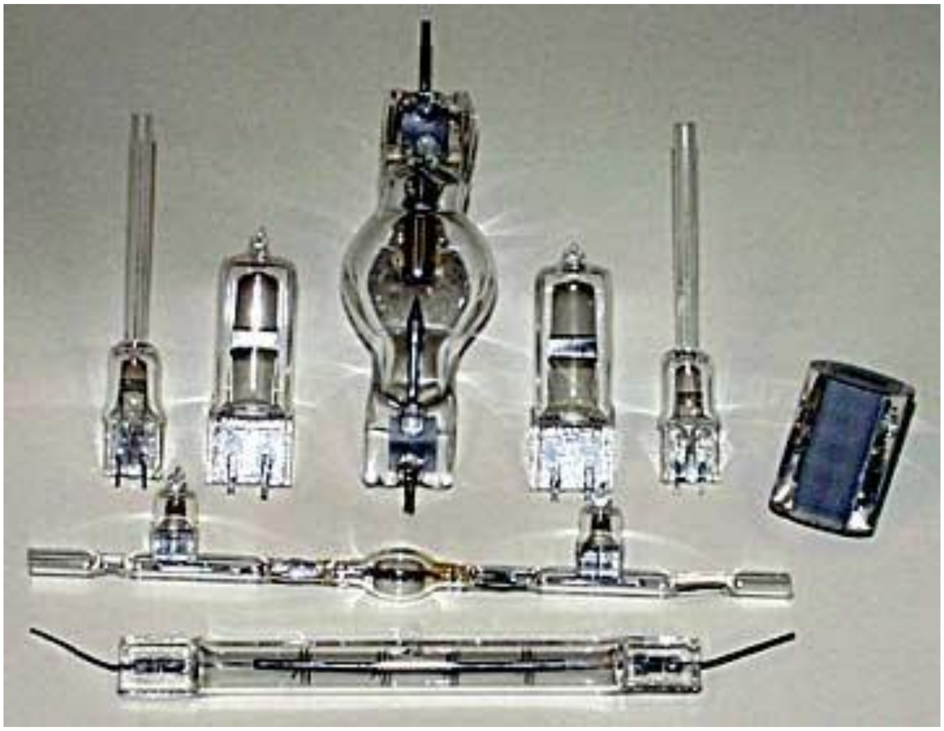
Etched Foils

H. Cross Co. is one of the largest suppliers of elliptically shaped etched molybdenum foil for hermetic sealing of quartz lamps. Etched molybdenum foil of all metals is used since its coefficient of expansion is the closest to quartz. The elliptical shape produces an air and gas tight lead into the lamp envelope, thus preventing filament degradation during lamp operation.

Etched foils form welded assemblies used as the lead wires in many types of hard glass or quartz encapsulated devices for high temperature applications. They provide the functions of internal and external electrical connection and mechanical support plus a hermetic sealing capability for pinch seals. Applications include mercury arc lamps, tungsten-halogen cycle lamps, infrared heat lamps and certain electronic and instrumental applications.



Tungsten-halogen lamp-capsule in several high-intensity-discharge arc-tubes

H. Cross Company starts with a very tightly controlled molybdenum wire made to our own specifications free from inclusions, splits or contaminations. It is then rolled very thin without creating pin holes or leaker lines.

After rolling, the material is electrolytically etched again under stringent controls, to arrive at the elliptical shape with the proper thickness and width to special requirements of each customer. It is then cleaned, annealed, inspected and spooled for shipment. For best protection of the sharp edges the spools of H. Cross Company design are slightly wider than the ribbon.

Size ribbons: Thickness—.0005” to .004”

Width—.030” to .945”

Platinum Clad Molybdenum

H. Cross Company also supplies a 15% platinum clad by weight molybdenum in both wire and flat ribbon. It is used as the welding interface between the etched molybdenum, lamp electrode and lead wire. The platinum clad molybdenum is manufactured under the same stringent controls as the etched molybdenum and is more economical as a welding flux that pure platinum that was used for years.

Sizes available:	Wire diameter	- .005” to .050”
	Ribbon thickness	-.0007” to .007”
	Width	- .020” to .125”

The etched molybdenum foil and platinum clad molybdenum are supplied on non returnable spools of H. Cross design. The spools are sealed in a polybag which is boxed and labeled for shipment.

HCR 100 Rhenium and Rhenium Alloys

History

This section attempts to provide historic background concerning Rhenium alloys most commonly used in such forms as rod, wire, tubing, sheet, foil, ribbon, and strip. A broad range of applications and a description of their properties may suggest new and other possible uses to H. Cross customers.

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1. Discovery of Rhenium

Rhenium was an unknown element when the periodic table was first produced about 1870. The properties predicted for an element of atomic number 75 turned out to be in general agreement with those of Rhenium when it was discovered in 1925.

By searching the ores of the elements close to Rhenium in the periodic system figure 101, W. Norddacrk, and O. Berg were the first to locate it, in platinum ores such as columbite and tungstite, J.G.F. Druce discovered it independently in crude manganese sulphate.

The presence of Rhenium was determined originally by lines in the X-ray spectrum in the calculated position for atomic number 75. The ores from which Rhenium was first extracted commercially came from the region of the River Rhine (Latin, Rhenus), hence the name of RHENIUM (symbol: Re).

2. Distribution of Rhenium in Nature

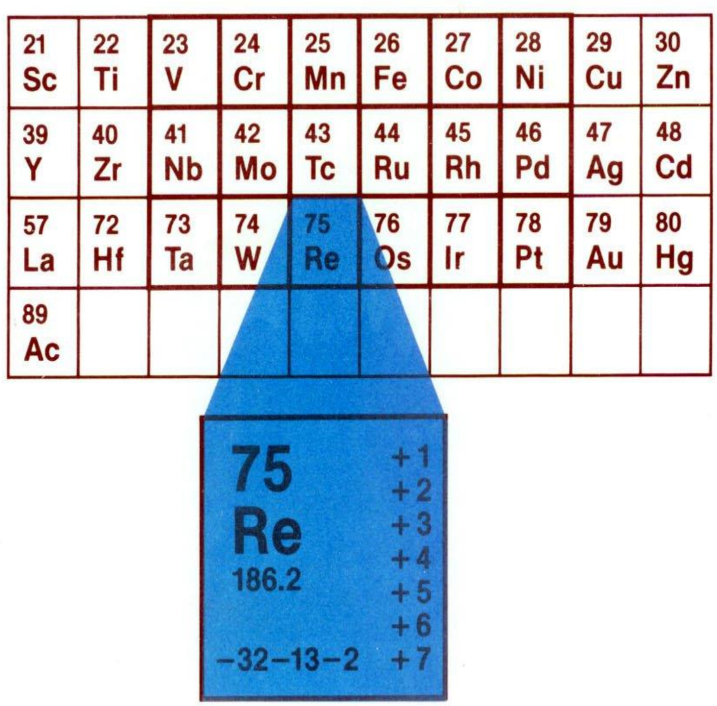
Rhenium is distributed in extremely minute quantities throughout nature, but does not exist as a mineral species. Only approximately 4 parts per billion of the Earth's crust are Rhenium, and no ore contains more than 1 part per million of Rhenium.

Rhenium is most commonly found as sulphide, in close association with molybdenite and in the presence of copper deposits. The similarity in mineralogical behavior between Rhenium and molybdenite ores allows the Rhenium to appear in the molybdenite concentrates (M0S2) that are a by-product of the processing of eporphyry copper deposits. A recent annual production of 40 million pounds on M0S2 (Free World only) contains an estimated 20,000 pounds of Rhenium. The U.S.A. and Chile produce approximately 70 and 25 percent. Respectively, of the by-product molybdenite in the Free World. Molybdenite reserves in the Free World contain 2,500,000 pounds of Rhenium (estimated).

3. Recovery and Purification of Rhenium

This section describes the process of extraction of Rhenium salts from molybdenite concentrates. Other processes are used, but are of minor significance in the United States.

FIGURE 101: Position of Re in the Periodic Table.



When molybdenite concentrates are roasted to molybic oxide, the volatility of Rhenium heptoxide results in a high percentage of the Rhenium appearing in the flue gases. The Rhenium is extracted by wet scrubbing, then separated and concentrated by ion exchange or liquid-liquid extraction techniques. A small percentage of Rhenium also appears in the flue ducts. These are usually returned to the roaster, so that Rhenium is extracted from the gases.

The last step in recovery involves crystallization of crude ammonia or potassium salts. Recovery of crude ammonium perrhenate is preferred because potassium presents problems in the processing of Rhenium metals.

The crude rhenium salts are next refined to high purity by sulfite precipitation, by fractional recrystallization of the salt, or by chemical separation of impurities.

The perrhenate is heated in hydrogen gas to produce a metal powder. This metal is washed and treated to eliminate potassium as far as possible.

4. Fabrication of Re and Re Alloys

Arc metaling of Rhenium in an inert atmosphere or in vacuum is possible. However, the metal produced has coarse grain size and may have segregation of Rhenium oxides in small amounts of grain boundaries. These features are objectionable in further fabrication and accordingly, powder metallurgy is preferred.

Rhenium powder is consolidated at pressures of 25 to 30 TSI (figure 102).

Figure 103.

Hydrogen Atmosphere Furnace for Rhenium Presintering and Annealing

The pressed bars or other compacts have densities of about 50 to 60 percent of the theoretical density of solid Rhenium.

The pressed compacts are presintered in a hydrogen atmosphere (figure 103).

Rhenium alloys are generally produced by the same powder metallurgy techniques used for Rhenium. Proper choice of powder sizes, carefully blending techniques, and adequate sintering times and temperatures produce bars of high yield and small grain size with the same homogeneity attainable by electron-beam or arc melting.

The alloys described specifically in this handbook and the related data sheets are designated as follows:

A. Molybdenum-50 Rhenium (Mo-50 Re) by weight composition.

B. Tungsten-25 Rhenium (W-25 Re) by weight composition.

C. Pure Rhenium

The subsequent fabrication into rods, wires, ribbons, ect., uses swaging, rolling, forging, and drawing with intermediate annealing.

Some at these operations may be conducted at elevated temperatures (figure 104).

The optimum sequence of operations and of working and annealing temperatures varies for Rhenium and each alloy, and depends on the desired end form. To some extent, this sequence can be predicted from the unknown mechanical properties of Rhenium and its alloys. However, optimum techniques have had to be worked out by trial and error.

5. Properties of Rhenium and Rhenium Alloys

Some of the important physical properties of Rhenium are listed in Table 101. Attention is called to the high melting point (only tungsten has a higher one), and high density (which is exceeded only by those of iridium, osmium, and platinum). Electrical and thermionic properties of Rhenium are given in Properties data HCR 300.

Figure 104. Swager

Deep Draw Applications

Rhenium and its alloys can be annealed and drawn into cups and other configurations without embrittlement. It is then used for crucibles for melting various materials without interaction on the melted material or can be made into items such as cathode caps.

H. CROSS COMPANY

HCR 200 Rhenium and Rhenium Alloys

Applications

This section illustrates several applications of Rhenium and its alloys and the related Data Sheets show others, but no attempt is made here to catalog all known or potential uses. Instead, some general suggestions will be given for answering the question:

Is Rhenium or one of its alloys useful in my application?

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The first step is to compare Rhenium or one of the alloys to other refractory metals with respect to the key properties for the application. For example:

A. For a cathode emitter, check the emissivity properties

B. For lining a chemical tank to HCI, check corrosion resistance to HCI.

C. For a resistance-heating crucible, check resistance to the molten metal involved, electrical resistivity, and high temperature rigidity.

D. For the crucible, check workability, weldability to loads, ect.

Filaments

In addition to Rhenium's excellent mechanical properties for use as filaments and heater elements, its electrical resistivity should be noted. Although about 3-1/2 times as high as that of tungsten and molybdenum at room temperature, the resistivity at 2500°C is about 1/5 higher than that of tungsten. (The temperature coefficient of Rhenium Is lower and decreases with increasing temperature). The high room-temperature resistivity permits rapid initial heating while the lower temperature coefficient minimizes the danger of "hot spots" or "burn throughs" as the filament is heated. (The Rhenium forms a stable conductive oxide film so that filament resistance is not increased appreciably).

The next step is a cost analysis. Rhenium is expensive; the alloys less so; they are therefore not used for large, structural applications. However, the material costs in relation to the total cost of the end item may be small (as for the HCI tank lining the components of X-ray or high voltage power tubes, mass spectrometers). In the case of heaters and crucibles, larger quantities may be required, but these have scrap savings in processing and in packaging and shipping (because of their greater ruggedness) must be calculated as possible offsets to higher material costs. If the cost figures at this stage are still unfavorable to Rhenium or alloys, possible advantages of a less obvious nature should be investigated, particularly with respect to service life and reliability. Long-term performance under extreme conditions of most applications may not be predictable, and may have to be determined from actual prototype units. An example to illustrate several aspects of the preceding discussion is provided by the anti-cathodes of a diagnostic X-ray tube as shown in figure 201.

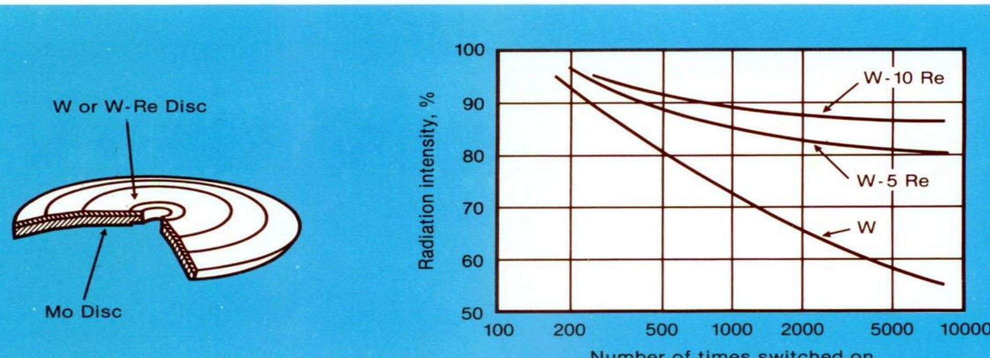
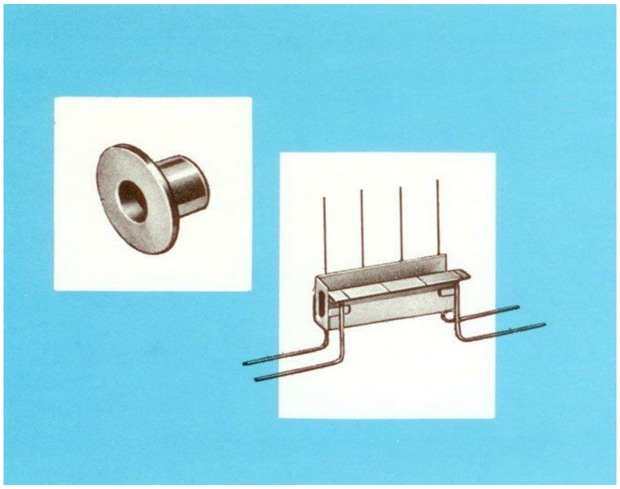


FIGURE 201. Effect of Rhenium Content of Anti-Cathode in Service Life of X-Ray Tube.



Microwave Tube Components

Mo-50 Re has outstanding ductility, so that its ease of fabrication has resulted in its displacing pure tungsten in these microwave tube components.

The anti-cathode was formerly made of tungsten, permitting production of high power at a small focus with the path heated by the electrons creating a gradient of several thousand degrees per millimeter. Because of non-uniform expansion, the surface of the anti-cathode becomes rough and cracks, resulting in a reduction in X-ray radiation intensity with time. When Rhenium is added, the improved performance depends on the percentage of Rhenium. The anti-cathode using W-10 Re loses only 11% of initial radiation intensity after being turned on 10,000 times as compared to the 50% loss for pure Rhenium. (This example, incidentally, shows that an alloy with a smaller Rhenium content that the “standard” W-25, can be used).

On the initial interruption, a thin, oxide film is formed which may prevent sticking, welding, or material transfer. However, the local heating of the contact causes violation; thus, maintain the oxide film at a thickness which does not increase electrical contact resistance significantly. The Rhenium contact is also resistant to the marine atmospheric environment.

Marine Engine Contacts

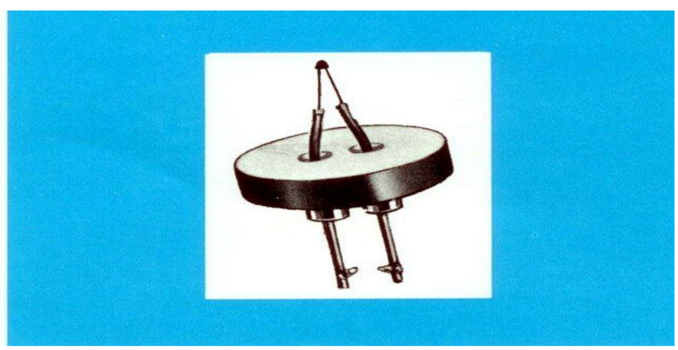
Rhenium can be used for contacts in marine engine magnetos because of its high resistance to material transfer and low arching in dc circuits, even when interrupting large currents.

Pen Nibs and Balls

Cold-worked Rhenium achieves a high hardness, making it useful for pen nibs and for pin bearing points in instruments. Various Rhenium alloys are used successfully in ball point pens and similar purposes where smooth action during long periods is required.

LANTHANUM BORIDE CATHODE

Rhenium is the choice as base material for lanthanum boride (LaB_6) electron emitters because of its inherent resistance to the formation of borides (combined, of course, with its excellent refractory metal properties). In this cathode, Rhenium wire (10 mil) is spot welded to stainless steel loads, then coated with LaB_6.



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The wrought Rhenium alloys exhibit corrosion resistance over a broad range of temperature in a wide variety of materials. Data on the resistance of Rhenium wire to molten materials is presented in Table 307. Rhenium, as well as the alloys, resist attack by molten or vaporous alkali and alkaline earth metals; they are also resistant to the molten oxides of aluminum, beryllium, calcium, and magnesium and to acetic, hydrochloric and dilute sulfuric acids. Rhenium resists attack by salt water, by humid air at 100° C, and by aluminum chloride up to about 2700°C, Rhenium and the alloys are stable in inert atmospheres, hydrogen or nitrogen until the melt, and in the air up to about 300°C (Rhenium specifically starts to produce a white, nontoxic vaporous oxide at about 600°C). The following materials attack Rhenium and the alloys: Nitric and concentrated sulfuric acids, hydrogen peroxide, molten alkali oxides in the air, and molten oxidants (e.g., nitrates, nitrites). Physical and thermal properties of Rhenium and Rhenium alloys are given in Table 306, while further mechanical properties are given in Table 308, supplemented by Table 309 and Figure 302 for high temperature stress-rupture data and by figure 303 for creep-rupture data. Table 303 shows the dependence of the properties of the final product on the fabrication method used to produce it. This dependence is shown in more detail for Rhenium wire in the test data summarized in Figure 304 and Table 310. Similar test data for Rhenium is shown in figure 305.

Figure 305 illustrates the effect of cold-working on the tensile properties of Rhenium-sheet. Typical improvements in hardness resulted from working Rhenium are illustrated in Figure 306, which also gives data for nickel for comparison. Investigation of how the addition of Rhenium affects workability and hardness of molybdenum and tungsten

Table 305. Typical Chemical Analysis of Rhenium and Rhenium Alloys. NOTE: All data are for wrought Products

Impurity	Commercially Pure Rhenium	Molybdenum-50 Rhenium	Tungsten-25 Rhenium
Al	0.0005%	0.0005%	0.0005%
B	0.0001	0.0001	0.0001
Ca	0.0001	0.0001	0.0001
Co	0.0003	0.0003	0.0005
Cr	0.0003	0.0003	0.0005
Cu	0.0002	0.0002	0.0002
Fe	0.0070	0.0070	0.0070
Mg	0.0001	0.0001	0.0001
Mn	0.0002	0.0004	0.0004
Mo	0.0025	53.0±½%	0.0004
Ni	0.0002	0.0004	0.0006
Sn	0.0002	0.0002	0.0004
Ti	0.0002	0.0002	0.0002
Zr	0.0001	0.0002	0.0002
K	0.0001	0.0002	0.0002
W	—	—	75.0±½%
C	0.0020	0.0030	0.0030
Si	0.0003	0.0006	0.0010
H	0.0005	0.0005	0.0005
N	0.0010	0.0010	0.0010
O	0.0040	0.0040	0.0040
Rhenium balance	99.97%	47.0±½%	25.0±½%

Table 306. Physical and Thermal Properties of Rhenium and Rhenium Alloys

Property	Rhenium	Molybdenum-50 Rhenium	Tunsten-25 Rhenium
Density at 20 C : (gm/cm3)	21.04	13.70	17.0
: (lb/in3)	0.755	0.494	0.61
Melting point : (˚C)	3180	2550	2815
: (˚F)	5755	4620	5100
Boiling Point : (˚C)	5900	—	—
: (˚F)	10,650	—	—
Vapor pressure: (mm Hg)		Initial behavior similar to that of molybdenum	Initial behavior similar to that of rhenium
at 1525˚C	1.10 x 10-11		
at 2000˚C	3.0 x 10-8		
at 2500˚C	4.5 x 10-5		
at 3000˚C	8.0 x 10-3		
Linear coefficient of micro-in thermal expansion: in.-C			
at 500˚C	6.12	5.72	4.48
at 1000˚C	6.65	6.45	5.04
at 200˚C	7.50	7.76	6.19
at 2500˚C	8.00	—	6.78
Specific heat: (cal/gm˚C)			
at 27˚C	0.0320	-	0.0335
at 500˚C	0.0354	-	0.0345
at 1000˚C	0.0390	-	0.0374
at 1500˚C	0.0405	-	0.0400
at 2000˚C	0.0434	-	0.0436
at 2500˚C	0.0513	-	0.0456
Thermal conductivity: watt · cm / cm2 · ˚C			
at 10˚C	0.396	0.366	-
at 200˚C	0.362	0.445	-
at 300˚C	0.358	0.480	-
at 500˚C	0.363	0.532	-
at 700˚C	0.379	0.584	-
at 1000˚C	0.408	0.640	-
at 1200˚C	0.500	0.660	0.660
at 1500˚C	0.480	0.690	0.647
at 1800˚C	0.459	0.710	0.638
at 2100˚C	0.435	—	0.630
Thermal conductivity: cal · cm / cm2 · sec · ˚C			
at 10˚C	0.095	0.088	-
at 200˚C	0.087	0.107	-
at 300˚C	0.086	0.115	-
at 500˚C	0.087	0.128	-
at 700˚C	0.091	0.140	-
at 1000˚C	0.098	0.153	-
at 1200˚C	0.120	0.159	0.158
at 1500˚C	0.116	0.166	0.153
at 1800˚C	0.110	0.171	0.151
at 2100˚C	0.104	—	0.150

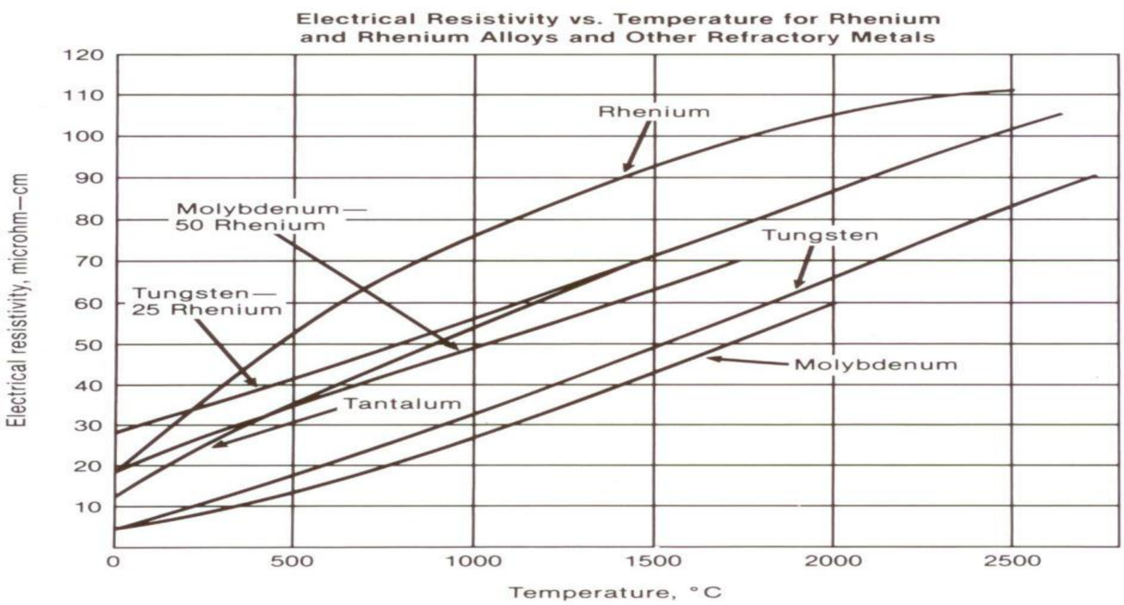
gave the results shown in Figure 307. The marked improvements in ductility obtained for mo-50 Re and W-25 Re led to the use of these two alloys for the many applications where the maximum increase in ductility is required.

The dramatic results for Mo-50 Re can best be appreciated by examining Figure 308. Bend ductility data for Rhenium and its alloys depends on the annealing temperature used during fabrication, as shown in Table 311.

Comparative data for unalloyed molybdenum and tungsten are included in the table.

Ductility is retained even after complete re-crystallization at high temperatures. This is illustrated for Mo-50 Re by Figure 309, which shows tubing being flexed as a coil spring after re-crystallization (using temperatures above 2000˚C for several hours).

One further high temperature characteristic of Rhenium may be noted here. Tungsten takes part in a “water Cycle”, that is, it vaporizes in the presence of water vapor. The rate of vaporization of Rhenium under similar conditions is only a fraction of the rate of tungsten, as shown by the data given in Table 312.



Attacking Metal	Temperature (°C)	Exposure Time (hr)	Decrease in initial 60-mil Diameter (mil)
Tin	330	1	0.1
Zinc	520	1	0.1
Aluminum	760	1.5	9.7
Silver	1060	1	0.0
Copper	1180	1	0.0
Nickel	1150	2	Specimen Dissolved
Iron	1650	1	Specimen Dissolved

Table 308. Mechanical Properties of Rhenium and Rhenium Alloys

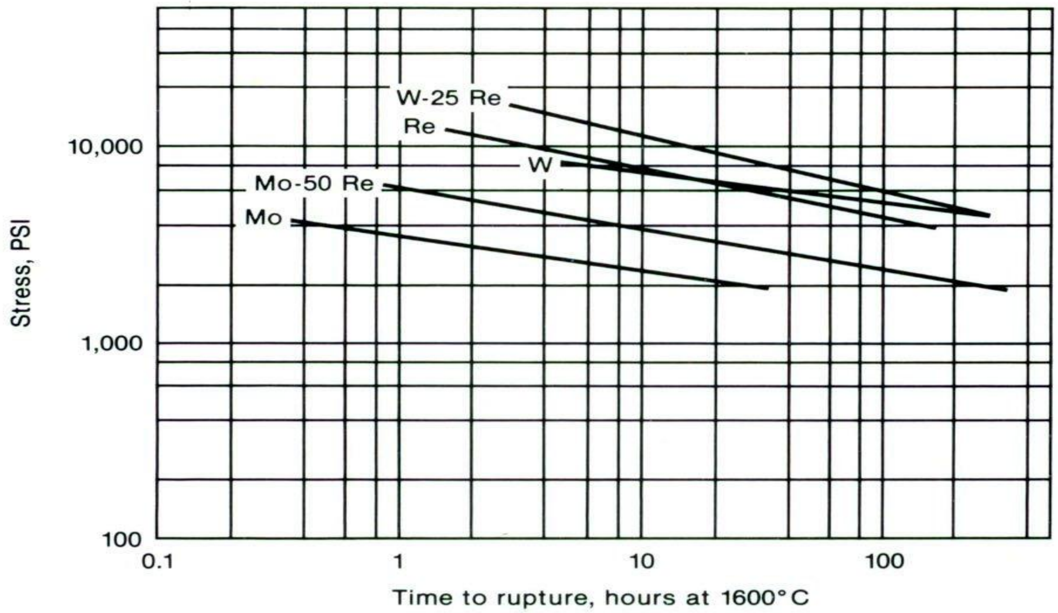
Property	Rhenium		Molybdenum-50 Rhenium		Tungsten-25 Rhenium	
Modulus of elasticity in tension (psi x 10^6)	Wrought:	Re-crystallized:	Wrought 95%:	Re-crystallized:	As Sintered:	Wrought:
at 65°C	-	-	50.8	55.7	-	-
at 20°C	-	68.0	52.3	53.3	53.6	62.5
at 200°C	-	64.5	-	-	-	-
at 400°C	-	61.0	-	-	-	-
at 600°C	-	58.5	-	-	-	-
at 800°C	-	55.5	-	-	-	-
Ultimate Tensile strength (psi x 10^3)	Wrought 15%:	Re-crystallized:	Wrought:	Re-crystallized:	Wrought:	Re-crystallized:
at 20°C	280	155	240	150	310	190
at 800°C	145	90	120	70	190	150
at 1200°C	80	60	50	35	110	105
at 1600°C	30	30	20	15	45	33
at 2000°C	18	18	-	-	-	-
Elongation (% in 3 in.)	Wrought:	Re-crystallized:	Wrought:	Re-crystallized:	Wrought:	Re-crystallized:
at 20°C	2	15-20	4	19	-	15-20
at 800°C	1	5	2	18	-	-
at 1200 °C	1	2	4	18	-	-
at 1600°C	1	2	8	17	-	-
at 2000°C	1	2	-	17	-	-
Micros-yield strength (psi x 10^3) to elon-gate 1 micro-in./in.	Wrought:	Re-crystallized:	Wrought:	Re-crystallized:	As Sintered:	Wrought:
at 20°C	10	-	-	-	90	176
Yield strength. 0.2% offset (psi x 10^3)	Wrought 15%:	Re-crystallized:	Wrought 50%:	Re-crystallized:	Wrought:	Stress-relieved:
at 20°C	255	42	210	116-123	-	249-294
at 800°C	-	-	-	-	-	131-150
at 1200°C	-	-	-	-	-	59-78
at 1600°C	-	-	-	-	-	15-20
at 2000°C	-	-	-	-	-	6-7
at 2500°C	-	-	-	-	-	1.5-2.5
Hardness at room temperature (VHN)	Wrought 10%: 450 Wrought 30%: 580	Wrought 20%: 530 Re-crystallized: 250	Wrought 95%: 600	Re-crystallized: 350	Wrought 50%: 590 Stress-relieved: 450	Wrought 90%: 740
Poisson’s Ration	0.49		-		-	

(*Samples annealed prior to testing for 2 hrs. at test temperature (1—in. guage length.)

Test Temp	Property	Rhenium			Molybdenum-50 Rhenium			Tungsten-25 Rhenium		
1600 °C	Stress (psi x 10^3)	1.5	6	12	2	4	6	4.8	10	15
	Rupture time (hr)	239	35.3	2.24	232	9.19	1.12	198	15.1	3.3
	Elongation at rupture (%)	2.4	11	6	56	48	109	44	41	53
	Time to produce 2% elongation (h2.)	-	-	-	-	-	-	-	-	-
2200 °C	Stress (psi x 10^3)	1	2.5	5	0.75	0.875	1	1.5	2.5	4
	Rupture time (hr)	352	20.4	0.91	8	5.60	1.60	6.20	1.1	0.18
	Elongation at rupture (%)	26	11	8	73	69	80	17	18	25
	Time to produce 2% elongation (h2.)	-	-	-	-	-	-	-	-	-
2600 °C	Stress (psi x 10^3)	1	2	3	-	-	-	0.34	0.9	1.5
	Rupture time (hr)	29.2	4.36	0.25	-	-	-	35	2.5	0.42
	Elongation at rupture (%)	15	10	25	-	-	-	14	14	26
	Time to produce 2% elongation (h2.)	-	-	-	-	-	-	-	-	-
2800 °C	Stress (psi x 10^3)	0.6	1	2	-	-	-	0.65	-	-
	Rupture time (hr)	11.4	2.9	0.55	-	-	-	1.12	-	-
	Elongation at rupture (%)	11	6	7	-	-	-	8	-	-
	Time to produce 2% elongation (h2.)	-	-	-	-	-	-	-	-	-

Table 310 Ductility vs. Temperature for Re-crystallized and Cold Worked Rhenium Wire (0.050 to 0.065 in. Diameter)

		Test Temperature (°C)				
Property	Room Temperature	500	1000	1500	2000	2300
Elongation, %						
Re-crystallization	10	9	1—2	1—2	-	1—2
Reduced 9% in Area	8	7	2—3	2	2—3	-
Reduced 15% in Area	-	1	1	1	1	-
Reduction, %						
Re-crystallized	16	19	2—3	2	-	2
Reduced 9% in Area	6	9	1	1	1	-
Reduced 15% in Area	2	1	3	10	4	-



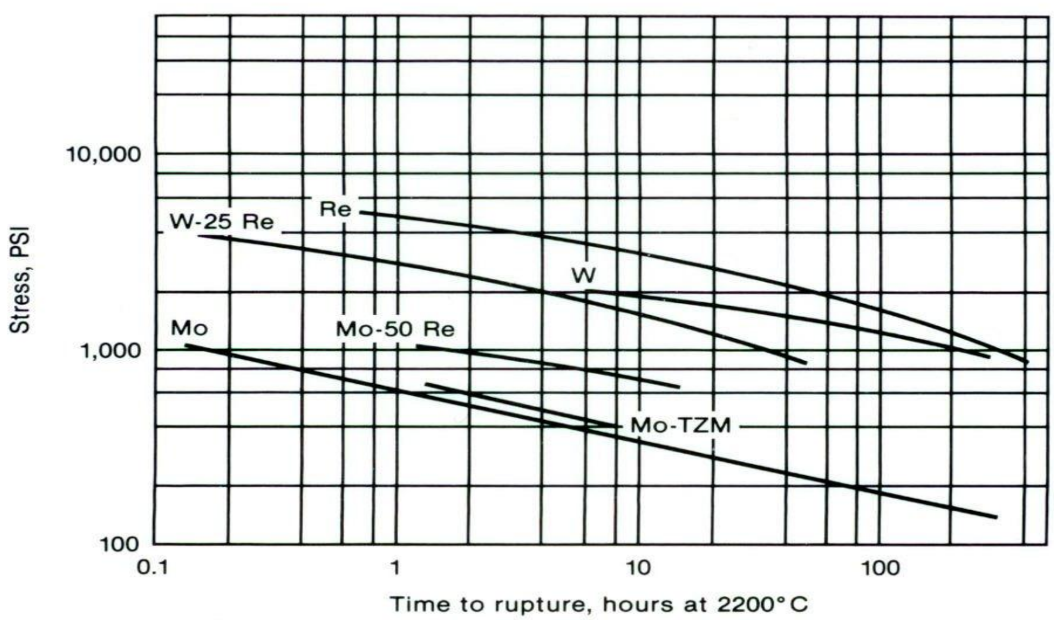


Figure 302. High Temperature Stress-Ruptures Data for Rhenium and Rhenium Alloys Compared to Molybdenum and Tungsten.

FIGURE 303. High Temperature Creep-Rupture Data for Rhenium and Rhenium Alloys Compared to Tungsten.

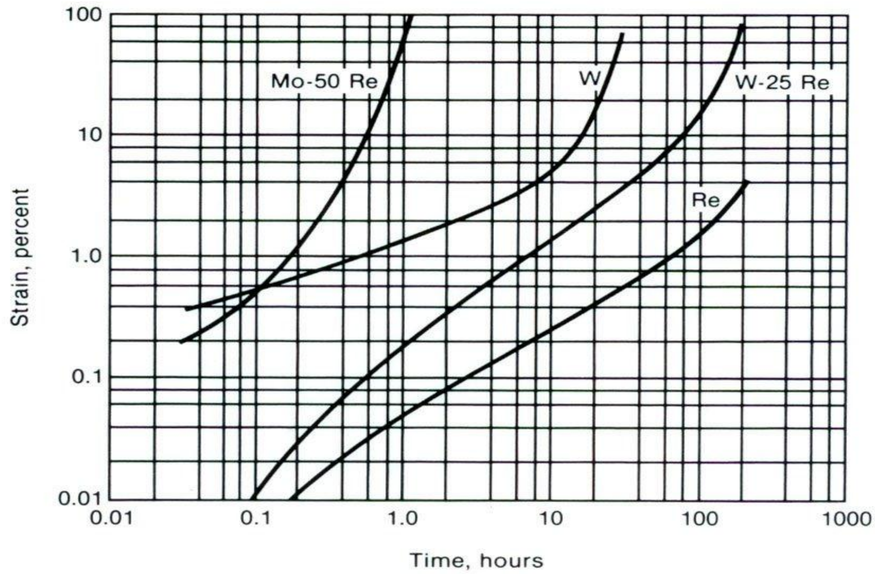


Table 311. Ductility of Rhenium, Rhenium Alloys, Molybdenum and Tungsten

Annealing Temperature (°C)	Re	Mo-50 Re	W-25 Re	Mo	W
As drawn	>6T	1T	2T	1T	1T
1000	1T	1T	2T	1T	1T
1200	1T	1T	1T	1T	2T to glass brittle
1400	1/2T	1/2T	1/2T	>6T	Glass brittle
1600	1/2Y	1/2T	1/2T	>6T	Glass brittle
1800	1/2T	1/2T	3T	>6T	Glass brittle
2000	1/2T	1/2T	5T	>6T	Glass brittle

Note: "1" is the ratio of the smallest bend diameter to wire diameter. All samples tested were 0.020 inch diameter.

Table 312. "Water Cycle" Effects for Rhenium and Tungsten

	Test Temperature (°C)		
Material	Initial	Final	Loss After 7800 Hours (mg/cm2)
Tungsten	1300	1275	1.5
Rhenium	1750	1660	8.25
	1300	1200	0.65
	1750	1660	0.98

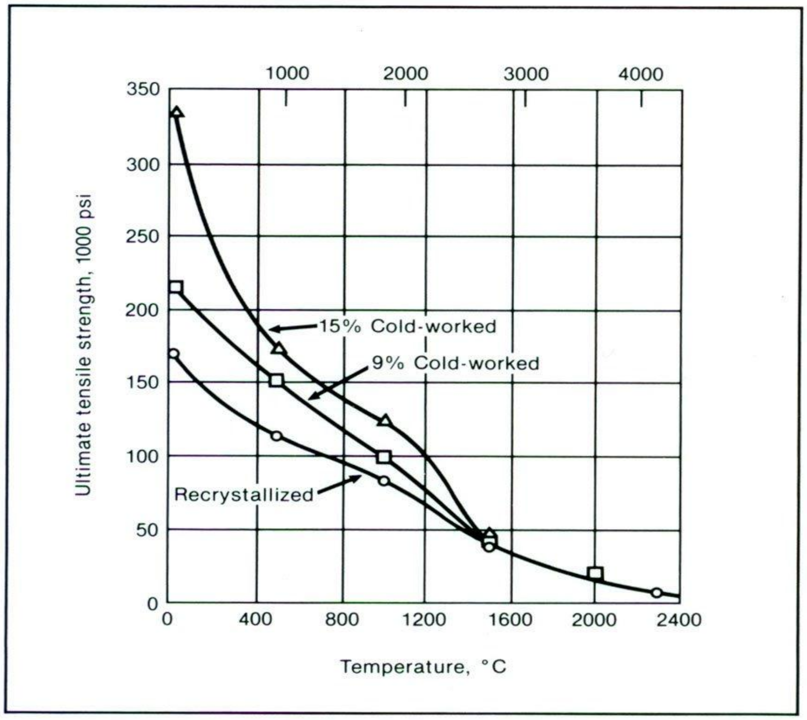


Figure 304. Ultimate Tensile Strength vs. Temperature for Re-crystallized and Cold -Worked Rhenium Wire (0.05 and 0.065 in. Diameter).

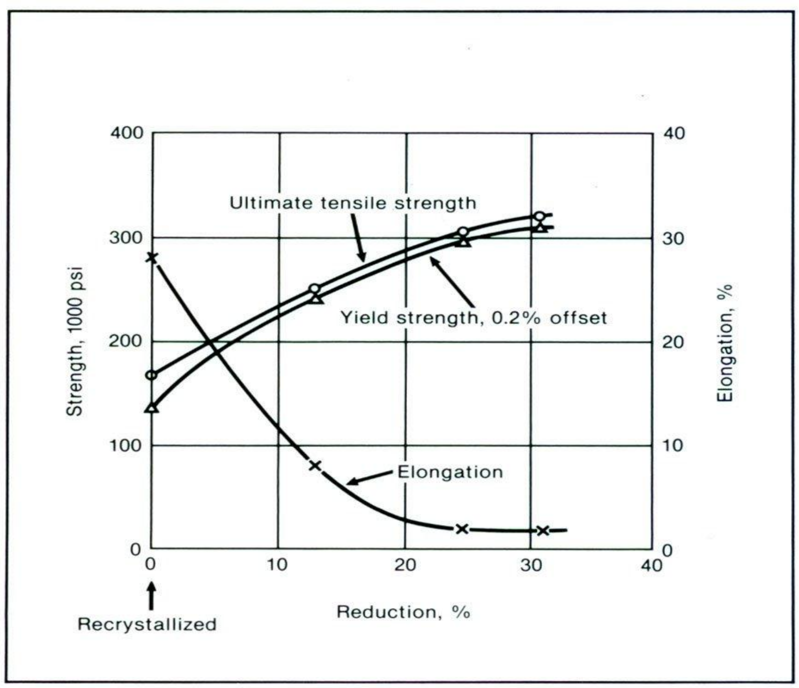


Figure 305. Tensile (at Room Temperature) for Re-crystallized and Cold-Rolled Rhenium Sheet.

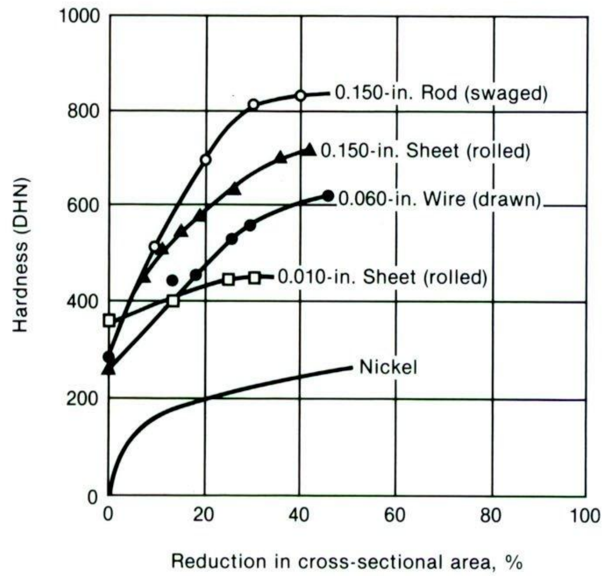


FIGURE 306. Work Hardening Characteristics of Rhenium.

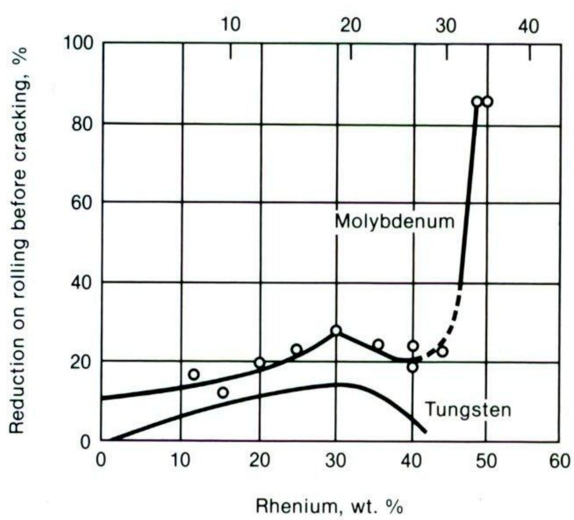


FIGURE 307. Rhenium % vs. Ductility of Molybdenum and Tungsten at Room Temperature.

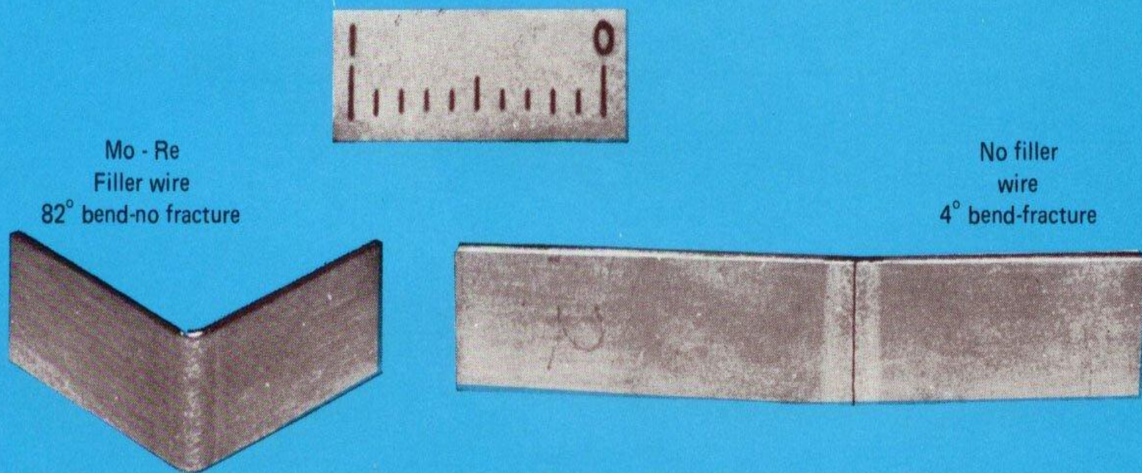


FIGURE 308. Ductility of Mo-Re Wire in Molybdenum Welding.

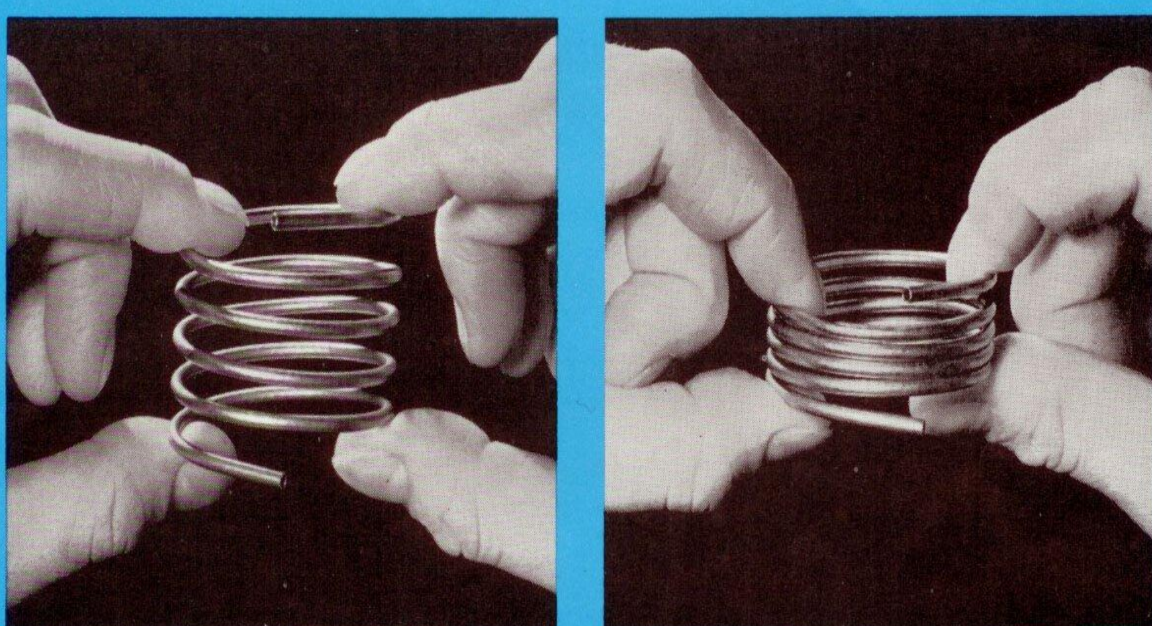


Figure 309. Ductility of Re-crystallized Mo-50 Rhenium.

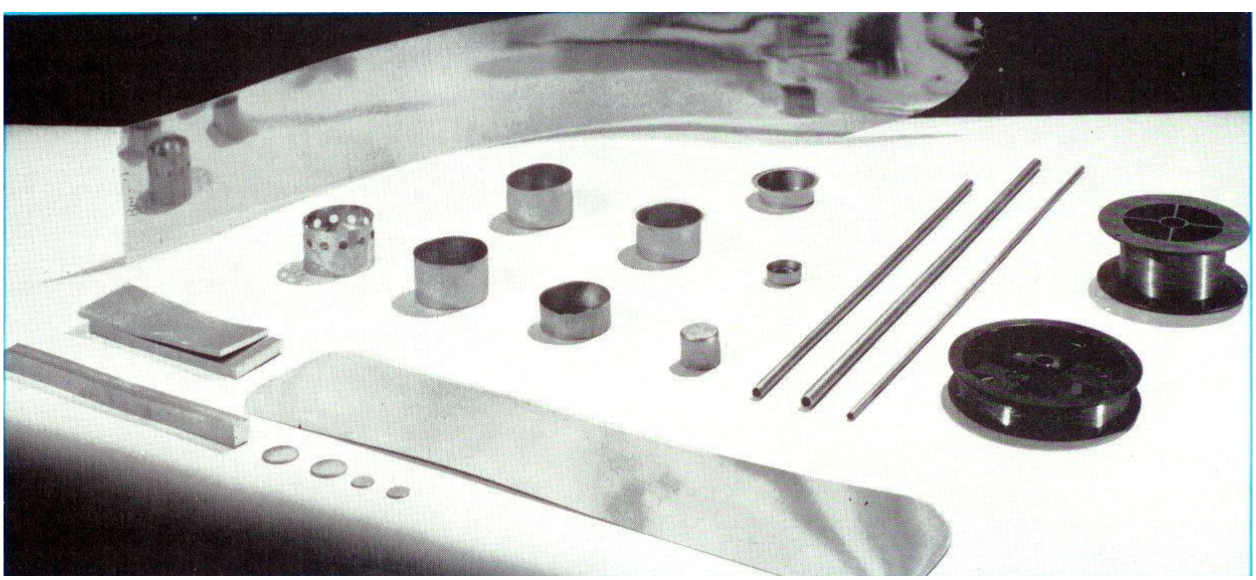
HCR 400 Rhenium and Rhenium Alloys

Fabrication

By working, welding, machine operations and subsequent fabrications H. Cross produces ribbons, strips, sheets, foil, rod and wire for a wide range of possible applications.

Machined Components

The variety of forms possible with Rhenium and its alloys (shown for Mo-50 Re below) illustrates its excellent metallurgical properties.



Fabrication

Metallurgical properties of Rhenium and Rhenium Alloys are summarized in Table 401. Characteristics of Rhenium and the alloys with respects to workability, weldability and machineability may be summarized as follows:

a. Working Re-Re Alloys

1. Rhenium—Formed readily at room temperature. "Hot shortness" avoided by cold working. Frequent intermediate annealing (inert or reducing atmospheres) is required because of rapid work hardening.

2. Molybdenum-50 Rhenium—Alloy in either stress-relieved or re-crystallized condition far surpasses pure molybdenum. Can be worked warm or cold. (For certain operations in fabrication, high yield strength requires 500-700°C temperatures).

3. Tungsten-25 Rhenium—Easier to work than pure tungsten. Warm working required except for thin sections. In general, 1200-1350°C is required, although forging can be done at temperatures as low as 800° C.

b. Welding Re-Re Alloys

1. Rhenium—Can be welded by inert gas or electron-beam methods if protected against oxidation. Resulting welds are extremely ductile and can be formed further at room temperatures.

2. Molybdenum-50 Rhenium—Same as for pure Rhenium. Outstanding fusion weldability (nearly as good as for pure Rheium.

3. Tungsten-25 Rhenium—Alloy is easier to weld than pure tungsten. Use inert gas or electron-beam process. The welds are not ductile, but possess great integrity and shock resistance (mechanical and thermal).

c. Machining Re-Re Alloys

1. Rhenium—Following methods should be used: ECM, EDM, abrasive cutting, or grinding. Machining is very difficult with carbide tools or conventional tools or conventional methods.

2. Molybdenum-50 Rhenium—Alloy can be machined using conventional methods and is particularly suited to EDM and to abrasive machining. (Silicon carbide and aluminum oxide wheels, with light pressure, constant movement and flood cooling recommended).

3. Tungsten-25 Rhenium—Same as for Molybdenum-50 Rhenium. Alloy is not as machinable as pure tungsten.

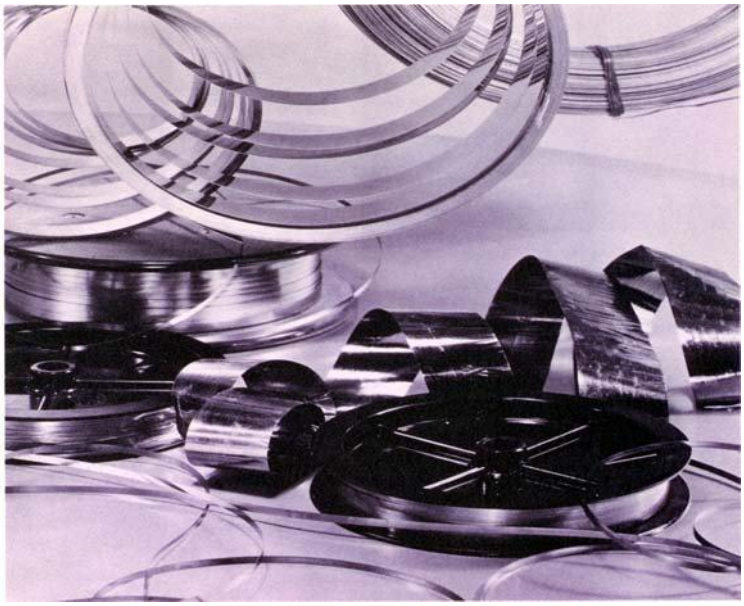
Table 401. Metallurgical Properties of Rhenium and Rhenium Alloys

Property	Rhenium	*Molybdenum-50 Rhenium	*Tungsten-25 Rhenium
Ductile-to-brittle transition temperature	Does not exist	Below-254°C (re-crystallized)	93°C (re-crystallized)
Re-crystallization temperature 1 hr*	1400-1600°C	1300-155-°C	1500-1650°C
Stress-relieving temperature	1200-1400°C	100-1200°C	1200-1400°C

* Shown as range (because temperature required varies with amount of work-hardening).

HCR 500 Rhenium and Rhenium Alloys

Ribbon and Strip Data



H Cross sells no product from stock. All products are made to your exact specifications. Accordingly alloys and sizes not shown herein can often be provided at no greater cost than similar “standard” products.

Standard Tolerances

Thickness (in.)	Tolerance * (in.)	Width (in.)	Tolerance (in.)
0.0005 to 0.0019	±0.00005	0.006 to 0.0109	±0.0005
0.002 to 0.0029	±0.0001	0.011 to 0.0209	±0.001
0.003 to 0.0039	±0.00015	0.021 to 0.309	±0.0015
0.004 to 0.0049	±0.0002	0.031 to 0.0609	±0.002
0.005 to 0.0069	±0.00025	0.061 to 0.0999	±0.003
0.007 to 0.0109	±0.00035	0.100 to 0.250	±0.005
0.011 to 0.0309	±0.0005		
0.031 to 0.040	±0.001		

*Closer tolerances can be maintained if necessary

Definitions

Ribbon—Up to 1/4 inch wide (up to 1/8 inch wide for W-25 Re)
Strip—Wider than 1/4 inch (wider that 1/8 inch for W-25)

Alloys Offered

a. Molybdenum-50 Rhenium (mo-50 Re) by weight composition.
b. Tungsten-25 Rhenium (w-25) by weight composition.
c. Rhenium 99.99% pure.
d. High Purity Rhenium 99.995%.

Properties of Rhenium and Rhenium Alloys

The "Properties Data HCR 300" contains detailed information on physical, chemical, electrical, mechanical and other properties for Rhenium and Rhenium alloys. Weights are given in lb/linear foot for Rhenium Multiply by: 0.645 for Mo-50 Re

0.0934 for W-25 Re
for gm/linear cm

Fabrication

Rhenium—In making strips, pressed and sintered compacts and bars are rolled.

Thickness Inches	Rhenium *lb/sq. in. ± 0.5%	Moly Rhenium *lb/sq. in. ± 0.5%	Rhenium Tungsten *lb/sq. in. ± 0.5%
.240	.188750	.123500	.176500
.187	.141485	.092378	.132022
.125	.094375	.061750	.088250
.100	.075500	.049400	.070600
.070	.052850	.034580	.049420
.060	.045300	.029640	.042360
.050	.037750	.024700	.035300
.040	.030200	.019760	.028240
.030	.022650	.014820	.021180
.025	.018875	.012350	.017650
.020	.015100	.009880	.014120
.015	.011325	.007410	.010590
.012	.009060	.005928	.00847
.010	.007550	.004940	.00706
.008	.006040	.003962	.00564
.006	.004530	.002964	.004236
.005	.003775	.002470	.003530
.004	.003020	.001976	.002824
.003	.002265	.001482	.0021180
.002	.001510	.000988	.001412
.001	.000755	.000494	.000706
.0005	.000377	.000247	.000353
.0003	.000226	.000148	.000212

HCR 600 Rhenium and Rhenium Alloys

Sheet and Foil Data Sheet

H Cross sells no product from stock. All products are made to your exact specifications. Accordingly alloys and sizes not shown herein can often be provided at no greater cost than similar "standard" products.

Typical Mechanical Properties of Rhenium and Rhenium Alloys

	Tensile Strength (psi)	Yield Strength 0.2% Offset (psi)	Elongation in 2 inches (percent)	Hardness (VHN)
Rhenium				
Wrought 20%	287,000	274,00	2	530
Re-crystallized	150,00	39,00	19	250
Molybdenum-50 rhenium				
Wrought 50%	240,000	210,000	1	510
Re-crystallized	150,000	123,00	22	340
Tungsten-25 rhenium				
Wrought 50%	310,000	295,000	1	600
Re-crystallized	190,000	180,00	16	475

Sheet and Foil

Weights given are in lb/linear in. for Rhenium based on density of 0.759 lb/in.3

Multiply by: 0.645 for Mo-50 Re

0.934 for W-25 Re

for gm/linear cm

Definitions

Sheet—0.005 inches and above

Foil—below 0.005 inches

Alloys Offered

a. Molybdenum—50 Rhenium (mo-50 Re) by weight composition.

b. Tungsten—25 Rhenium (W-25 Re) by weight composition.

c. Rhenium 99.99% pure.

d. High Purity Rhenium 99.995%.

Fabrication

Rhenium—Pressed and sintered compacts and bars are reduced to final thickness by a series of rolling passes. The product is normally furnished in fully recrystallized form. Mo-50 Re—This alloy is worked as Rhenium. W-25 Re—This alloy is rolled to size. W-25 Re is normally supplied in stress-relieved condition.

Properties of Rhenium and Rhenium Alloys

The "Properties HCR300" contains detailed information on physical, chemical, electrical, mechanical, and other properties for Rhenium and Rhenium alloys. Typical mechanical properties are given in Table 1.

Benefits in Applications

The significant properties of sheet and foil of Rhenium and Rhenium alloys in most applications are:

-Outstanding ductility and formability

-Weld ductility—even after re-crystallization

-High temperature strength

-Low temperature workability

-Unique and favorable electrical characteristics

-Second-highest melting point of any metallic element

-Third-highest modulus of elasticity of any metallic element

-Good corrosion resistance

The sheet and foil materials are used where their outstanding ductility and formability (as evidenced in the examples shown) are combined with one or more other desirable properties (e.g., low vapor pressure at elevated temperatures for emission applications). Significant benefits of using these materials are:

-Longer part life

-Wear resistance

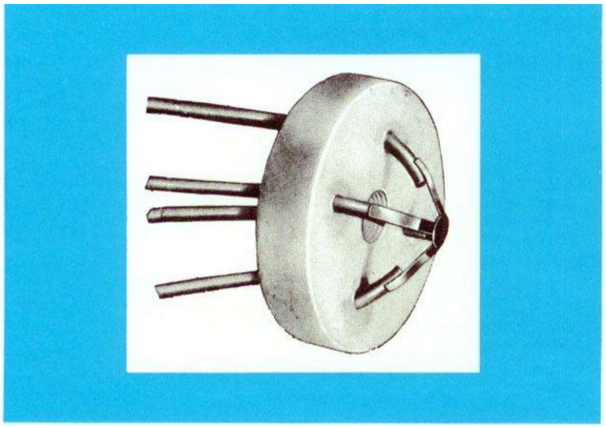
-Mechanical and thermal shock resistance

-Corrosion resistance

-Increased electrical resistivity

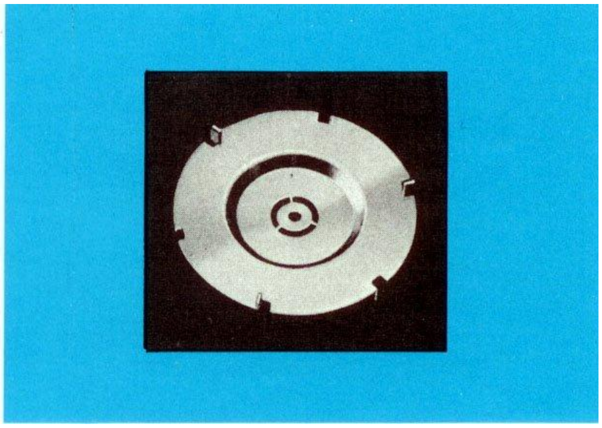
-Higher part reliability

-Increased production yields



Lanthanum Boride Cathodes

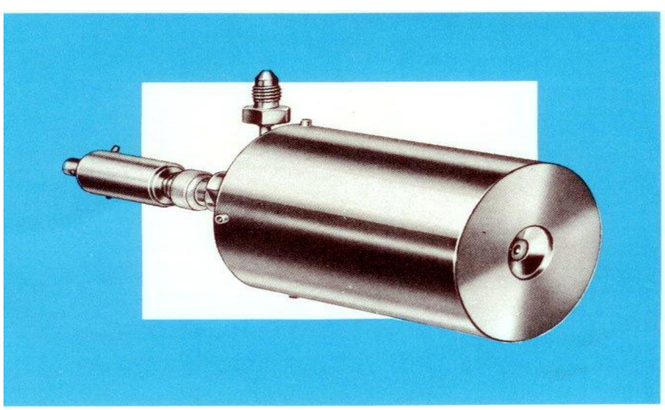
The emission source for this GE cathode is a lanthanum boride coating on a disc punched from Rhenium foil. The disc is welded to four supporting strips of Rhenium (taking advantage of its high-temperature strength) which are in turn welded to stainless steel wires.



Focusing Electrode and Anode

Mo-50 Re has desirable thermal and electrical properties combined with outstanding ductility and workability. The parts are drawn and punched in a single operation and the three slots surrounding the center whole in the anode are formed by EDM machining.

Thickness Inches	Rhenium *lb/sq. in. ± 0.5%	Moly Rhenium *lb/sq. in. ± 0.5%	Rhenium Tungsten *lb/sq. in. ± 0.5%
.240	.188750	.123500	.176500
.187	.141485	.092378	.132022
.125	.094375	.061750	.088250
.100	.075500	.049400	.070600
.070	.052850	.034580	.049420
.060	.045300	.029640	.042360
.050	.037750	.024700	.035300
.040	.030200	.019760	.028240
.030	.022650	.014820	.021180
.025	.018875	.012350	.017650
.020	.015100	.009880	.014120
.015	.011325	.007410	.010590
.012	.009060	.005928	.00847
.010	.007550	.004940	.00706
.008	.006040	.003962	.00564
.006	.004530	.002964	.004236
.005	.003775	.002470	.003530
.004	.003020	.001976	.002824
.003	.002265	.001482	.0021180
.002	.001510	.000988	.001412
.001	.000755	.000494	.000706
.0005	.000377	.000247	.000353
.0003	.000226	.000148	.000212



Radiation Shield for Rocket Nozzle

Rhenium sheet is punched and impact formed in making the radiation shield surrounding a rocket nozzle. An inner pressure case is also made from Rhenium sheet, but in this case by roll forming, TIG welding, and ball drawing. Rhenium was selected because it is easily workable and maintains structural integrity after thousands of hours at high temperatures.

Thermionic Converter

The thermal energy storage capsule consists of four parts fabricated from Rhenium sheet. The emitter uses Rhenium because of its desirable thermionic work function coupled with low vapor pressure at elevated temperatures. The structural members use Rhenium because it remains ductile after high temperature operation, sustained or intermittent.

Standard” Sizes Dimensional Tolerances

Re and Mo-50 Re					W’25 Re			
Standard Thick-ness (inches)	Thickness Tolerance (±inches)	Maxi-mum Width (inches)	Width Tolerance (±inches)	Maxi-mum Length (inches)	Thickness Tolerance (±inches)	Maximum Width (inches)	Width Tolerance (±inches)	Maximum Length (inches)
Sheet Gauges								
0.250	0.0100	4	1/32	5	0.0125	4	1/32	4
0.125	0.0050	4	1/32	5	0.0063	4	1/32	4
0.100	0.0040	5	1/32	8	0.0050	5	1/32	6
0.090	0.0036	5	1/32	8	0.0045	5	1/32	6
0.080	0.0032	5	1/32	8	0.0040	5	1/32	6
0.075	0.0030	5	1/32	8	0.0038	5	1/32	6
0.070	0.0028	5	1/32	8	0.0035	5	1/32	6
0.060	0.0024	6	1/32	10	0.0020	5	1/32	8
0.050	0.0015	6	0.020	10	0.0020	5	0.020	8
0.040	0.0015	6	0.020	15		5	0.020	12
0.035	0.0010	6	0.010	15	0.0015	5	0.010	12
0.030	0.0010	6	0.010	15		3	0.010	12
0.025	0.0010	6	0.010	15		3	0.010	12
0.020	0.0010	6	0.010	24		3	0.010	12
0.015	0.0008	6	0.010	24	0.0010	3	0.010	12
0.012	0.0008	6	0.010	24		3	0.010	12
0.010	0.0008	6	0.010	24		3	0.010	12
0.009	0.0005	6	0.005	24	0.0008	3	0.005	12
0.008	0.0005	6	0.005	24		3	0.005	12
0.007	0.0005	6	0.005	24		3	0.005	12
0.006	0.0050	6	0.005	24		3	0.005	12
0.005	0.0005	6	0.005	24		3	0.005	12
Foil Gauges								
0.0040	0.0005	5	0.005	18		3	0.005	12
0.0035	0.0005	4	0.005	12		3	0.005	12
0.0030	0.0005	2.5	0.005	12		3	0.005	12
0.0020	0.0005	2.5	0.005	12	0.0008	2	0.005	12
0.0025	0.0005	2	0.005	12				
0.0012	0.0001	2	0.005	12				
0.0010	0.00005	1	0.005	12				
0.0005	0.00005	2	0.005	12				
0.0003	0.00005	2	0.005	12				

*Closer tolerances can be maintained if required.

HCR 700 Rhenium and Rhenium Alloys

Rod and Wire Data Sheet

H Cross sells no product from stock. All products are made to your exact specifications. Accordingly, alloys and sizes not shown herein can often be provided at no greater cost than similar “standard” products.

Refer to “Properties Data book HCR 300” for extensive technical data about Rhenium and Rhenium alloys.

Definitions

Rod—Round material 0.040 dia. and above usually furnished in straightened and cut lengths.

Wire—Round material below 0.040 dia., usually furnished in coiled form.

Alloys Offered

a. Molybdenum—50 Rhenium (Mo-50 Re) by weight composition.

b. Tungsten—25 Rhenium (w-25 Re) by weight composition.

c. Pure Rhenium—99.99%.

Fabrication

Centerless grinding may be used in rod fabrication for superior finish and tolerance control.

Rhenium—Pressed and sintered compacts and bars are reduced by swaging and by cold drawing.

The rod and wire are normally furnished in fully re-crystallized form.

Alloys—The alloys are swaged and drawn. Mo-50 Re normally furnished in fully re-crystallized form; W-25 Re normally supplied stressed relieved.

Weight Data

Feet/lb are given for Rhenium (based on density of 0.759 lb/in.^3).

Multiply by: 1.55 for Mo-50 Re
1.07 for W-25 Re
for meters/kg

Properties of Rhenium and Rhenium Alloys

The “Properties Data HCR300” contains detailed information on physical, chemical, electrical, mechanical, and other properties for Rhenium and Rhenium alloys. Typical properties are given in Table 701.

The significant properties and associated benefits of rod and wire Rhenium and Rhenium alloys in most applications are:

-High electrical resistivity across a wide temperature range—without sacrificing high-temperature strength—opens new flexibility in design.

-Outstanding ductility—even after re-crystallization—minimizes or eliminates problems of thermal or mechanical shock.

-Excellent corrosion resistance—especially at high temperatures—ensures reliable part performance.

-Workability and weldability—surpassing that of other refractory metals—simplifies fabricating operations.

One of the outstanding properties of Rhenium and Rhenium alloys is beyond their bend ductility as compared to that of molybdenum and tungsten. Bend ductility data is reproduced in table 702.

Table 701. Typical Properties of Rhenium and Rhenium Alloys Compared to those of Tungsten and Molybdenum

(All values at 1200°C)

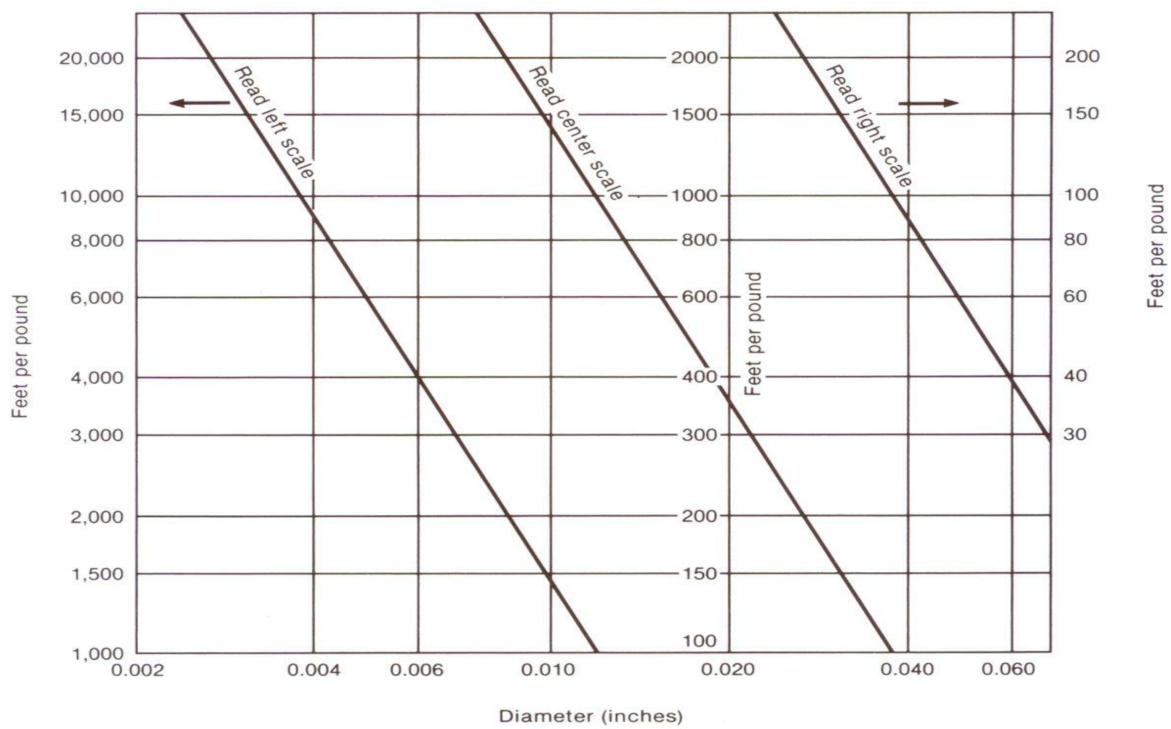
Material	Linear Coefficient of Thermal Expansion micro · in. In. ° C	Thermal Conductivity cal · cm cm^2 · sec · ° C	Electrical Resistivity (microhm · cm)
Re	6.82	0.120	83.5
Mo-50 Re	6.71	0.159	55.0
W-25 Re	5.27	0.158	61.5
W	4.82	0.266	39.7
Mo	5.95	0.222	37.2

Table 702. Bend ductility of Rhenium and Rhenium Alloys and of Molybdenum and Tungsten

	Bend Ductility				
Annealing Temperature (°C)	Re	Mo-50 Re	W-25 Re	Mo	W
As Drawn	>6T	1T	2T	1T	1T
1000	1T	1T	2T	1T	1T
1200	1T	1T	1T	1T	2T to
1400	1/2T	1/2T	1/2T	>6t	Glass
1600	1/2T	1/2T	1/2T	>6T	Glass
1800	1/2T	1/2T	3T	>6T	Glass
2000	1/2T	1/2T	5T	>6T	Glass

"Standard" Sizes and Dimensional Tolerances

Diameter (Inches)		Tolerance (± Inches)	
Decimal	Fraction	Swaged & Drawn Products	Center-less Ground Products
0.500	1/2	0.0050	0.0020
0.438	7/16	0.0050	0.0010
0.375	3/8	0.0030	0.0010
0.312	5/16	0.0030	0.0010
0.250	1/4	0.0030	0.0010
0.188	3/16	0.0010	0.0010
0.125	1/8	0.0020	0.0010
0.100	-	0.0020	0.0010
0.090	-	0.0020	0.0010
0.080	-	0.0020	0.0010
0.070	-	0.0020	0.0010
0.060	-	0.0020	0.0010
0.050	-	0.0020	0.0010
0.040	-	0.0020	0.0010
0.035	-	0.0010	-
0.030	-	0.0010	-
0.025	-	0.0010	-
0.020	-	0.0010	-
0.015	-	0.0005	-
0.010	-	0.0005	-
0.009	-	0.0003	-
0.008	-	0.0003	-
0.007	-	0.0003	-
0.006	-	0.0003	-
0.005	-	0.0003	-
0.004	-	0.0003	-
0.003	-	0.0003	-

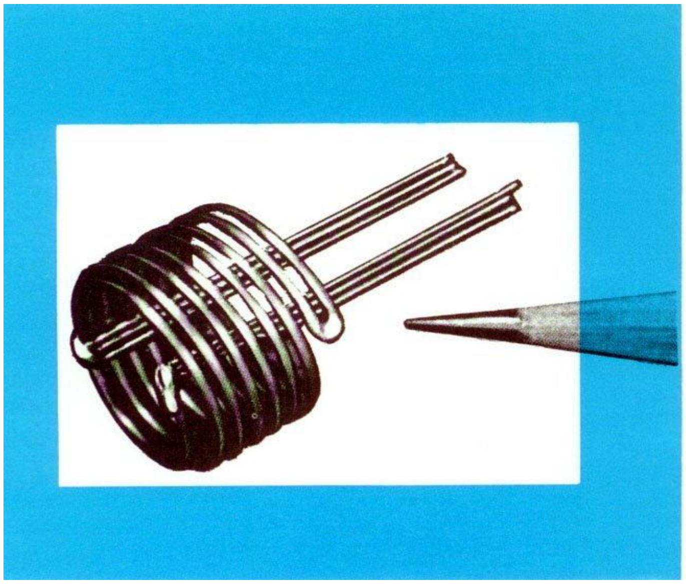


Size Dia	Mo-50 Re	Size Dia	Mo-50 Re
.003"	.000042 lbs/ft	.100"	.00388 lbs/inch
.004"	.000075 lbs/ft	.125—1/8"	.00606 lbs/inch
.005"	.000116 lbs/ft	.156—5/32"	.00944 lbs/inch
.006"	.000168 lbs/ft	.187—3/16"	.01371 lbs/inch
.007"	.000228 lbs/ft	.250—1/4"	.02425 lbs/inch
.008"	.000298 lbs/ft	.312—5/16"	.03777 lbs/inch
.009"	.000377 lbs/ft	.375—3/8"	.05456 lbs/inch
.010"	.000465 lbs/ft	.437—7/16"	.07443 lbs/inch
.012"	.000670 lbs/ft	.500—1/2"	.09700 lbs/inch
.015"	.001048 lbs/ft	.562—9/16"	.12254 lbs/inch
.020	.001863 lbs/ft	.625—5/8"	.15156 lbs/inch
.025"	.002910 lbs/ft	.687—11/16"	.18365 lbs/inch
.030"	.004191 lbs/ft	.750—3/4"	.21824 lbs/inch
.040"	.007449 lbs/ft	.875—7/8"	.29705 lbs/inch
.045"	.009428 lbs/ft	1.000—1"	.38799 lbs/inch
.050"	.011640 lbs/ft		
.062"	.017897 lbs/ft		
.080"	.02987 lbs/ft		

H. CROSS COMPANY

Size Dia	Rhenium	Size Dia	Rhenium
.003”	.000064 lbs/ft	.100”	.00593 lbs/inch
.004”	.000114 lbs/ft	.125—1/8”	.00927 lbs/inch
.005”	.000178 lbs/ft	.156—5/32”	.01443 lbs/inch
.006”	.000256 lbs/ft	.187—3/16”	.02096 lbs/inch
.007”	.000349 lbs/ft	.250—1/4”	.03706 lbs/inch
.008”	.000456 lbs/ft	.312—5/16”	.05772 lbs/inch
.009”	.000576 lbs/ft	.375—3/8”	.08338 lbs/inch
.010”	.000711 lbs/ft	.437—7/16”	.11376 lbs/inch
.012”	.001025 lbs/ft	.500—1/2”	.14824 lbs/inch
.015”	.001619 lbs/ft	.562—9/16”	.18729 lbs/inch
.020	.002846 lbs/ft	.625—5/8”	.23163 lbs/inch
.025”	.004448 lbs/ft	.687—11/16”	.28068 lbs/inch
.030”	.006405 lbs/ft	.750—3/4”	.33355 lb/inch
.040”	.011385 lbs/ft	.875—7/8”	.45400 lbs/inch
.045”	.014409 lbs/ft	1.000—1”	.59298 lbs/inch
.050”	.017789 lbs/ft		
.062”	.027353 lbs/ft		
.080”	.045541 lbs/ft		

Size Dia	Rhenium-25 Tung	Size Dia	Rhenium-25 Tung
.003”	.000060 lbs/ft	.100”	.00554 lbs/inch
.004”	.000107 lbs/ft	.125—1/8”	.00866 lbs/inch
.005”	.000166 lbs/ft	.156—5/32”	.01349 lbs/inch
.006”	.000240 lbs/ft	.187—3/16”	.01960 lbs/inch
.007”	.000326 lbs/ft	.250—1/4”	.03466 lbs/inch
.008”	.000426 lbs/ft	.312—5/16”	.05398 lbs/inch
.009”	.000539 lbs/ft	.375—3/8”	.07797 lbs/inch
.010”	.000665 lbs/ft	.437—7/16”	.01638 lbs/inch
.012”	.000958 lbs/ft	.500—1/2”	.12862 lbs/inch
.015”	.001497 lbs/ft	.562—9/16”	.17513 lbs/inch
.020	.002662 lbs/ft	.625—5/8”	.21660 lbs/inch
.025”	.004159 lbs/ft	.687—11/16”	.26247 lbs/inch
.030”	.005989 lbs/ft	.750—3/4”	.31190 lbs/inch
.040”	.010646 lbs/ft	.875—7/8”	.42453 lbs/inch
.045”	.013474 lbs/ft	1.000—1”	.55449 lbs/inch
.050”	.016635 lbs/ft		
.062”	.025578 lbs/ft		
.080”	.042585 lbs/ft		

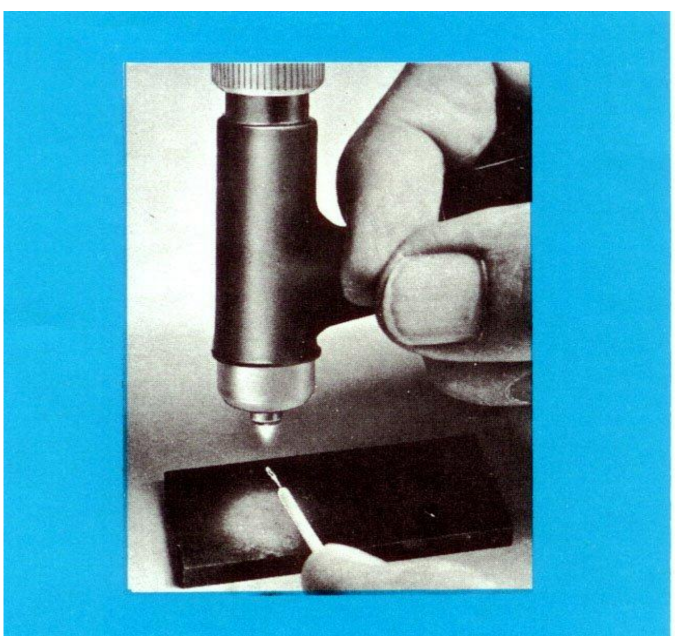


LEADS AND FILLERS IN BILFILAR HEATER

The hairpin bends in the refractory metal heater have fillers of pure Rhenium wire that provide the ductility required for the bends. The leads are also of Rhenium wire, and are heliarc welded to the heater.

LANTHANUM BORIDE CATHODE

Rhenium is the choice as base material for lanthanum boride (La B_6) electron emitters because of its inherent resistance to the formation of borides (combined, of course, with its excellent refractory metal properties). In this cathode, Rhenium wire (10 mil) is spot welded to stainless steel loads, then coated with La B_6.

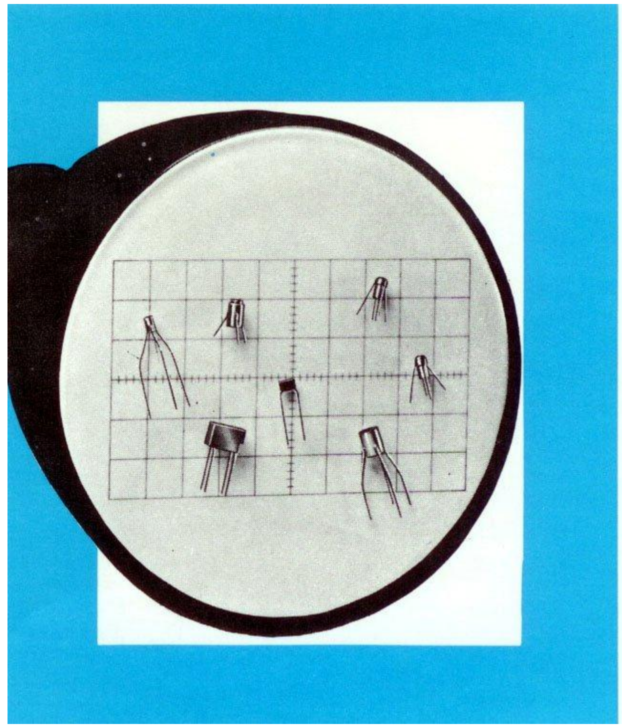


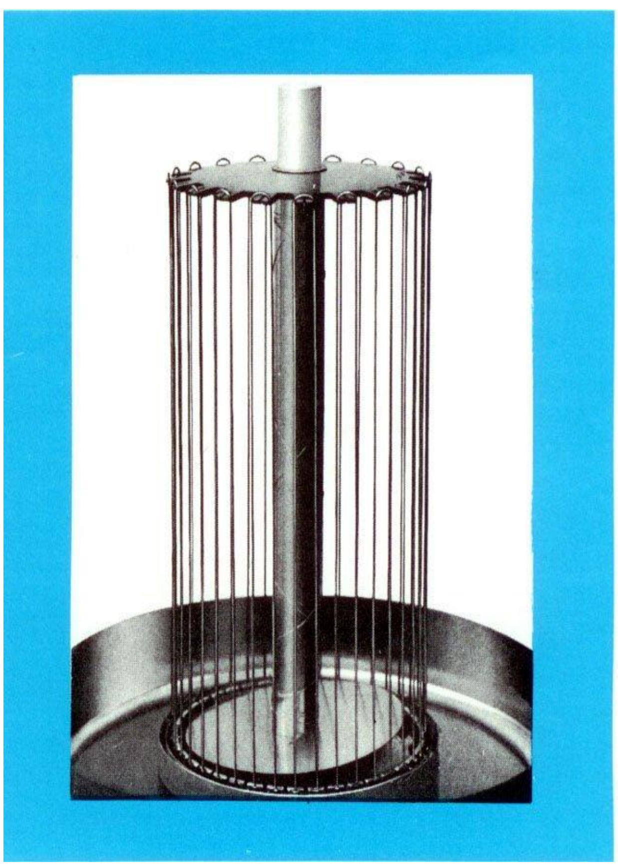
THERMOCOUPLE

A thermocouple for use above 2000°F can be prepared with W-25 Re wire as one lead and a tungsten wire containing 3% Rhenium (W-3 Re) as the other lead. The leads are plasma arc welded. (Tubing of Mo-50 Re is superior for thermocouple sheaths in many applications.)

Mesh Filament

The desirable heat dissipation characteristics of W-25 Re wire and its great ductility are used to advantage in this mesh filament of a power grid transmitting tube. In such applications involving high voltage coupled with high operating temperatures the W-25 alloy has been displacing pure tungsten and molybdenum wire.





Support Struts for Cathode Assembly

Pure Rhenium wire supports are attached to the cathodes by molybdenum/ruthenium eutectic brazing in hydrogen at 2100°C. Only Rhenium provides the required ductility during manufacture and operation.

Table 101. Physical Properties of Rhenium

Parameter	Unit	Value
Atomic Number		75
Atomic Weight		186.31
Crystal Structure		
Lattice Type		HCP
Lattice Constant a0 at 20°C	Å	2.760 ± 0.001
Lattice Constant c0 at 20°C	Å	
Lattice constant c/a at 20°C		4.458 ± 0.001
Atomic Radius	Å	1.38
Minimum Interatomic Distance	Å	2.740
Natural Isotopes		
Thermal Neutron Cross Section		Re 185, Re 187
	barns/atom	86
Thermal Neutron Cross Section-Re 185	barns/atom	110
Thermal Neutron Cross Section-Re 187	barns/atom	70
Spectral Emissivity, 0-2000°C	=0.655	0.42
Magnetic Susceptibility	micro-in.	
Ionization Voltage of Metal	10.^6 cgs	67.6
Vapor	V	7.8
Density @ 20°C	gm/cm^3	21.04
	lb/in^3	0.755
Melting Point	°C	3180
Boiling Point (approximate)	°C	5630
Latent Heat of Fusion	K cal/mole	7.9
Latent Heat of Vaporization	K cal/mole	152.0
Linear Coefficient of		
Expansive Vapor Pressure		
Specific Heat		
Thermal Conductivity		

Physical Properties of Tungsten

Atomic Number	74	
Atomic Weight	183.85	
Isotopes (natural)	180, 182, 183, 184, 186	
Melting Point	3410°C ± 20°C	
Boiling Point	5900°C	
Vapor Pressure (mm Hg):		
1527°C (2780°F)	1.93 x 10^-15	
2127°C (38360°F)	7.9 x 10^-9	
2727°C (4940°F)	6.5 x 10^-5	
3227°C (5840°F)	4.68 x 10^-3	
Specific Heat at 20°C (68°F) (cal/gram-atom)	6.25	
Thermal Conductivity (Cal/sq cm/cm/sec/°C):		
20°C (68°F)	0.31	
927°C (1701°F)	0.275	
1127°C (2061°F)	0.268	
1327°C (2421°F)	0.260	
1527°C (2781°F)	0.253	
1727°C (3141°F)	0.245	
Lattice Type	Body centered cubic	
Lattice Constant (A) @ 25°C	3.1652	
Density (g/cc):		
Rod	19.3	
ASTM Wire	19.17	
Coefficient Linear Expansion, mean value 0°C—500°C (32°-932°F)		
Worked	4.98 x 10^-6	
Annealed	4.45 x 10^-6	
Atomic Volume (cc/gram-atom based density 19.3)	9.53	
Heat of Fusion (Cal/g)	44	
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 (gram-atom)	± 40.0 x 10^-6	
Elastic Properties: @ 25°		
Young Modulus	41 x 10^3 kg/mm^2	58.3 x 10^6 psi
Shear Modulus	16 x 10^3 kg/mm^2	22.8 x 10^6 psi
Poisson's Ratio	0.27	
Electrical Resistivity (micro-ohms-cm):		
24°C (75°F)	5.89	
100°C (212°F)	7.28	
700°C (1292°F)	22.43	
1100°C (2012°F)	34.65	
1500°C (2732°F)	49.66	
1800°C (3272°F)	57.52	
2100°C (3812°F)	69.61	
Temp. Coeff. Of Elec. Resistivity (avg. for annealed wire, per °C)	.0044	

Chemical Reactions of Tungsten

Substance	Reaction
Water, Steam	May tarnish depending on purity and temperature; significant oxidation begins at about 700°C.
Air, Oxygen	Oxidation begins at about 500°C.
Acids	Resists strong acids such as HCI, HF, HNO3, H2SO4, and H3PO4 over a wide range of concentrations and temperatures with the exception that a *mixture* of HF and HNO3 attacks rapidly. No reaction with organic acids.
Alkalis	Aqueous solutions of NaOH, KOH, NH4OH have no effect in the absence of oxygen. Dissolved oxygen or presence of oxidizing agents will result inI corrosion. Fused NaOH and KOH show no attack unless temperature exceeds 500°C. Presence of oxidizers such as nitrates will result in extremely rapid attack even at melting point. No reaction with liquid ammonia.
Salts	As above, generally no reaction unless alkaline and oxidizing. Sea water OK. FeCI3 solutions are a mildly corrosive exception.
Halogens	Reacts with fluorine at ambient temperature. CI2 and Br2 react above 250°C and iodine at red heat.
Liquid Metals	Up to 600°C there is no reaction with sodium, potassium, lithium, gallium, mercury, magnesium or zinc and in many cases much higher temperatures can be tolerated.
Carbon	Forms carbide at 1200°C and higher.
Nitrogen	No reaction up to 1500°C.
Sulfur	Some attack at red heat.
SO2CO2NOx	Oxidation at elevated temperatures.

*This information is presented as a general guide. Unusual circumstances (such as the combination of substances) or the presence of foreign material (impurities) can alter the nature or rate of the reactions.

References:

H.H. Uhling, Corrosion Handbook 1948, John Wiley and Sons, Inc.
W.L. Achermann et al, Bureau of Mines rI6715 (1966).
Rare Metals Handbook, 1961, Reinhold Publishing Corporation.
W.T. Machmann, Materials in Design Engineering, page 106, November 1966.

Physical Properties of Molybdenum (Mo)

Atomic Number	42
Atomic Weight	95.95
Isotopes (natural)	92, 94, 95, 96, 97, 98, 100
Melting Point	2622° ± 10°C
Boiling Point	4800°C
Vapor Pressure (mm Hg):	
1600°C (2912°F)	2.5 x 10^-8
2200°C (3992°F)	5 x 10^-4
2500°C (4532°F)	1 x 10^-2
Specific Heat at 20°C (68°F) (cal/gram-atom)	6.24
Thermal Conductivity (Cal/sq cm/cm/sec/°C):	
20°C (68°F)	0.382
927°C (1701°F)	0.259
1127°C (2061°F)	0.230
1327°C (2421°F)	0.202
1527°C (2781°F)	0.173
1627°C (2961°F)	0.159
Lattice Type	Body centered cubic
Lattice Constant (A) @ 25°C	3.1399
Density (g/cc):	
Rod	10.2
ASTM Wire	10.14
Coefficient Linear Expansion, per °C	
0°- 20°C (32° -68°F)	5.35 x 10^-6
25°-700°C (77°-1292°F)	5.8-6.2 x 10^-6
Atomic Volume (cc/gram-atom based density 10.2)	9.41
Heat of Fusion (Cal/g)	70
Heat of sublimation (kcal/mol)	160
Heat of combustion (cal/g)	1812
Thermionic Data:	
Apparent Electron work function (eV)	4.37
Apparent Positive ion emission (eV)	8.6
First ionization potential	7.18
Elastic Properties: @ 25°	
Young Modulus kg/mm^2	32-35
Poisson's Ratio	0.325
Electrical Resistivity (micro-ohms-cm):	
0°C (32°F)	5.2
27°C (81°F)	5.78
727°C (1341°F)	23.9
927°C (1701°F)	29.2
1127°C (2061°F)	35.2
1327°C (2421°F)	41.2
1527°C (2781°F)	47.2
1727°C (3141°F)	53.5
1927°C (3501°F)	59.5
Temp. Coeff. Of Elec. Resistivity (avg. for annealed wire, per °C)	0.0047

Chemical Reactions of Molybdenum (Mo)*

Substance	Reaction
Water, Steam	Surface oxidation, may discolor depending on purity and temperature.
Air, Oxygen	Rapid oxidation above 600°C, oxide sublimes from surface.
Acids	HF—None HCI—Slow (hot, concentrated) H_2SO_4—Fast (hot, concentrated) HNO_3—Fast (cold, dilute); will passivate at high concentration Aqua Regia—Fast Organic Acids—None
Alkalis	Aqueous solutions—none if oxidizing agents absent Molten—No attack unless temperature exceeds 500°C or oxidizers present
Salts	Aqueous chlorides of copper, iron, mercury can be corrosive. Extremely rapid by molten oxidizers such as nitrates, nitrites.
Halogens	Flourine reacts at room temperature; chloride and bromine above 250°C; iodine slowly above 800°C
Liquid Metals	Good resistance to: sodium, potassium, lithium, lead, bismuth, mercury, copper. Attacked by tin, zinc, aluminum, iron. gallium.
Carbon	Carbide formation begins at 1100°C
Nitrogen, Ammonia	Nitride forms above 1000°C
Sulfur, H_2S	Forms sulfide above 450°C.
Phosphorus	No reaction
SO_2, NOx	Oxidation above 600°C
Silicon	Forms silicide above 1000°C

*This information is presented as a general guide. Unusual circumstances (such as the combination of substances) or the presence of foreign material (impurities) can alter the nature or rate of reaction.

References:

H.H. Uhlig, Corrosion Handbook 1948, p. 252, John Wiley and Sons, Inc.

W.L. Achermann et al, Bureau of Mines RI6715 (1966).

Rare Metals Handbook, 1961, p. 295, Reinhold Publishing Corporation.

W.T. Bachmann, Materials in Design Engineering, page 106, November 1966.