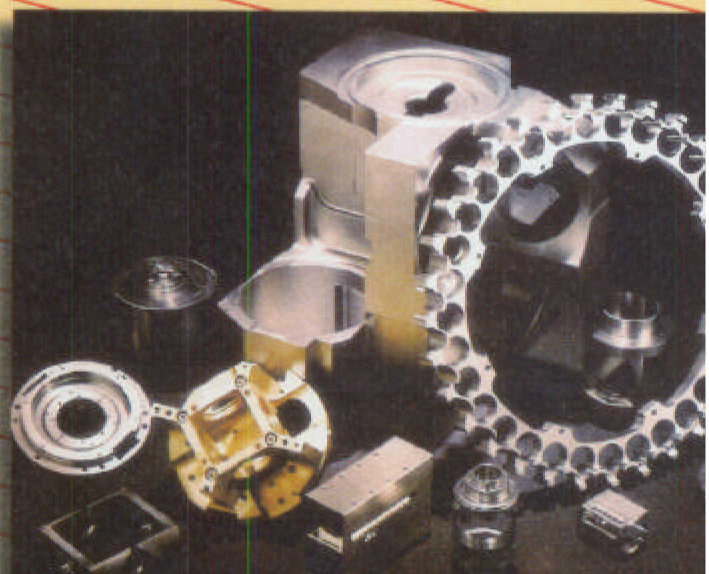
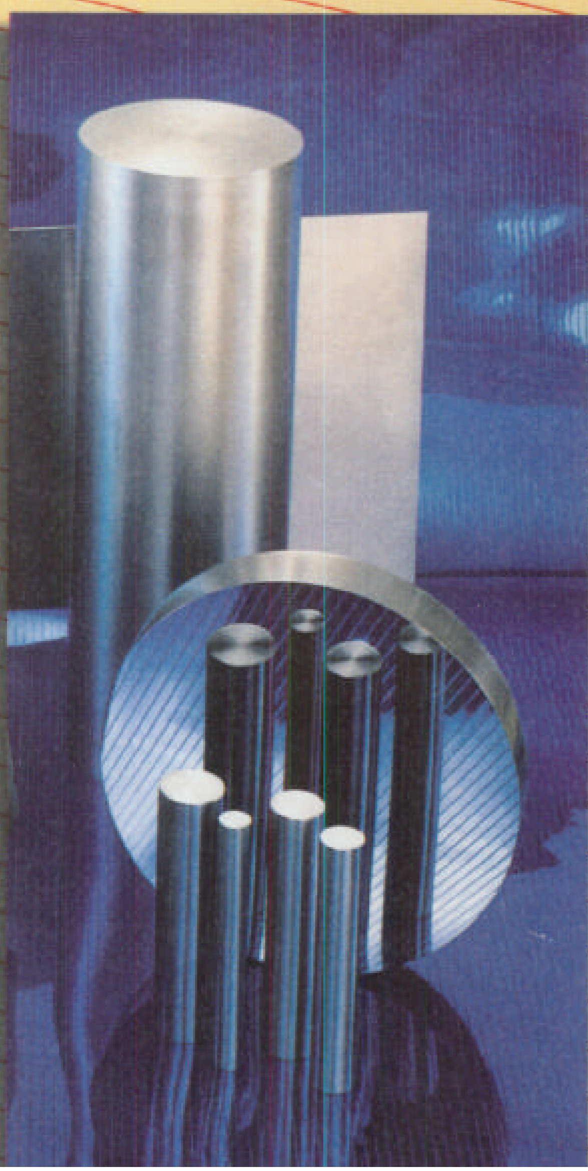
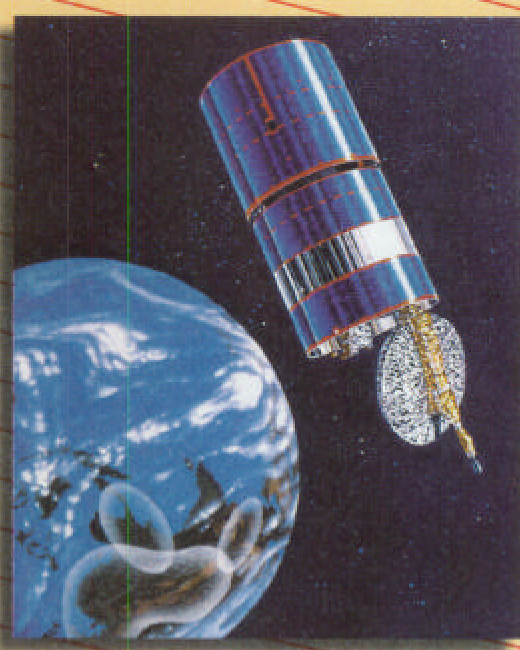
Designing With BERYLLIUM







Brush Wellman Inc.

Brush Wellman Inc. is the world's major producer of beryllium and its related products. We start with our own ore reserves and mining operations, and process the raw materials through extraction, refinement and fabrication of beryllium mill shapes and beryllium-containing materials.

Brush Wellman has invested more than 70 years in the development of the technology, facilities and marketing of beryllium, becoming a fully integrated producer of several different beryllium containing products.

The company started in 1921 as Brush Laboratories. In 1931, we were incorporated as Brush Beryllium Company to develop commercial opportunities stemming from our research on beryllium, beryllium oxide, beryllium copper, and other beryllium-containing alloys. Brush Beryllium Company was the first to recognize the tremendous potential of these materials and remained the only producer until the late 1950s when market growth attracted the interest of other producers.

Between 1959 and 1979 there were as many as four producers in the world, but, soon thereafter the demand for metallic beryllium again declined, leaving Brush Wellman as the only producer in the Western World.

In 1971, The Brush Wellman Company was created with the acquisition of the S.K. Wellman Division of Abex Corporation. This division was later sold to MLX Corporation, but the name Brush Wellman remains our corporate signature.

Brush Wellman's Electrofusion Products facility in Fremont, California, was acquired in 1990. It is a specialist in the field of beryllium sheet and foil fabrications and assemblies. Product end-uses are primarily in high purity metal x-ray windows for medical, analytical, industrial, and scientific applications.

Brush Wellman mines domestic low grade ores called bertrandite in the Topaz Spor Mountain area of Utah while a higher grade ore, beryl, is imported from various areas of the world (Brazil, China, Africa, etc.). Both ores are processed concurrently at our Delta, Utah, extraction plant. The Delta plant has recently been modified and expanded to accept a wider variety of ore, and to produce a greater quantity of product.

Here ores are processed using wet chemical techniques to produce an intermediate product, beryllium hydroxide, which is shipped to our Elmore, Ohio, plant for conversion to metallic beryllium and other beryllium-containing products.

Brush Wellman's domestic reserves of bertrandite ore assures a reliable supply of beryllium-bearing materials well into the 21st century. But we also have an active program of evaluating other beryllium-containing minerals from all areas of the world. This effort is designed to extend the life of our ore reserves far into the future.

Brush Wellman's confidence in the future of beryllium is demonstrated by the continued investment in modern facilities and extensive environmental controls at both of its beryllium processing facilities.

Open pit mines are operated by Brush Wellman in Delta, Utah, for the extraction of bertrandite ore.

A truck from the mine dumps its load of ore for processing at Brush Wellman's Delta, Utah, ore processing plant.

A series of settling tanks is used at one point in the process to separate beryllium concentrate from the ore.

High grade beryl ore, shown here, is processed with bertrandite to produce the starting materials for beryllium.

Processing operations at the Delta, Utah facility continue around the clock.

Raw materials are transformed into various forms of beryllium metal at our modern processing plant in Elmore, Ohio.

Introduction

Beryllium is a space age material in the truest sense of the word.

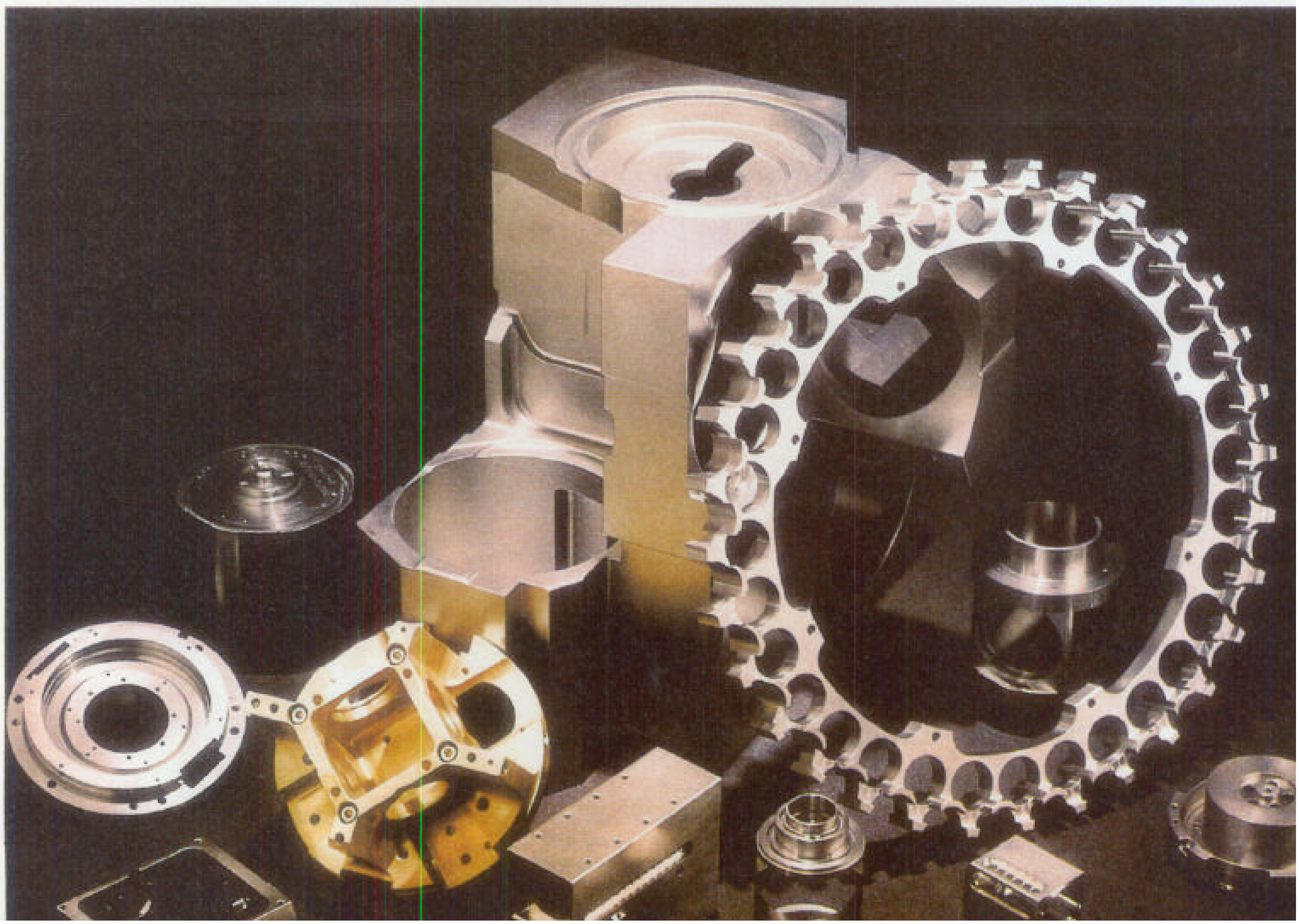
One of the lightest metals known, it presents the designer with a combination of desirable properties not found in any other material. Strength-to-weight and stiffness-to-weight ratios of beryllium are outstanding. It has high specific heat and excellent thermal conductivity, and it retains useful properties at both elevated and cryogenic temperatures.

Beryllium also has significant ductility, is substantially uniform in properties, is readily machinable and can be rolled, drawn or extruded.

Nuclear reactors, infrared target acquisition systems, inertial guidance instrumentation, military aircraft disc brakes, audio components, high speed computer parts, and satellite structures are among the many exciting applications for this versatile material.

In recent years, beryllium has won growing acceptance in military avionics systems as an optics material in advanced targeting systems and heat sink constraining cores for surface mounted electronic circuits (SMT).

Brush Wellman, which pioneered the development of beryllium and its derivitive materials, is recognized throughout the world as the leader in this technology. Our company developed methods for making high quality beryllium powder and consolidating it into



large blocks of high density, fine grain material. Our method of hot pressing large sections in a vacuum atmosphere (VHP) remains the standard of the industry.

Developments in microalloying and heat treating have enabled Brush Wellman to produce materials with preselected properties for specific customer requirements, greatly enhancing the use of beryllium in a broad range of applications.

Brush Wellman has made substantial investments to produce parts to near net shape using hot and cold isostatic pressing (HIP, CIP). These processes significantly reduce the amount of machining required to produce a finished part and at the same time impart properties that are superior to those of standard vacuum hot-pressed material.

As the Western World's only primary producer and fabricator of beryllium metal, we are continuing to work toward improvement in the quality and dependability of our materials. Our continuing goal is to develop cost effective materials to meet the future needs of the designers.

The purpose of this brochure is to acquaint the reader with the properties and range of uses for beryllium products.

For more detailed information, contact Brush Wellman Inc., Beryllium Products Division, in Elmore, Ohio.

CONTENTS

These precision guidance system parts attest to the excellent fabricating and machining characteristics of beryllium metal.

TABLE I — PHYSICAL PROPERTIES

• Atomic Number	4	• Reflectivity:	Optical reflectivity 50%, ultraviolet reflectivity 55%, infrared (10.6 um) reflectivity 98%.
• Atomic Weight:	9.01	• Sonic Velocity:	Velocity of sound in beryllium is 41,300 ft./sec., (12,588 m/sec.) two and one-half times that in steel.
• Latent Heat of Fusion:	488 BTU/lb. (1133 $\frac{KJ}{Kg}$)	• X-ray Transparency:	Due to its low atomic number, beryllium transmits x-rays seventeen times better than an equivalent thickness of aluminum. Beryllium x-ray windows allow the most efficient use of generation radiation in medical and analytical applications.
• Specific Gravity:	1.85 grams/cm^3		
• Melting Point:	2345 F (1285°C)		
• Electrical Conductivity:	40.7% of IACS (0.24 mhos/cm)		
• Magnetic Characteristics:	Beryllium is diamagnetic, -1.0 x 10^{6} cgs units		

TABLE II — THERMAL PROPERTIES COMPARISON AT ROOM TEMPERATURE

Metal	Specific Heat		Melting Point		Thermal Conductivity		Coeff. of Linear Expan.	
	$\frac{BTU}{lb.\ °F}$	$\frac{J}{kg.\ °K}$	[°F]	(°C)	$\frac{BTU\text{-}ft}{hr.\ ft^2\ °F}$	$\frac{W}{m.\ °K}$	[$\times 10^{-6}$/in/in/°F]	($\times 10^{-6}$/cm/cm/°C)
Beryllium	0.46	(1925)	2345	(1285)	125	(216)	6.3	(11.4)
Aluminum	0.22	(920)	1220	(660)	128	(221)	13.1	(23.6)
Steel	0.12	(502)	2800	(1538)	27	(47)	8.3	(14.9)
Copper	0.09	(337)	1980	(1082)	226	(391)	9.8	(17.6)
2124 T6-30% V/O SiC	0.19	(795)	1220	(660)	72	(125)	7.5	(13.5)
2024 T6-25% V/0 F-9	0.20	(837)	1220	(660)	89	(154)	9.1	(16.4)

Figure 1

RELATIVE DENSITY OF LIGHT WEIGHT MATERIALS

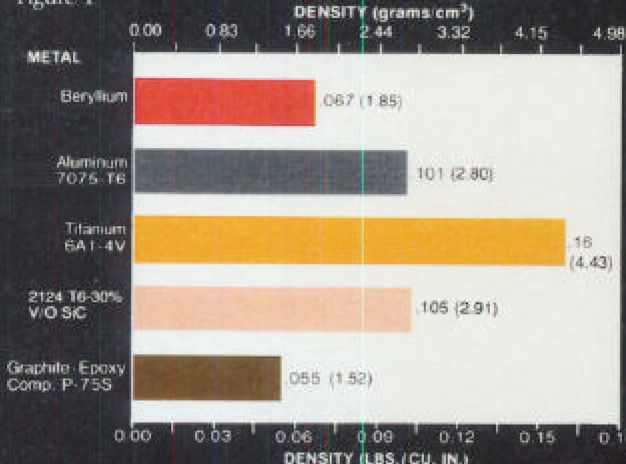


Figure 2

WEIGHT OF MATERIALS FOR EQUAL HEAT ABSORPTION

Figure 3

SPECIFIC HEAT COMPARISON

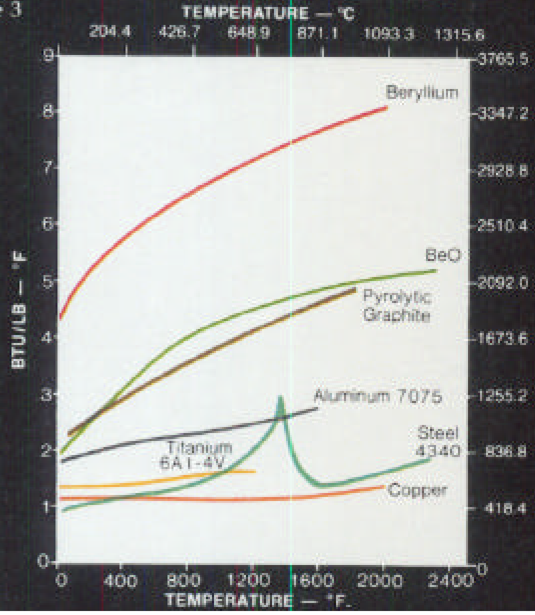
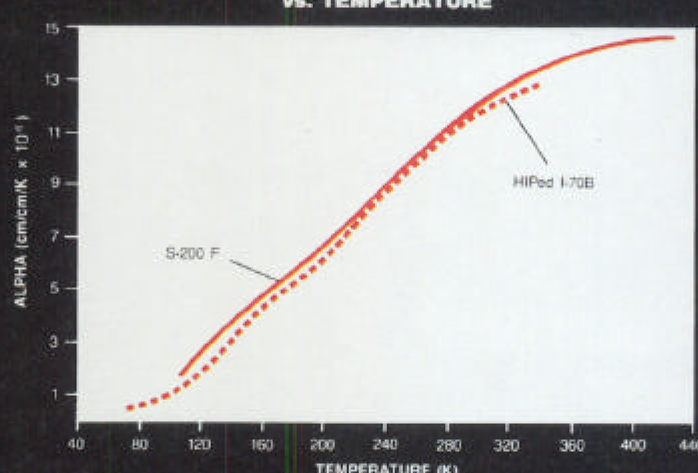
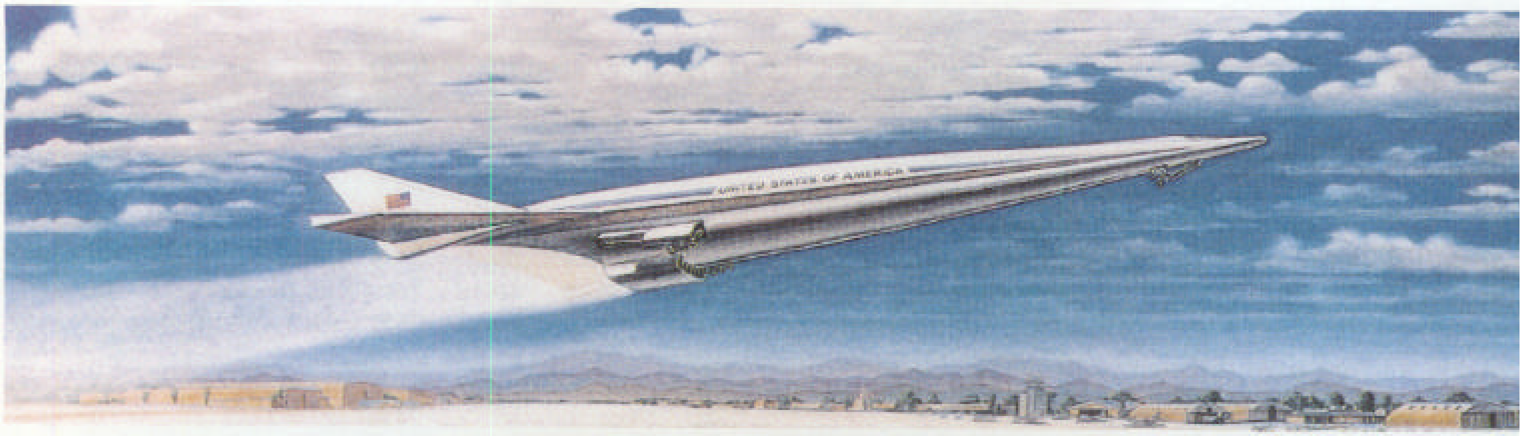


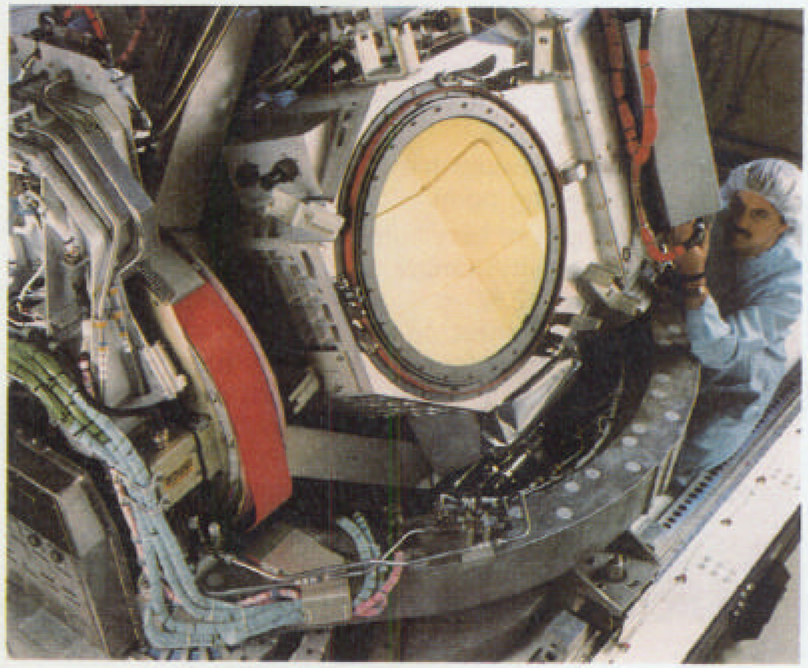
Figure 4

COEFFICIENT of THERMAL EXPANSION vs. TEMPERATURE





The national aerospace plane, designed to reach Mach 25 after conventional takeoff, will use liquid hydrogen as both a fuel and the cooling medium for the engine. The excellent thermal conductivity of beryllium, as well as its nonpermeability to hydrogen, makes it suitable for parts in the engine heat exchanger and internal cooling panels. (Courtesy, Rocketdyne Division of Rockwell International)



Aerospace designers use beryllium for mirror support structures because of the material's light weight, specific strength and dimensional stability over a wide range of temperatures. (Photo, courtesy Hughes Aircraft Company)

Physical Properties

Low Densities

Beryllium is one of the lightest structural metals known. Its density of 0.067 lbs.lin.^{3} (1.85 g/cc) is two-thirds that of aluminum. Beryllium's light weight, coupled with its high stiffness and strength, make it ideal for applications requiring a favorable weight-to-stiffness ratio. The density of beryllium is compared with other structural materials in Figure 1.

Thermal Properties

Beryllium has a specific heat at room temperature of 0.46 BTU/lb.F (1925 J/Kg °K), the highest heat capacity of all metals. This means for any given weight and temperature change, beryllium has the ability to absorb more heat than any other metal (Figures 2 and 3). This superiority is maintained up to its melting point of 2352°F (1289°C).

Beryllium also has the best heat dissipation characteristics among metals on an equal weight basis with a thermal conductivity at room temperature of 125 BTU-ft/ft^2 hr °F (216 W/M/°K). The material's coefficient of thermal expansion is 6.4×10^{-6} (11.5×10^{-6}/°C) /°F. This value is comparable to those for stainless steel, nickel alloys, and cobalt alloys (See Table II).

Thermal expansion as a function of temperature for two grades of beryllium across the temperature range of 100°K to 450 °K is shown in Figure 4.

The thermal diffusivity of beryllium, 2.28 ft.^{2}/hr., assures rapid temperature equalization, which tends to eliminate or greatly reduce distortion which might otherwise occur as a result of thermal gradients.

Nuclear Properties

The nuclear properties of beryllium, combined with its low density, are attractive characteristics for neutron reflectors and moderators in the design of reactors. Beryllium's high scattering cross section makes it effective in slowing neutron speed to a level required for efficient reactor operation. This ability classifies beryllium as one of the few good solid moderators available. Its major application, however, is as a reflector. In this capacity, beryllium acts to scatter leaked neutrons back into the reactor core. Neutrons are conserved because of beryllium's low thermal neutron capture cross section. Furthermore, beryllium acts to increase flux density through the Be^9 (n, 2n) Be^8 reaction.

Mechanical Properties

Strength

The mechanical properties of beryllium vary with the production method used. Ultimate tensile strengths range from 50 ksi (345 MPa) for hot-pressed block to 120 ksi (827 MPa) for extruded rod. At elevated temperatures up to 1500°F (816°C), beryllium retains useful strength, while other structural metals such as aluminum and magnesium have exceeded their melting point.

The specific strength of beryllium (tensile strength/density) ranges from 11.5 × 10^5 in. (2.92 × 10^4m) for cross-rolled sheet, to 7.0 × 10^5 in. (1.98 × 10^4m) for hot-pressed block (see Figure 5). At both room and elevated temperatures the specific strength for wrought beryllium is greater than other structural metals.

Rigidity

One of beryllium's most outstanding features is high elastic modulus and the resultant stiffness-to-density ratio. Compared to other metals on this basis, beryllium is superior by a factor of seven from room temperature to 1200°F (649°C) (See Figures 6 and 7). Beryllium has a modulus of elasticity of 44.0 × 10^6 PSI (3.03 × 10^5 MPa), four times that of aluminum, two and one-half times that of titanium, twice that of SiC reinforced aluminum and various grades of graphite epoxy. For light weight applications requiring a high specific modulus of elasticity, beryllium is unsurpassed.

Creep

Creep data for hot-pressed beryllium block, S-200F grade, and cross-rolled sheet, SR-200 grade, are provided in Figures 8 and 9, respectively. Through the use of the Larson-Miller parameter, the time and temperature to produce 0.1%, 0.5% and 1.0% plastic creep at any given stress can be obtained. Creep properties should be given serious consideration if high operational stresses are to be maintained at temperatures above 1000°F (538°C). Figure 10 shows microcreep data.

Figure 5 **SPECIFIC STRENGTH COMPARISON**

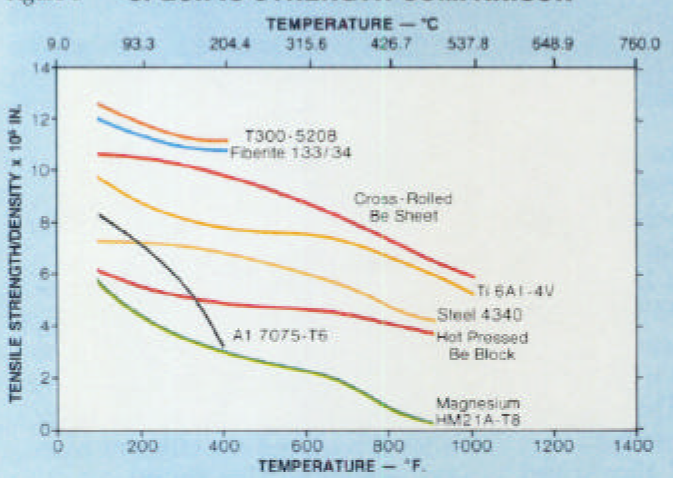


Figure 6 **YOUNG'S MODULUS**

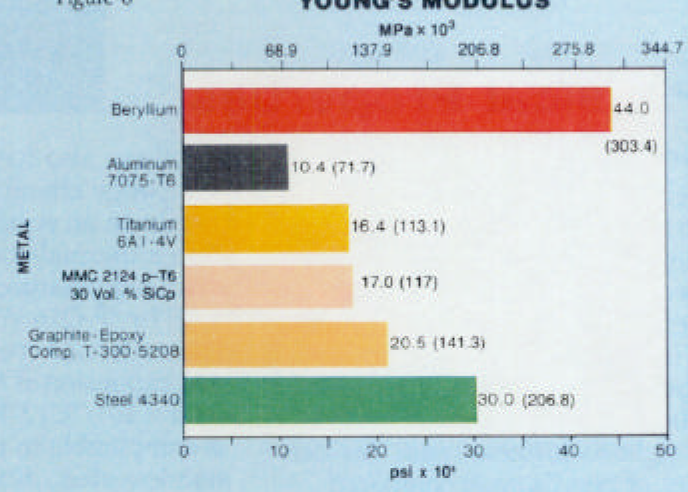


Figure 7 **SPECIFIC MODULUS COMPARISON**

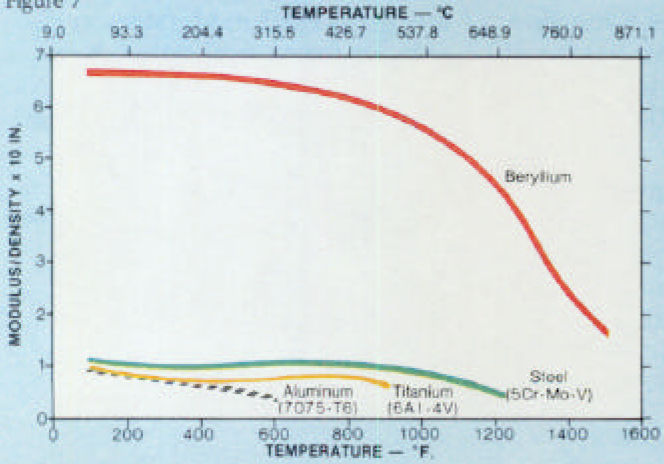
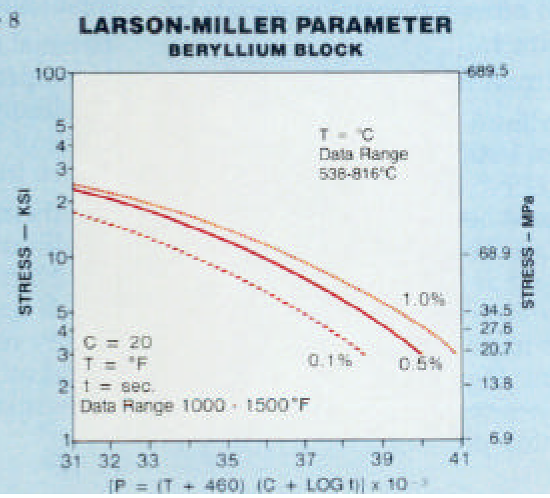


Figure 8 **LARSON-MILLER PARAMETER**
BERYLLIUM BLOCK



Notched Properties

Notch strengthening occurs in beryllium at temperatures around 400°F (204.4°C) over a wide range of stress concentration factors. In fact, S-200F, with a notched ratio of 1.21 at 400°F (204.4°C), has a notched tensile strength that is greater than the unnotched strength. Also at room temperature, the notched strength ratio of S-200F is approximately one (1.0) and therefore does not exhibit any notch sensitivity. (See Figure 11).

Shear Strength

The shear strength characteristics of beryllium in both hot-pressed and sheet form are unusual (see Figure 12). The relationship between shear strength and tensile strength is greater than most materials at low temperatures, but at temperatures greater than 900°F (482°C), the ratio is lower than expected. These tests are conducted using tear-type specimens.

The shear modulus for beryllium is typically 19.6 ± .07 msi for both the longitudinal and transverse directions. The average shear rupture modulus for S-200F is 44.8 + 1.2 ksi.

Compressive Yield Strength

The compressive yield strength (0.2% offset) at room temperature of beryllium is typically 10 percent higher than the tensile yield strength. At 400°F (204.4°C) the compressive yield strength is equal to the tensile yield strength. This is a unique property of beryllium and is demonstrated by S-200F where the room temperature tensile yield strength is 37 ksi and the compressive yield is 41 ksi.

Fracture Toughness

A growing interest in beryllium as a structural material has been accompanied by an increasing interest in the toughness of this material.

When the more common vacuum hot-pressed structural grades of beryllium, S-65 and S-200F, are tested, a K_{IC} value of 9-12 ksi in$^{1/2}$ (10.65-12.3 MPa-in$^{1/2}$) at room temperature can be expected.

Figure 9

LARSON-MILLER PARAMETER
BERYLLIUM SHEET

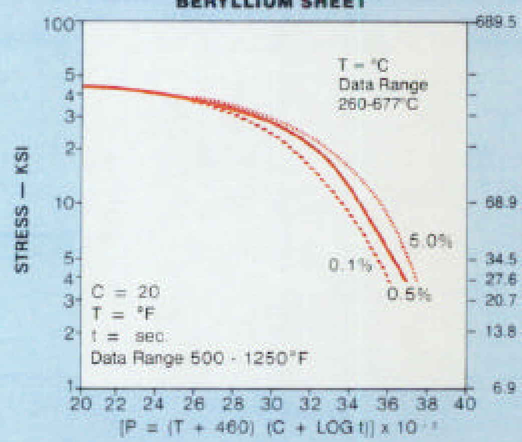
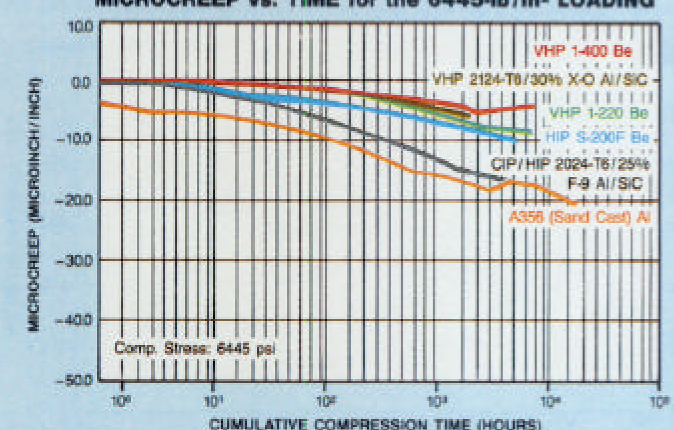


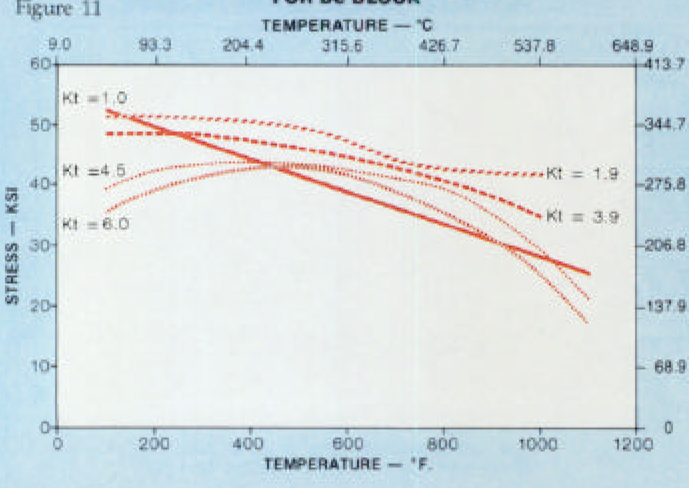
Figure 10

MICROCREEP vs. TIME for the 6445-lb/in² LOADING



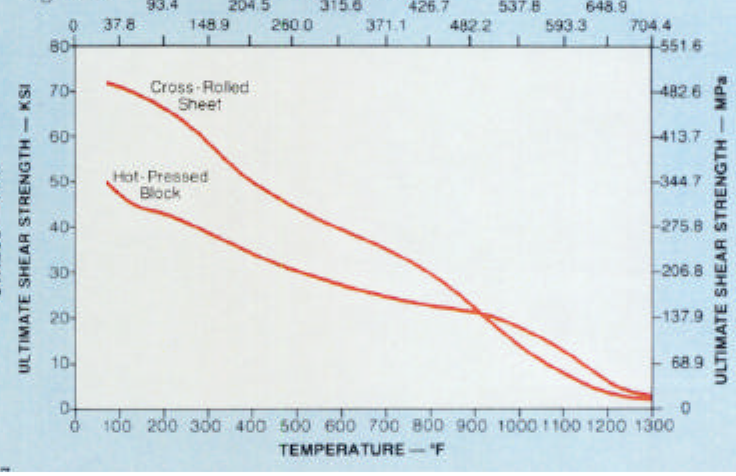
NOTCHED STRENGTH vs TEMPERATURE
FOR Be BLOCK

Figure 11



ULTIMATE SHEAR STRENGTH
OF BERYLLIUM

Figure 12



At elevated temperatures of 500°F (255°C) the fracture toughness of vacuum hot-pressed block is 15-20 ksi-in$^{1/2}$ (16.5-22 MPa-m$^{1/2}$). Beryllium sheet at room temperature (RT) typically has a Kq value of 25 ksi-in$^{1/2}$. Fracture toughness testing has been limited and metallurgical factors which affect the toughness values have not been clearly identified.

Fatigue

Beryllium has an unusually high resistance to fatigue cracking and a high endurance strength level. Fatigue tests have shown that for hot-pressed block, the endurance limit is near the static yield strength (see Figure 13). Based on its ratio of fatigue strength to density, beryllium appears truly outstanding compared to both aluminum and titanium. Figures 14 and 15 show that beryllium is superior for both notched and smooth specimens at all lifetimes.

Fatigue data on S-200F is the most complete available for a structural beryllium grade. In Krause rotating beam fatigue tests, S-200F shows essentially no difference in the 10^7 cycle endurance limit in the longitudinal and transverse directions. That means components can be expected to undergo 10^7 cycles from -38 to +38 ksi (-261 to +261 MPa) without failure – quite remarkable in view of a specification yield stress of 38 ksi (261 MPa). This means designers can use yield stress as the primary design criterion and not worry about redesigning at a later date because of fatigue considerations. Judging by comparisons to other engineering materials, this is a unique advantage for beryllium.

The fatigue ratio of S-200F (ultimate tensile strength-to-fatigue endurance limit) also indicates an unusually high fatigue life in structural design. This ratio is 0.7 for S-200F beryllium, 0.5 for steel, and only 0.35 for aluminum and magnesium, the other "light weight" structural metals.

Figure 13

AXIAL S-N CURVE FOR HOT-PRESSED Be BLOCK
NOTCHED AND SMOOTH AT ROOM TEMPERATURE

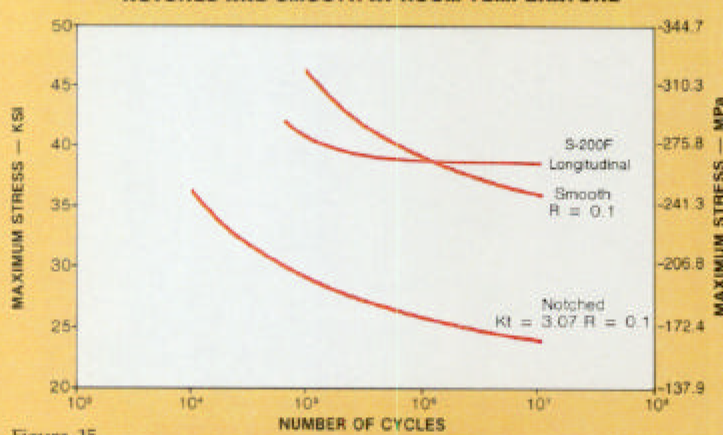


Figure 14

AXIAL FATIGUE STRENGTH COMPARISON
SMOOTH SPECIMEN

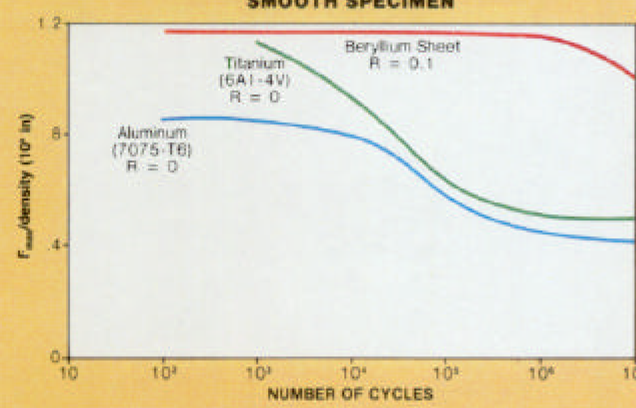


Figure 15

FATIGUE STRENGTH TO DENSITY RATIO
OF NOTCHED MATERIAL

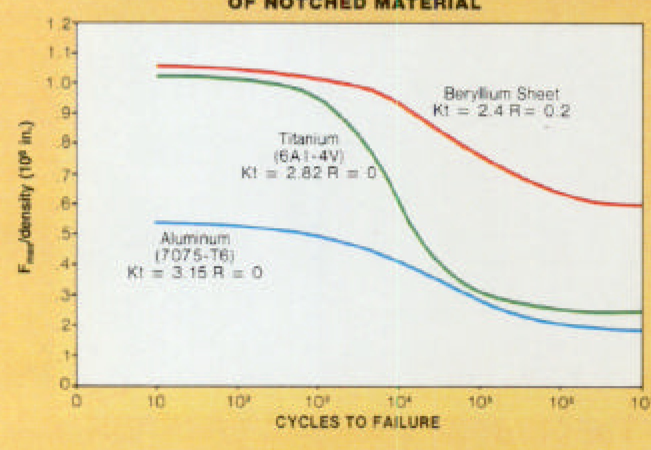
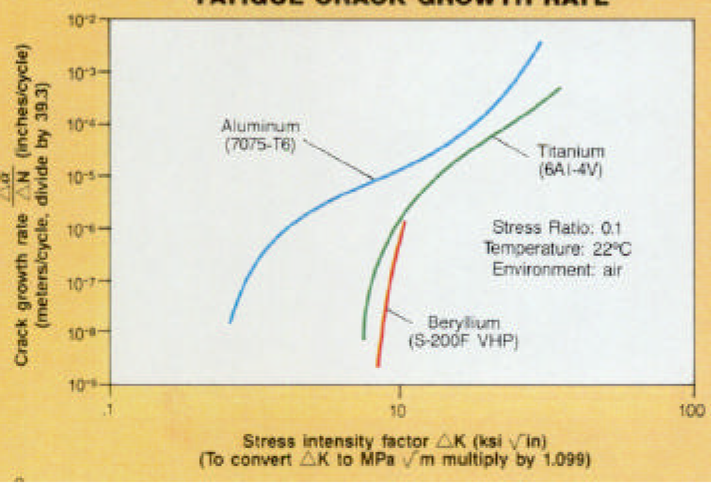


Figure 16

FATIGUE CRACK GROWTH RATE



Properties of Mill Products

Beryllium Powder

The production of beryllium powder begins at Brush Wellman Inc. with the extraction of the metal from the ore through a series of chemical operations. Primary beryllium is produced as "pebble" by the magnesium reduction of anhydrous beryllium fluoride. The pebbles are vacuum remelted to remove reduction slag and cast into ingots. In the cast form, the metal is very difficult to machine and mechanical properties are poor. For these reasons, virtually all beryllium enters service as a powder metallurgy-derived product. Powder is prepared by chipping the ingots and mechanically grinding the chips to the appropriate particle size distribution for consolidation into essentially full density billets by powder metallurgy techniques. The beryllium powders commercially available from Brush Wellman Inc. are shown in Table III. For non-standard requirements contact Brush Wellman Inc.

The mechanical grinding system used to manufacture beryllium powder of a given particle size distribution has been shown to have an effect upon the characteristics of the fully dense body prepared with the powder. This is most notable in the level of minimum tensile elongation which can be generated in any direction at room temperature as will be discussed later. This is true because of the anisotropy of the basic beryllium crystal with room temperature slip capability limited to a single direction coupled with basal plane cleavage as a major fracture mode. Most grinding procedures for beryllium result in a powder with a high fraction of particles with a flat plate configuration which tends to orient in powder handling and consolidation operations.

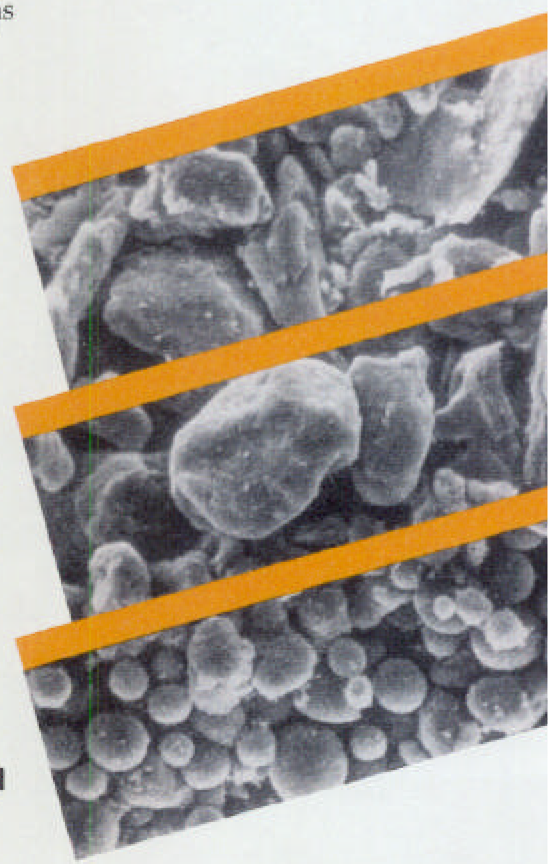
Impact grinding (also known as jet milling) is a procedure for grinding chips to powder involving the impact of beryllium chip propelled by a high pressure gas against a beryllium target. Powder produced in this manner is more equiaxed than ball milled or attritioned powder and has less tendency towards crystallographic orientation in handling and consolidation procedures. The consolidated beryllium manufactured from this type of powder may exhibit, among other characteristics, high elongation so that a minimum of more than 1% at room temperature may be guaranteed. SP-65, SP-200F and IP-70 powders are impact ground.

SP-65 is the highest purity beryllium powder offered by Brush Wellman. It is used for beryllium foil X-ray sources and detector windows, two applications in which impurities may adversely affect performance.

These powders, or variations of these powders, are used to produce vacuum hot-pressed block and as input for wrought products.

TABLE III—BERYLLIUM POWDERS

	Grade		
	SP-65	SP200F	IP-70
Be Assay, min %	99.0	98.5	98.0
BeO, max %	1.0	1.5	0.7
Al, max ppm	600	1000	700
C	1000	1500	700
Fe	800	1300	1000
Mg	600	800	700
Si	600	600	700
B	2		
Cd	2		
Ca	100		
Cr	100		
Co	10		
Cu	150		
Pb	20		
Li	3		
Mn	120		
Mo	20		
Ni	300		
N	300		
Ag	10		
Other Metallic impurities as determined by normal spectrographic methods, each, max ppm	200	400	400
Partical Size	95% minus 325 mesh	95% minus 325 mesh	95% minus 325 mesh



Attrited

Impact Ground

Gas Atomized

They are also used for other powder metallurgy processes, such as cold pressing, cold isopressing followed by sintering, hot isopressing, slip casting, plasma spraying, pressureless sintering, powder extrusion, powder forging, powder rolling and explosive compaction. There is also a specifically formulated powder for block that offers improved properties or better fabricability.

Brush Wellman has developed gas atomization as a useful technology in producing spherical beryllium powders. This method produces a material that is totally isotropic and overcomes the basic anisotropy of the beryllium crystal. In the past, this condition has led to low minimum tensile elongation and variability in the coefficient of thermal expansion of the consolidated powder due to preferential alignment of the powder particle.

Hot-Pressed Block

The most basic form of beryllium is vacuum hot-pressed block. The hot pressing operation, consisting of the application of heat and pressure to beryllium powder contained in a suitable die, results in a uniform, fully dense, fine-grained beryllium which has been thoroughly out-gassed by the use of vacuum during the operation.

Through variation in chemical composition, particle size distribution, and temperature, it is possible to produce a variety of beryllium grades with differing characteristics for many divergent applications. The standard grades of vacuum hot-pressed beryllium produced by Brush Wellman Inc. and the size ranges available, are summarized in Table IV.

TABLE IV - GRADES OF VACUUM HOT-PRESSED BERYLLIUM

	S-65C	S-200F	I-70B	I-220C
Chemical Composition				
Be, min%	99.0	98.5	99.0	98.0
BeO, max %	1.0	1.5	0.7	2.2
Al, max ppm	600	1000	700	1000
C max ppm	1000	1500	700	1500
Fe, max ppm	800	1300	1000	1500
Mg, max ppm	600	800	700	800
Si, max ppm	600	600	700	800
Other, each max ppn	400	400	400	400
	*BeO specified is minimum in this instance			
Tensile Properties				
Ftu, psi min	42,000	47,000	35,000	55,000
(MPa min)	(290)	(324)	(241)	(379)
Fty, psi min	30,000	35,000	25,000	40,000
(MPa min) (0.2% offset)	(207)	(241)	(172)	(276)
Elongation, % min	3%	2%	2%	2%
Microyield, psi min	–	4,000	1,800	5,000
(MPa min)		(27) Typical	(12.4) Typical	(34)
Standard Sizes*				
inches	32 Dia x30 lg	32 Dia x45 lg	32 Dia x30 lg	32 Dia x30 lg
(cm)	(81x76)	(81x114)	(81x76)	(81x76)

*Pressing (billet) sizes can range from 7" (18cm) to 72" (186cm) and 6" (15cm) to 66" (168 cm) in length, depending upon grade and chemistry.

Figure 17 **STRESS-STRAIN CURVE FOR HOT-PRESSED BLOCK**

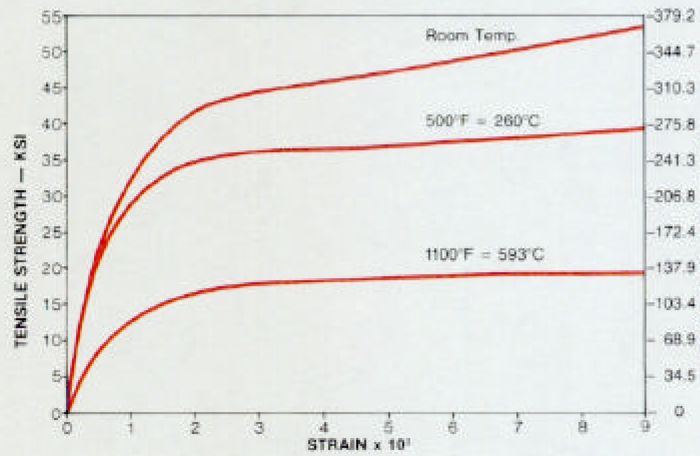
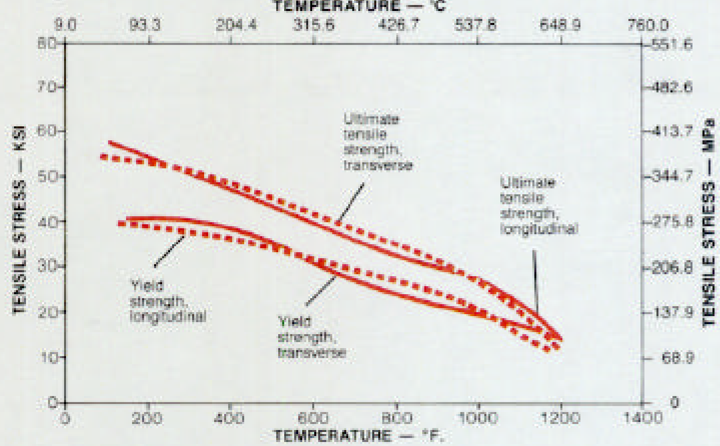
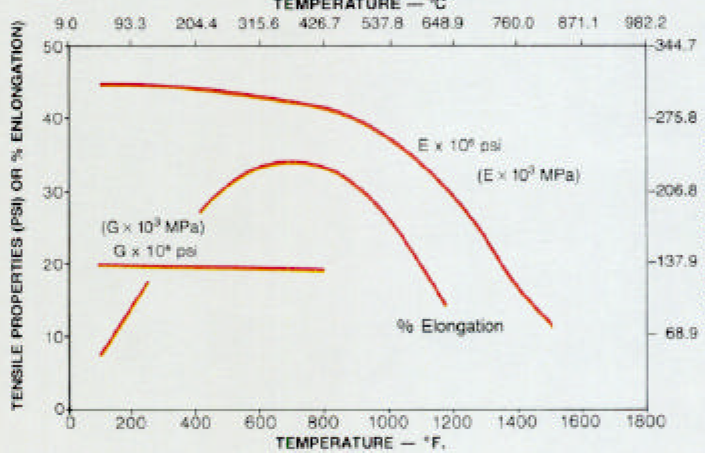


Figure 18 **TENSILE PROPERTIES FOR HOT-PRESSED BLOCK**



MODULUS AND ELONGATION PROPERTIES FOR HOT-PRESSED BLOCK

Figure 19



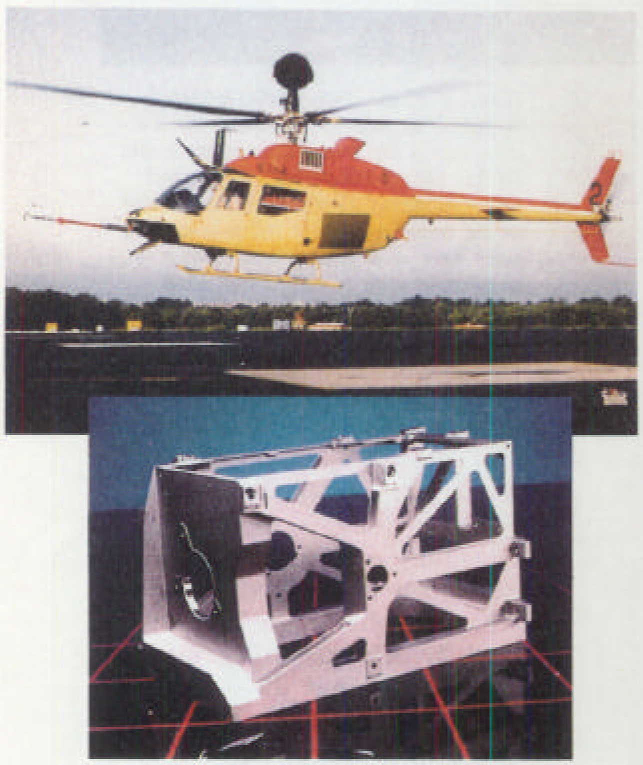
Structural Grades

The specification numbers which identify the structural grades of beryllium vacuum hot-pressed block are S-65C and S-200F.

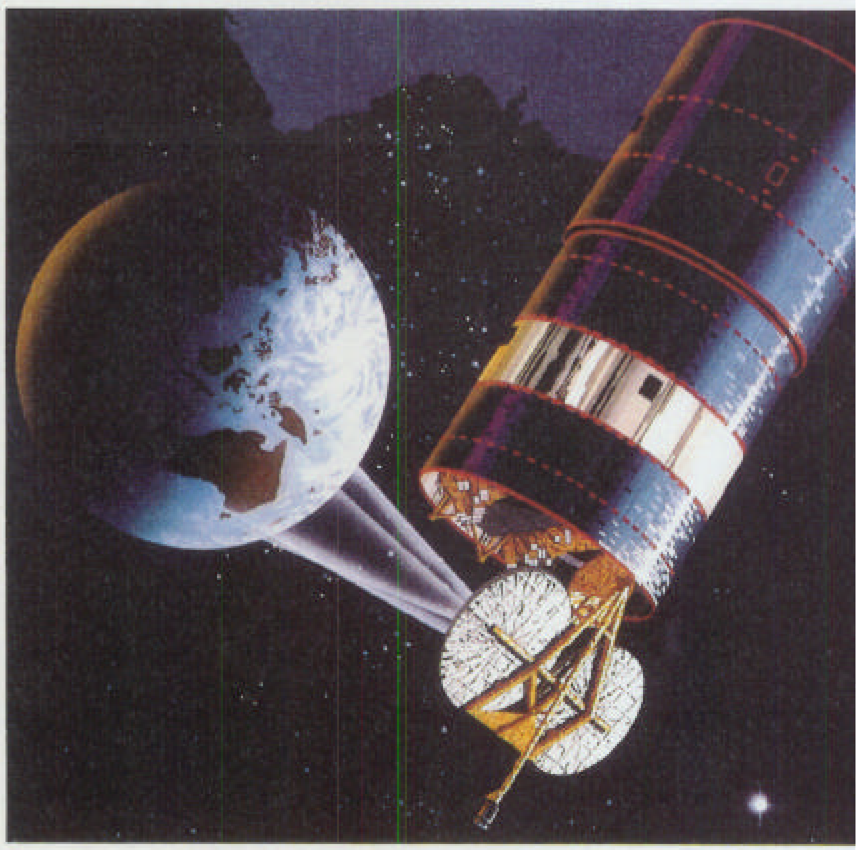
S-65C is a premium material which is guaranteed to exhibit a minimum of 3% tensile elongation at room temperature in any test direction. This strain capacity is obtained through the use of impact grinding during powder manufacture and by holding the micro-alloying elements, iron and aluminum, to the proper ratios. S-65C is utilized in the window frames, umbilical doors and navigational base of the Space Shuttle.

S-65C is lower in oxide content at 1.0% maximum than other grades. While it has a higher guaranteed minimum room tensile elongation, it is lower in strength than our standard purity structural grade, S-200F.

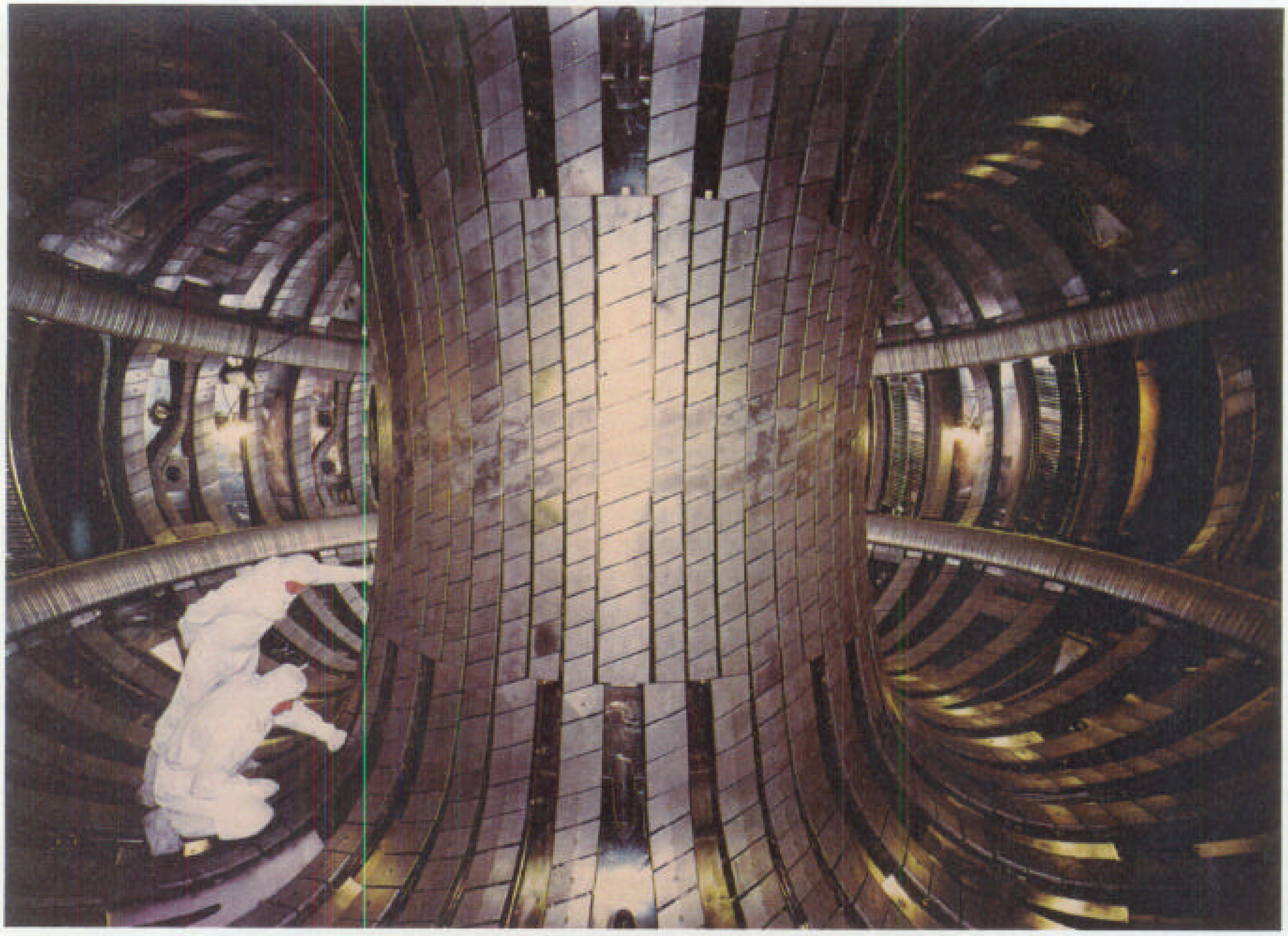
Grade S-200F is most frequently used for parts machined from hot-pressed block. Typical data for this material is given in accompanying charts. Figure 17 shows typical stress-strain curves at various temperatures; Figure 18 indicates typical tensile properties in both the transverse and longitudinal directions, and Figure 19 shows Young's Modulus (E), shear modulus (G) and elongation (el). S-200F is a versatile material, and it has become a successful entity in a wide variety of applications such as inertial guidance systems, missile interstages, optical substrates, spacecraft structures and small rocket nozzles.

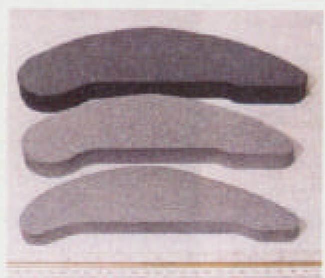


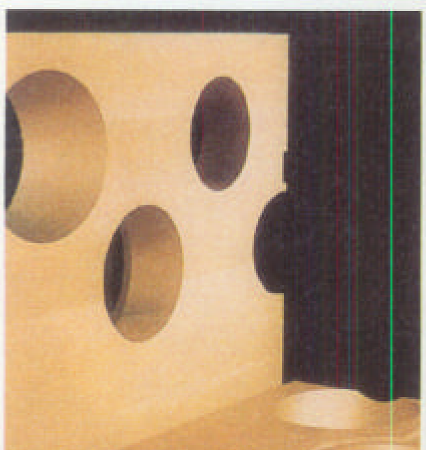
The sensor support structure, inset, is mounted on the mast of the helicopter and must combine a high degree of stiffness with minimum weight. The 16 x 10 x 10 inch (41 x 25 x 25 cm) part weighs only 5 pounds (2.3 kg). (Photos courtesy of McDonnell Douglas Corp. (top) and Speedring Inc. (bottom))



With six times the stiffness-to-weight ratio of aluminum and titanium, beryllium provides the required structural integrity in satellites like this HS 376 at a reasonable launch cost. When the cost of the launch (@ $25K per kilo), fuel for station keeping and the extra payload are factored in, lightweight beryllium becomes highly cost effective. (Photo, courtesy Hughes Space and Communications Group)







Because of its low atomic number, beryllium is the material of choice for the antenna tiles and belt limiters in this thermo-nuclear fusion chamber. Beryllium helps control the purity of the fusion plasma. In addition, the material has the mechanical and thermal properties at high temperature to permit higher power densities on the surface to be maintained at up to 1000°C. Inset shows stages of antenna tile manufacture: cold pressed and formed, cold pressed and sintered, machine shape. (Courtesy, Joint European Torus)

Reflector element for a research reactor takes advantage of beryllium's low thermal neutron capture cross section, enabling the material to control neutron energy to efficient reactor levels. (Courtesy, Interatom GmbH.)

Nuclear Applications

For situations where weight or volume are a consideration, or a high neutron flux is desired, beryllium is very useful both as a moderator and reflector of neutrons. There is considerable interest in using beryllium as the neutron multiplier for solid blanket fusion reactor designs because it enhances the breeding process by providing additional neutrons. This increases the overall reactor efficiency and decreases the hazardous waste production several fold. In fact, beryllium is transparent to most forms of radiation and absorbs a smaller percentage than conventional materials. Beryllium maintains this advantage at elevated temperatures, thereby increasing its usefulness in fusion energy applications over the conventional graphite materials.

Brush Wellman's S-65C grade is the reference grade of beryllium for the International Thermonuclear Experimental Reactor (ITER), a fusion energy program, because it has superior resistance to cracking under high heat flux thermal cycling.

Optical components inside the Lantirn targeting pod on the F-15E tactical fighter require a vibration-free environment to operate with the extreme accuracy required for target acquisition. The yaw/pitch gimbal housing shown here is made of beryllium to achieve the stiffness and dampening capacity needed to maintain dimensional stability. (Courtesy, Lockheed Martin, McDonnell Douglas Aircraft Inc.)

This telescope support, used on spacecraft for exploring deep space, is made of beryllium to capitalize on the material's strength to stiffness ratio and its ability to be machined to close tolerances. (Courtesy, Santa Barbara Research Laboratories)

Instrument Grades

I-220C and I-220H identify the instrument grades of beryllium.

The newest of these materials is I-220H. It is a hot isostatically pressed beryllium that has been developed for applications where a high micro-yield strength i.e., the stress required to produce the first micro-inch of permanent strain (also known as the precision elastic limit or PEL), is required.

Grade I-220H is manufactured using impact ground powder consolidated by an isostatic process (hot isostatic pressing or HIP), thus yielding more isotropic material than I-220C. A comparison of the typical room temperature tensile data between these grades is shown in Table V.

For beryllium made from vacuum hot-pressed block, Grade I-220C remains the standard instrument specification. This material was developed to provide the inertial guidance industry with a low weight, high micro-yield strength material with excellent dimensional stability.

Table V - Typical Room Temperature Tensile Data

	Ultimate Tensile Strength ksi (MPa)	0.2% Offset Yield Strength ksi (MPa)	Micro-Yield Strength ksi (MPa)	% Elongation
I-220C	63.7 (439)	49.0 (338)	7.2 (50)	2.6
I-220H	82.0 (565)	78.0 (538)	14 (96)	2.5

Figure 20

ELEVATED TEMPERATURE TENSILE PROPERTIES OF I-220H

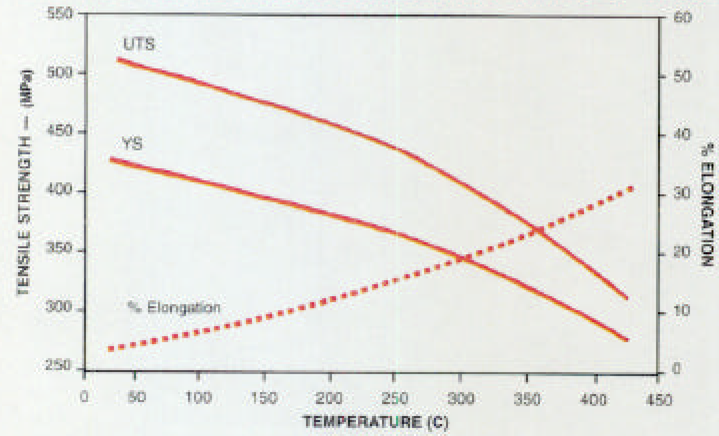


Figure 21

DELTA L/L at CRYOGENIC TEMPERATURES

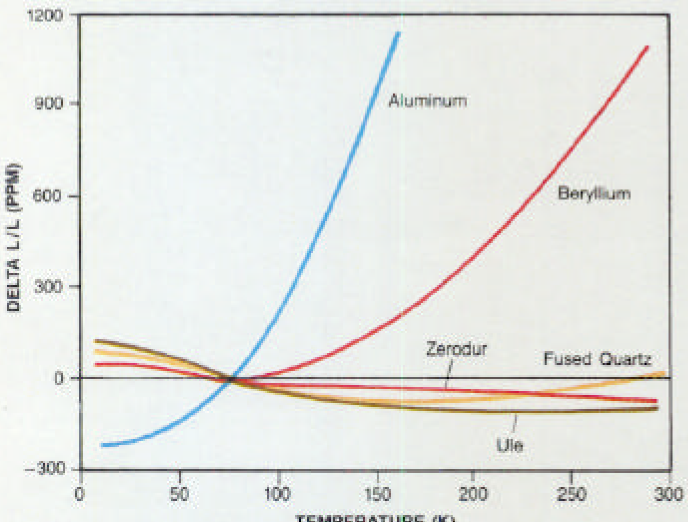
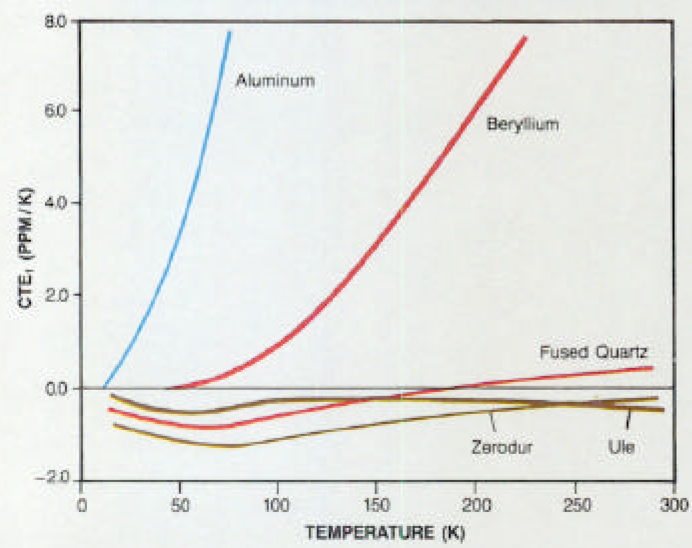


Figure 22

CTE at CRYOGENIC TEMPERATURES



Optical Grades

The specification numbers which identify optical grades of beryllium are I-70H, I-220H and S-200F.

A hot isostatically pressed optical grade of I-70H was developed to provide an improvement over the standard grade for bare polished beryllium optics.

At 0.5% maximum BeO, it is the lowest oxide beryllium which has ever been marketed. It is manufactured by controlling impact ground powder in an isostatic process (HIP), yielding a more isotropic material than any previously available optical grade of beryllium.

TABLE VI - OPTICAL MATERIALS

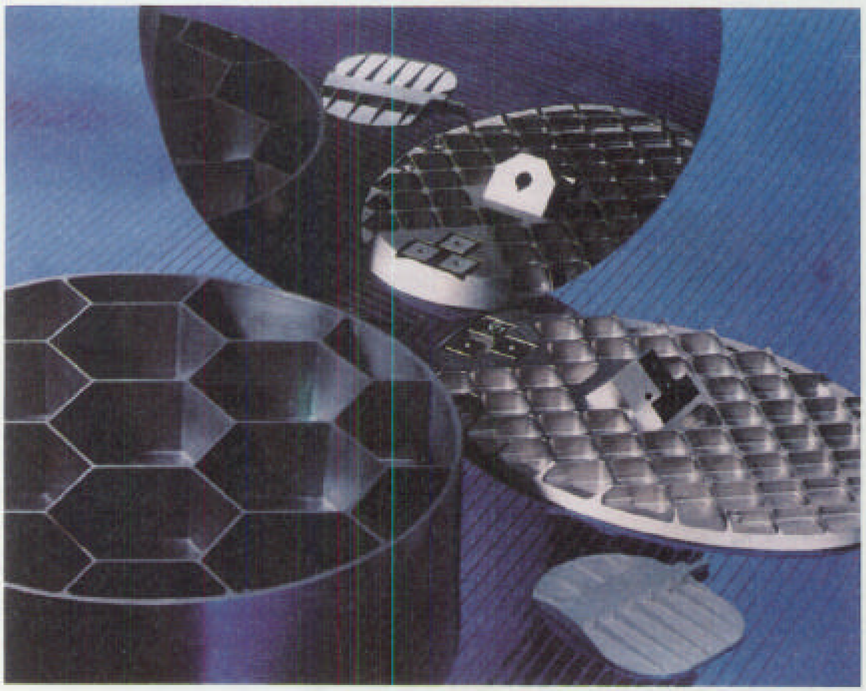
Property	Beryllium	Precision Formed SiC	30% SiC/AL Metal Matrix Composite	Aluminum
Young's Modulus GPA (Msi)	303 (44)	311 (45)	130 (18)	69 (10)
Density g/cm³ (lb/in³)	1.85 (.067)	2.92 (.105)	2.96 (.107)	2.78 (.10)
Specific Modulus (Stiffness/Weight)	163	106	40	28
Coefficient of Thermal Expansion 10^{-6}/°K (10^{-6}/°F)	11.4 (6.3)	2.6 (1.4)	12.2 (7.0)	23.4 (13)
Thermal Conductivity W/cm-hr°K (BTU/ft-hr°F)	2.16 (116)	1.56 (90)	1.2 (67)	1.89 (109)
Microyield (MPa) (KSI)	15-110 (2-16)	None	03 (15)	15-55 (2-8)

TABLE VII BRDF, COMPARISON OF SELECT SAMPLES

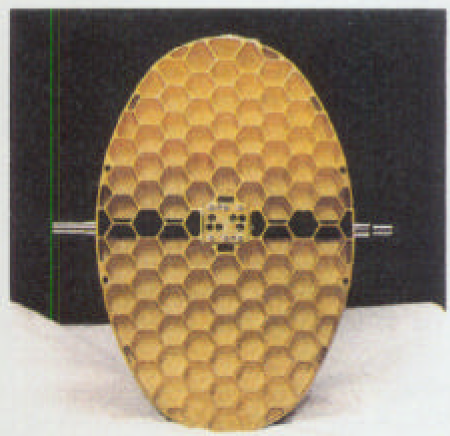
SAMPLE	3° BRDF	10° BRDF	20° BRDF
HIPed I-70 Beryllium	8.1×10^{-5}	6.3×10^{-5}	5.2×10^{-5}
Fused Silica	7.5×10^{-5}	2×10^{-5}	1×10^{-5}
Super Polished Nickel	1.8×10^{-4}	1×10^{-5}	3×10^{-6}

Grades S-200FH and I-220H beryllium, with guaranteed minimum micro-yield strengths, are used where the optical surface is a hard polished electroless nickel. Mirrors of this type are used in the visible and infrared wavelengths of light or any system that may require high resistance to plastic deformation due to severe G-loads or other working stresses.

Grade S-200F has been used successfully as an optical substrate and support bench in many astronomical telescopes, in fire control and FLIR systems, and in earth resources and weather satellites. In most applications, the optical surface of S-200F is a hard polished coating of electroless nickel, 24 micrometers to 150 micrometers thick. Electroless nickel is harder than bare beryllium and more easily polished to a fine surface finish. See Table VI for a comparison of beryllium to other optical substrate candidates.



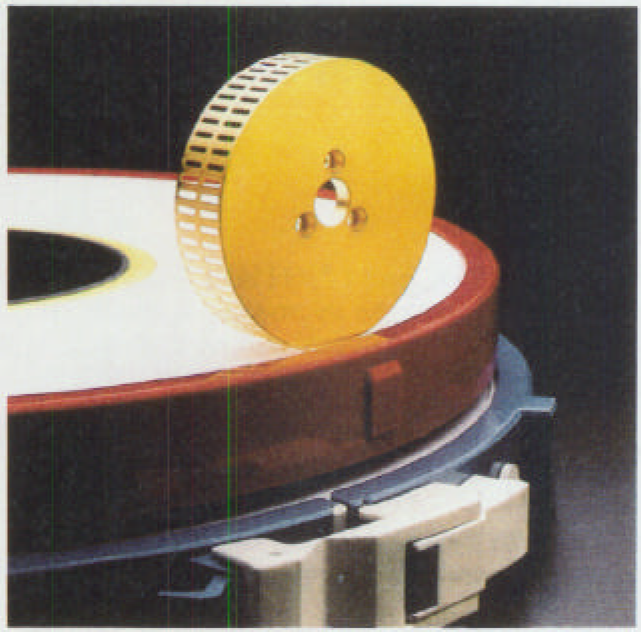
Open and closed back beryllium mirror blanks are hot isostatically pressed to near net shapes, providing a combination of light weight, stiffness, and improved optical performance over former methods.



Intricate design of this open back mirror for GOES satellite capitalizes on the near net forming technology now utilized in making beryllium optics. (Courtesy of Applied Optics Center)

Inside the gunners primary sight for the West German Leopard I and II main battle tanks, an exactly stabilized deviation mirror made from near net shape (NNS) beryllium provides the high resolution that produces reliable data for the fire control system. (Courtesy, Krauss Maffei Wehrtechnik GmbH and ESW)

Beryllium's stiffness, low weight, high micro-yield strength and stability make it ideal for the Metosat scanning mirror shown here. (Courtesy of CNES and SAGEM)



In data processing equipment, beryllium is used for fabricating lightweight capstans in tape drives in computer storage devices.

Wrought Forms Of Beryllium

Wrought forms of beryllium are usually produced from vacuum hot-pressed blocks by conventional working techniques carried out either in warm or hot working temperature ranges. Wrought products exhibit improved strength and tensile elongation relative to the hot-pressed block in the direction of metal working, but lower properties (particularly tensile elongation) transverse to the direction of working. This is due to the crystallographic orientation resulting from the working operations. Multi-directional working schedules are frequently used to alleviate this effect.

Beryllium Foil

By convention, beryllium foil is flat stock with a thickness of 0.020 inch (0.508 mm) or less. The foil is manufactured by rolling the material at elevated temperature in steel cans. As beryllium cannot be successfully rolled at room temperature, a cold-rolled surface is not available.

Because of its low absorption of radiation, beryllium foil is used in windows that transmit different wavelengths of radiation, both in detector and source applications.

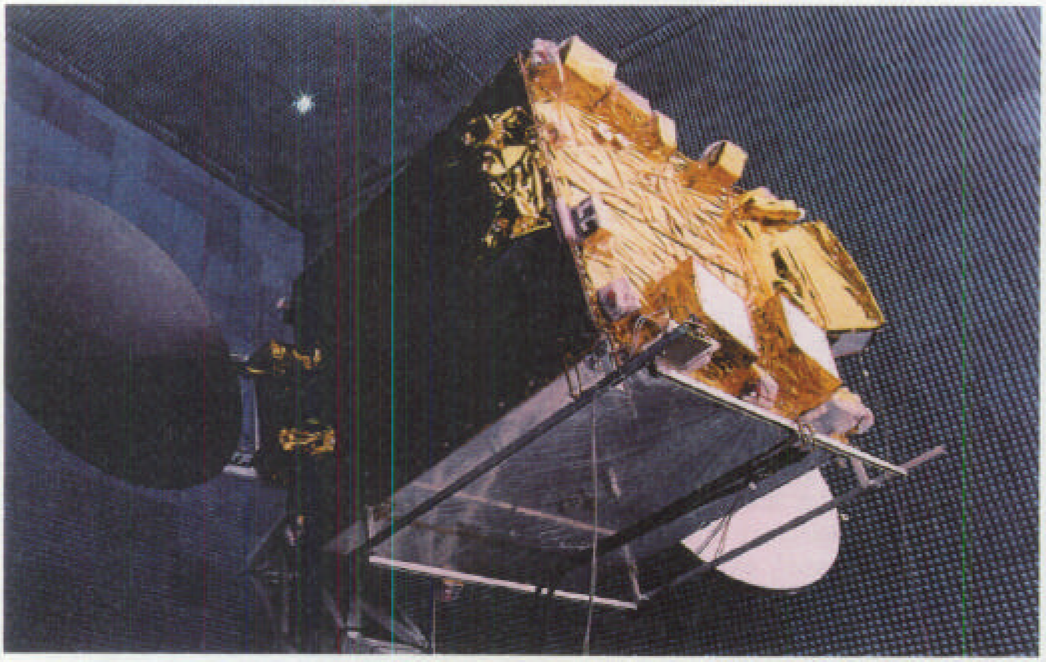
Due to the nature of these applications, it is only available in two high purity grades, PF-60 and IF-1. IF-1 is the highest purity material and is available as a standard product in thicknesses between 0.0003 (0.008 mm) and 0.020 (0.508 mm) inches. PF-60 is available at gauges from 0.0003 (0.008 mm) and 0.125 (3.175 mm) inches. The chemical composition of these foils is shown in Table VIII.

TABLE VIII - BERYLLIUM FOIL

Grade	IF-1	PF-60
Chemical Composition		
Beryllium Content, % Min.	99.8	99.0
Beryllium Oxide, % Max.	0.03	0.8
Aluminum, ppm max.	100	500
Boron	3	3
Cadmium	2	2
Calcium	200	100
Carbon	300	700
Chromium	25	100
Cobalt	5	10
Copper	50	100
Iron	300	700
Lead	5	20
Lithium	—	3
Magnesium	60	500
Manganese	30	120
Molybdenum	10	20
Nickel	200	200
Nitrogen	—	400
Silicon	100	400
Silver	5	10
Titanium	10	—
Zinc	100	—
Available Gauge	0.0003" – 0.020" (0.008mm – 0.508mm)	0.0003" – 0.125" (0.008mm – 3.175mm)

TABLE IX - FLAT ROLLED BERYLLIUM PRODUCTS TENSILE PROPERTIES AND SIZES AVAILABLE

Thickness Inches (mm)	Spec No.	Minimum Ultimate Tensile Strength 1000 psi (MPa)	Minimum Yield Strength (0.2% Offset) 1000 psi (MPa)	Minimum % Elong.	Typical Sizes Available in. (cm)
0.021 - 0.030 (0.533 - 0.762)	SR-200	70.0 (482.6)	50.0 (344.7)	10	24 × 72 (61 × 183)
0.031 - 0.125 (0.763 - 3.175)	SR-200	70.0 (482.6)	50.0 (344.7)	10	24 × 84 (61 × 213)
0.126 - 0.250 (3.176 - 6.350)	SR-200	70.0 (482.6)	50.0 (344.7)	10	24 × 66 (61 × 168)
0.251 - 0.450 (6.351 - 11.430)	PR-200	65.0 (448.2)	45.0 (310.3)	4	24 × 50 (61 × 127)
0.451 - 0.600 (11.431 - 15.240)	PR-200	60.0 (413.7)	40.0 (275.8)	3	24 × 40 (61 × 102)



A beryllium central thrust cylinder is used inside this communications satellite to provide the required rigidity for the structure, and it does so at a weight factor that is far less than any other candidate material. (Courtesy, Space Systems LORAL)

Beryllium Plate & Sheet

By convention, beryllium rolled stock with a gauge between 0.020 (0.508 mm) and 0.250 (6.35 mm) inches is known as sheet, while thicker gauge material is referred to as plate. The specification numbers are SR-200 for sheet and PR-200 for plate. The chemical composition of both of these products conforms to that previously listed for S-200F vacuum hot-pressed block. The guaranteed room temperature tensile properties in the plane of the sheet or plate and the maximum standard sizes available are shown in Table IX. These rolled products are manufactured by warm rolling billets of vacuum hot-pressed block encased in steel. The crystallographic orientation and thus the properties of the sheet are balanced by cross rolling (i.e., rotation of the rolling direction 90°) during the reduction schedule.

Tensile Properties

Typical tensile properties of SR-200 sheet as a function of temperature and typical stress-strain curves are shown in Figures 23, 24 and 25. The shear strength of cross-rolled sheets and vacuum hot-pressed block as a function of temperature is shown in Figure 12.

The relationship of shear strength to tensile strength is higher than for most materials in the lower part of the temperature range and is lower than expected at temperatures exceeding 900°F (482°C). The shear tests were conducted using a tear-type specimen. Compression stress-strain curves indicate that the compressive yield strength is at least equal to the tensile strength based on a limited number of tests.

Figure 23

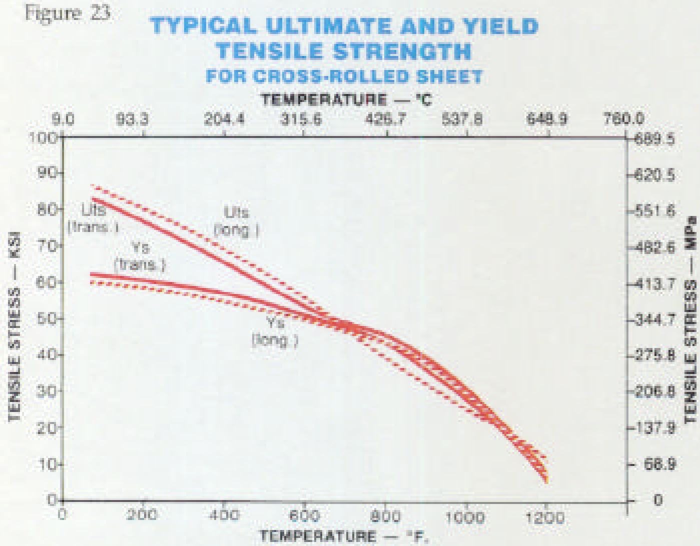
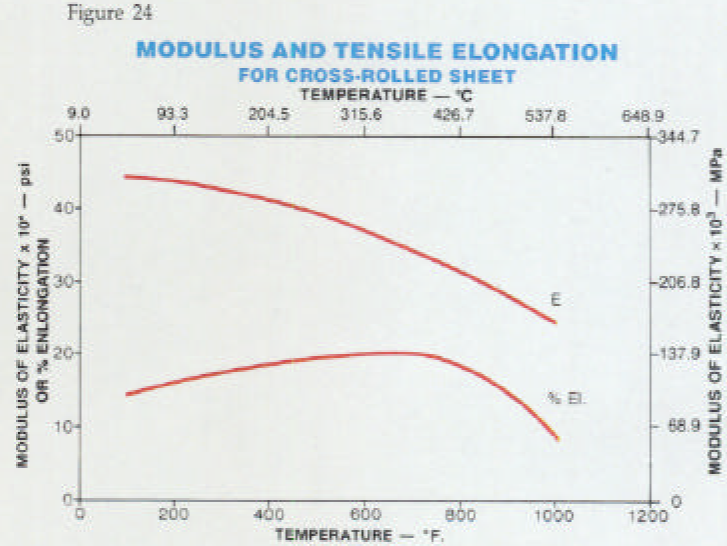


Figure 24



When a structural member is designed to span a given distance or cover a given area, weight saving is usually limited to reducing the thickness of the component. Resistance to deflection or buckling is then the primary consideration and rigidity, not strength, is often the controlling design parameter. Weight comparisons in typical design cases are helpful in evaluating the structural efficiency of beryllium sheet for this type of application.

Figure 26 illustrates a comparison of weight per square foot of compression panels as a function of loading intensity. It is shown that beryllium is superior to H-11 tool steel, beta III titanium, HM21A-58 magnesium and 15-7PH stainless steel. This superiority is maintained from the lowest intensities up to 50,000 pounds per inch width (8.95×10^5 kg/m width). Figure 27, which provides information on relative weight for various compression panels, augments Figure 26. An H-11 tool panel, for instance, with a buckling resistance equal to a beryllium panel, will weigh five times as much if the buckling load is less than 4,000 pounds per inch of width (7.16×10^4 kg/m width).

While Figure 27 deals with initial buckling calculations, Figure 28 shows test data dealing with buckling and collapse of flat panels. Beryllium sheet exhibits post-buckling behavior similar to that of other metals.

Figure 25

STRESS-STRAIN CURVES
FOR CROSS-ROLLED SHEET

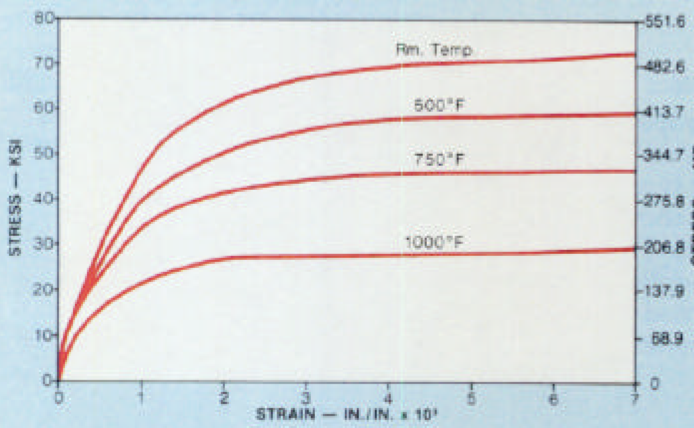


Figure 26

COMPARATIVE WEIGHTS OF COMPRESSION PANELS
TEMPERATURE = 600°F (315.6°C)

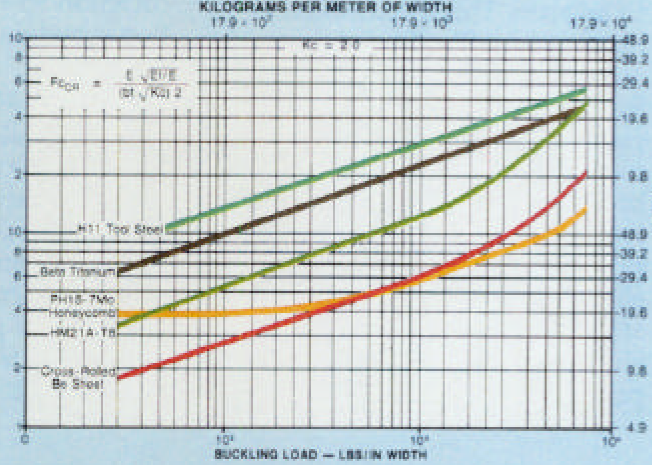


Figure 27

RELATIVE WEIGHTS OF COMPRESSION PANELS
TEMPERATURE = 600°F (315.6°C)

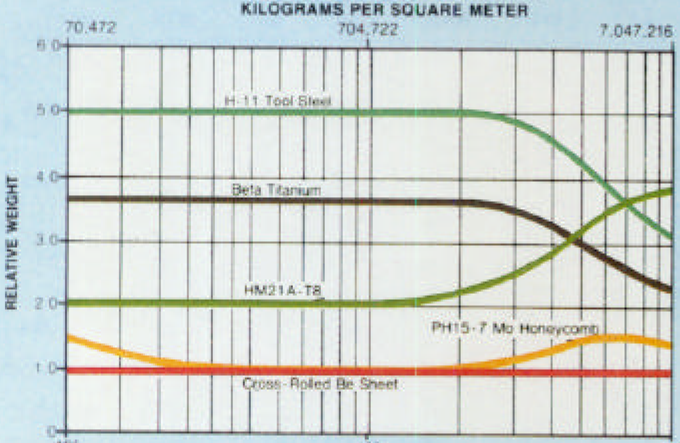
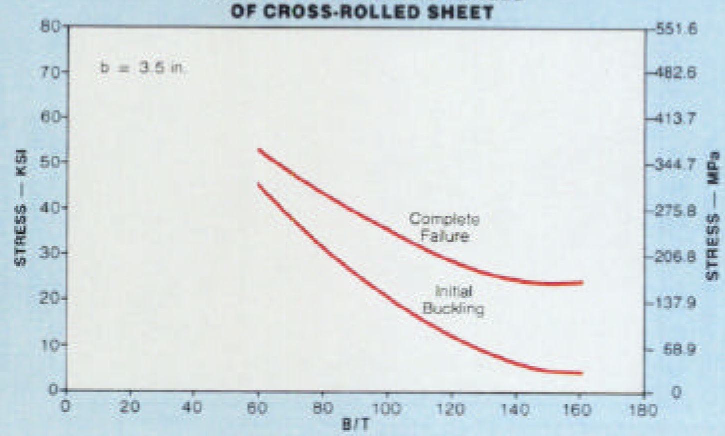
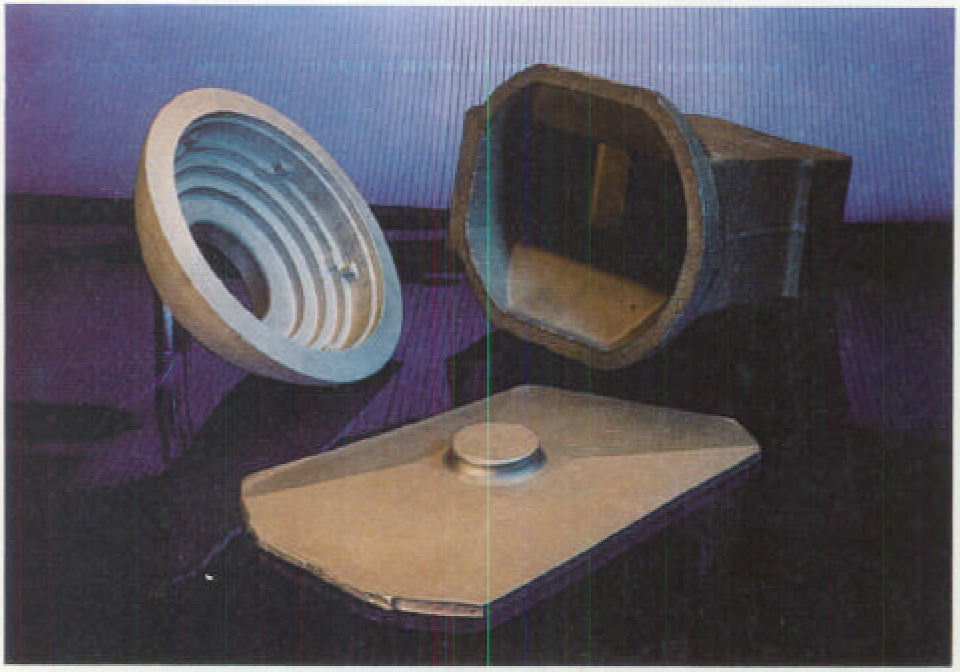


Figure 28

COMPRESSION BUCKLING TESTS
OF SIMPLY SUPPORTED PANELS
OF CROSS-ROLLED SHEET





Brush Wellman uses both cold and hot isostatic pressing methods to produce complex metallic beryllium components to near net shape.

Near Net Shapes

Despite a combination of physical, mechanical and thermal properties that is unequalled by any other material, beryllium's use has been limited until recently by its availability in primarily one single form, vacuum hot-pressed block. This form involves high costs in both producing the material and in fabricating machined components, making beryllium a less cost effective engineering material.

Brush Wellman has solved this problem with the development of production facilities to produce near net shapes. The use of hot isostatic pressing (HIP) and cold isostatic pressing (CIP), along with the conventional cold pressing technology, has brought beryllium within reach of a wider range of applications.

Hot Isostatic Pressed Grades

The specification numbers which identify the grades that are available by hot isostatic pressing (HIP) are S-200FH, S-65H and I-220H.

The S-200FH grade utilizes impact ground powder that is consolidated in a sheet metal can formed into the shape of the final part. In production, the can is degassed, sealed, and HIP'ed, typically at 1000°C and 15,000 psi (103 MPa). This process conserves material (powder) and reduces the total finish machining time.

The S-200FH material is more isotropic, has higher density (99.8% of theoretical) and higher mechanical properties than the traditional vacuum hot-pressed material. It is useful for structural applications or those requiring low weight, high mechanical strength and a high fatigue endurance limit.

Grade I-220H is a high strength, moderate ductility material useful for structural, instrument and optical applications and those requiring high resistance to plastic deformation at low stress levels. It offers the best combination of high tensile strength, ductility and micro-yield strength of any grade of beryllium. Its micro-yield strength (amount of stress required to produce one micro inch of permanent strain) is typically 14 ksi.

MINIMUM SPECIFIED PROPERTIES FOR BRUSH WELLMAN HOT ISOSTATIC PRESSED GRADES				
	Minimum Ultimate Tensile Strength ksi (MPa)	Minimum 0.2% Offset Yield Strength ksi (MPa)	Minimum Micro-Yield Strength ksi (MPa)	Minimum % Elongation
S-200FH	60.0 (414)	43.0 (296)	not specified	3.0
S-65H	50 (345)	30 (217)	2.5 (17)	2.0
I-220H grade 1	65 (448)	50.0 (345)	6.0 (41)	2.0*
I-220H grade 2	65 (448)	50.0 (345)	10 (69)	2.0*

*1.0% elongation should be used when a major dimension is greater than 20 in. (508 mm)

S-65H has a lower impurity content which is more compatible with nuclear energy applications. It is recommended for applications which need high ductility at elevated temperatures.

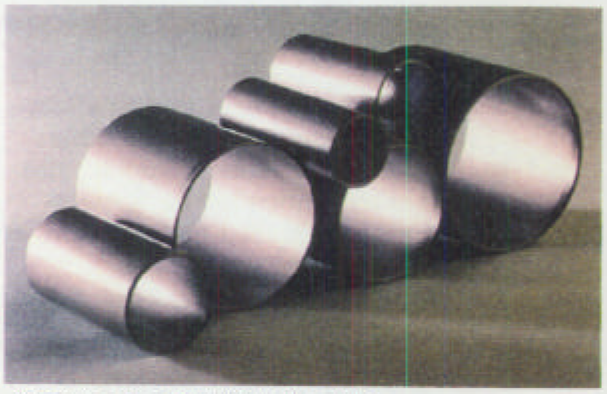
Cold Isostatic Pressed Grades

Specification number S-200FC identifies the only grade currently available by cold isostatic pressing (CIP).

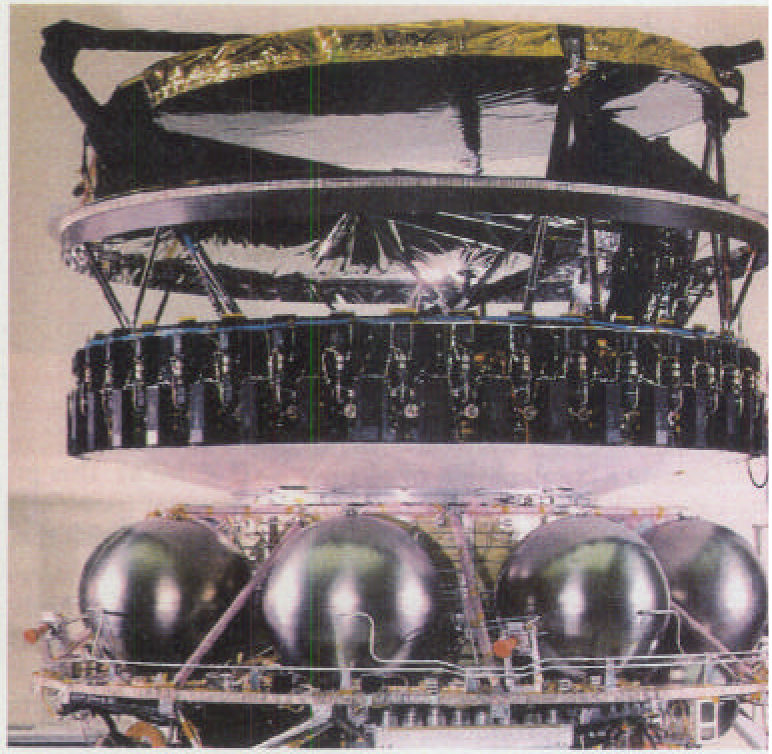
This grade utilizes impact ground powders that are consolidated in a flexible rubber bag that approximates the final shape of the part. The powder is loaded into the bag and is degassed, sealed and CIP'ed at typically 60,000 PSI (414 MPa) at room temperature. The part is then sintered to final density, 99+%, and, if required, may be hot formed to final shape. Typical properties of S-200FC beryllium are 46 ksi (319 MPa) UTS, 33 ksi (231 MPa), yield strength, and 3% elongation.

This process is useful for applications requiring lesser properties than obtained by HIP. The tooling is reusable, making it advantageous for parts required in the hundreds. Typical applications for these grades are optics for fire control systems in tanks and aircraft, as well as instrument applications such as inertial measurement units.

Brazed panel for the National Aerospace Plane includes thin wall tubes (.38" OD, .050" wall), mounting pads, stiffening ribs and skin, all made of beryllium. (Courtesy Electrofusion Corporation, a Brush Wellman Company)



Typical size range of extruded beryllium tubing. (Courtesy, Nuclear Metals, Inc.)



Extrusions

Extrusion is a conventional approach to the creation of thick-walled beryllium tubes and shapes. For specific applications, extrusion provides consistent mechanical properties, dimensions and tolerances.

Sections are made to dimensions that are well within commercial tolerances, and mechanical properties are superior to those of hot-pressed block in the direction of metal flow. Directional properties are produced in varying degrees as a function of crystallographic orientation.

The input billets for extrusions are usually machined from hot-pressed block. The billets are jacketed in mild steel cans with shaped nose plugs and are extruded through a steel die in temperature ranges between 1650°F (899°C) and 1950°F (1066°C). The jackets are later removed by chemical means.

TABLE XI - TYPICAL EXTRUDED BERYLLIUM TENSILE PROPERTIES

MATERIAL			LONGITUDINAL			CIRCUMFERENTIAL			RADIAL		
FORM	TYPE	DIAMETER	Ftu	Fty	e	Ftu	Fty	e	Ftu	Fty	e
		in. (cm)	ksi (MPa)	ksi (MPa)	(%)	ksi (MPa)	ksi (MPa)	(%)	ksi (MPa)	ksi (MPa)	(%)
Rod[14]	S-200	1 - 2½ (2.54-6.35)	108 (745)	50 (345)	10	66 (455)	57 (393)	0.6	63 (434)	54 (372)	0.6
		⅜ - ½ (0.95-1.27)	111 (765)	60 (414)	10						
		O.D. I.D.									
Tubing[14]	S-200	6.5 (16.51) 3.7 (9.40)	95 (655)	51 (352)	13	62 (427)	50 (345)	1.0	60 (414)	47 (324)	0.7
	S-200	4.6 (11.68) 3.2 (8.13)	104 (717)	48 (331)	11	57 (393)	47 (324)	0.7			
	S-200	2.5 (6.35) 1.3 (3.30)	111 (765)	55 (379)	9						
	S-200	1.2 (3.05) 0.8 (2.03)	116 (800)	63 (434)	9						

Beryllium structural parts are being used extensively by Hughes Aircraft Co. in building two communications satellites for Japan Communications Satellite Company. (Courtesy, Hughes Aircraft Space and Communications Division)

Rod, tubing and structural sections are the most common extruded shapes. Rod is available in sizes from 0.375″ to (0.953 cm) to 5.75″ (14.605 cm) diameter; tubing from 0.25″ (635 mm) OD by 0.020″ (0.015 mm) wall thickness to 4.0″ (101.6 mm) OD by 0.250″ (635 mm) wall thickness.

Current applications of extruded shapes include boom arms for solar array panels, satellite truss supports, draw stock for wire, fuel element cladding and input for coextrusions with dissimilar metals, to name a few.

Mechanical properties and chemistry are tailored to the specific application. Beryllium extrusions have been typically made from the standard structural grade, S-200. Typical ultimate tensile strength, yield strength and elongation values are given in Table XI.

Brush Wellman Inc. has a 3,000 ton (2,720 tonne) extrusion press at its Elmore, Ohio, facility. That capability, plus those of the independent extruders, gives the design engineer a wide range of products from which to choose in solving his weight and stiffness problems.

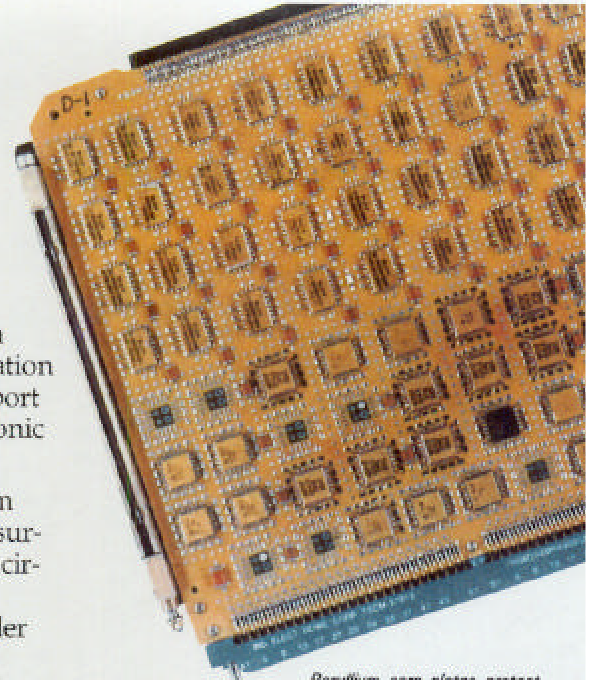
Electronic Grades

Cross-rolled SR-200 beryllium sheet is utilized as a combination heat sink and structural support in military electronic and avionic systems.

Constraining cores made from this material are attached to surface mounted (SMT) printed circuit boards to alleviate the mechanical stress on the solder joints of leadless and leaded ceramic chip carriers (LCCCs). The high thermal conductivity of beryllium is needed to dissipate the heat generated by the combination of large scale integration and high switching speeds.

The application also requires a coefficient of thermal expansion (CTE) that is a good match to the alumina and polyimide glass substrates used in the system.

The major appeal of beryllium, however, is its low density. Since about seven pounds of payload or fuel can be added for every pound saved in the electronics systems of space and airborne vehicle, this is a matter of prime importance. Compared to other core plate materials, beryllium weighs about one-fifth as much as copper clad molybdenum and one-fourth as much as copper clad invar.



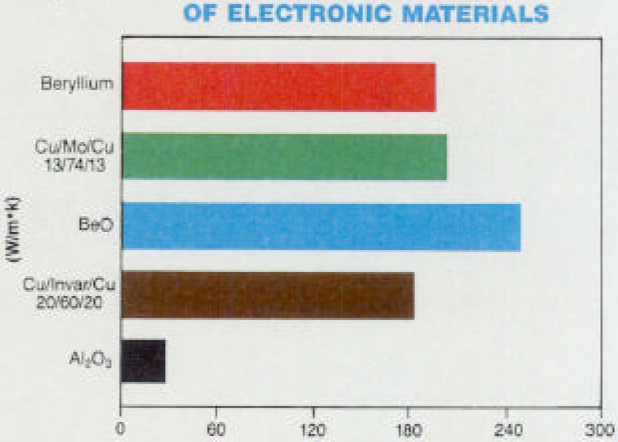
Beryllium core plates protect densely packaged SMT circuit boards from the effects of mechanical stress and heat.

In addition to its light weight and desirable thermal properties, beryllium possesses high specific stiffness, high modulus of elasticity, and minimal interaction with magnetic fields.

Dimensional stability is an important attribute in constraining core plates because any tendency of the material to vibrate, flex or bend would be just as traumatic to the PCB as expansion/contraction. In terms of specific modulus, beryllium far outperforms the other candidates.

Beryllium not only dissipates heat, but readily absorbs it when necessary. The specific heat of beryllium is four times that of Cu/Invar/Cu and six times that of Cu/Mo/Cu.

Figure 29 **THERMAL CONDUCTIVITY OF ELECTRONIC MATERIALS**



Fabrication Processes

Forming Procedures

Beryllium sheet, plate and strip can be formed in the temperature range of 200 to 1100°F (204 to 593°C) although the optimum forming temperature is above 1300°F (704°C).

Sheet and plate have been shaped, bent, spun, deep drawn, joggled, shear formed, stamped and cupped using both reduction and bending techniques. SR-200 sheet has been characterized by forming it into ninety degree angles. The results for these tests are summarized in Figures 30 and 31. As indicated by these curves, the forming of beryllium is strain-rate sensitive and therefore should be kept as slow as practical. Our production shop experience indicates that good 5t bends can be formed consistently around 1350°F (732°C).

In addition to angles, SR-200 sheet has been formed by straight bends into channels, zee sections and tee sections. Depending on the task to be performed, a specific tool material is to be used, such as tool steel, stainless steel or Glassrock.

Shop forming practices should include etching the sheet prior to forming, heating the dies to the temperature of the metal and for best results, forming slowly.

Due to beryllium's abrasive nature, it is generally desirable to use thin foil of stainless steel or mild steel between the die and the beryllium in applications where the beryllium is dragged against the die. This practice extends the die life. Normal practice during forming is to hold the beryllium sheet at temperature for up to twenty minutes. Any oxide film which forms on the hot-formed or stress-relieved part may be removed by liquid honing or polishing with a fine abrasive. Incomplete removal of the film will result in a masking effect and cause uneven etching.

Channel ring segments have been formed using SR-200 sheet in thicknesses of 0.020″ (0.51 mm) and 0.120″ (305 mm). This demonstrates that the forming of curved channel segments on a production basis is feasible using forming temperature of 1350°F (732°C) and a punch travel speed of less than one inch per minute.

The spinning of beryllium is possible and should be done at temperatures between 1300°F (704°C) to 1400°F (760°C). Propane torches may be used as a source of heat. Steel mandrels are used with as many as six stages being necessary to produce a full hemisphere. Glass lubrication has been found to work successfully. Using this technique, it has been possible to produce hemispheres up to 31″ (79 cm) in diameter, 0.2″ (0.51 cm) thick. It has also been possible to spin cones, flat bottom cups and flanged as well as beeded configurations.

Machining Beryllium

Generally, beryllium is easily machined to intricate forms, maintaining excellent surface finishes and close tolerances. Machining practices for beryllium parallel those for cast iron. Generally, tool design for cast iron will be applicable. Beryllium has a machinability factor of 55% using 1113 steel as 100%. It is comparatively soft material (Rb 80-90) but abrasive, producing a discontinuous chip. Generally, a Grade

Figure 30

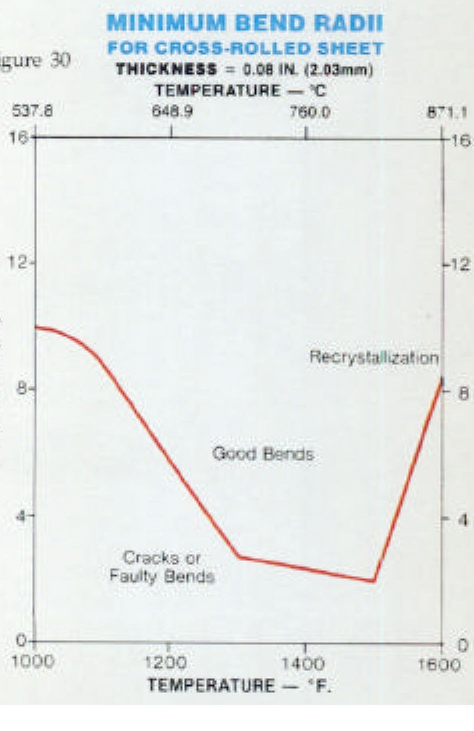
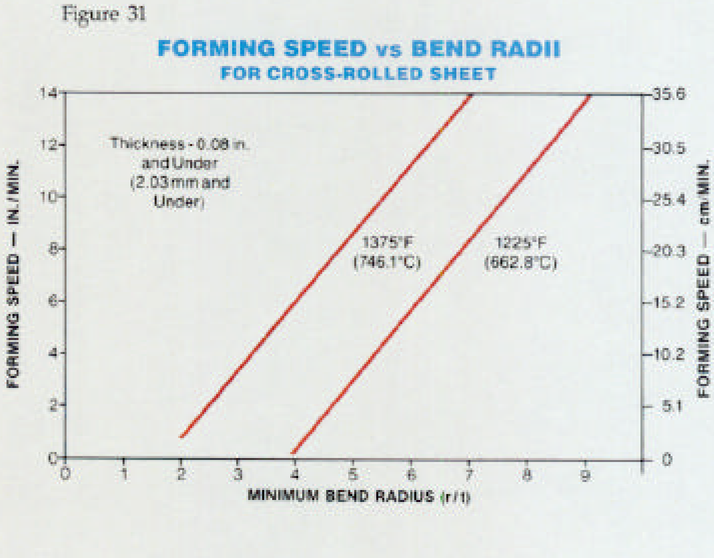


Figure 31



Good machinability is required for these parts for inertial measurement systems on missiles. These sensitive instruments are protected from the effects of vibration, temperature, and magnetics by placing them inside a beryllium sphere that floats on a thin layer of fluid. Beryllium was selected because it can maintain dimensional stability through a wide range of pressures and temperatures. (Courtesy, Speedring Inc.)

The excellent detail and smooth finishes that can be achieved by machining beryllium is aptly demonstrated by these parts for missile and spacecraft systems. (Courtesy, Speedring Inc.)

2 general purpose carbide, for cast iron and non-ferrous materials, is selected as the cutting tool material. Selective specific grades in this class, such as Valenite VC-2 or equivalent, will give excellent results.

Care should be taken to secure clean, uncontaminated beryllium chips when removing substantial quantities of metal for economic reasons because of the high value of such clean chips. Contamination of chips results in the necessity of expensive reclamation procedures before such metal can be reintroduced into the manufacturing stream. For this reason, beryllium is machined dry whenever practical. Beryllium should not be machined until it is certain that the required limits on airborne beryllium will be observed. For detailed information on these requirements, consult Brush Wellman Inc.

Beryllium is quite susceptible to surface damage as a result of machining operations. This damage may be seen by careful sectioning of machined material and observation of the disturbed surface layer, twins, and perhaps actually cracking in severe cases. The damaged layer may be of varying depth dependent upon severity of machining operation, condition of tooling cutting edges, etc. Generally with good practice it does not exceed 0.002″ (0.015 mm) in depth, but may reach 0.008 - 0.010″ (0.203 - 0.254 mm) in severe cases.

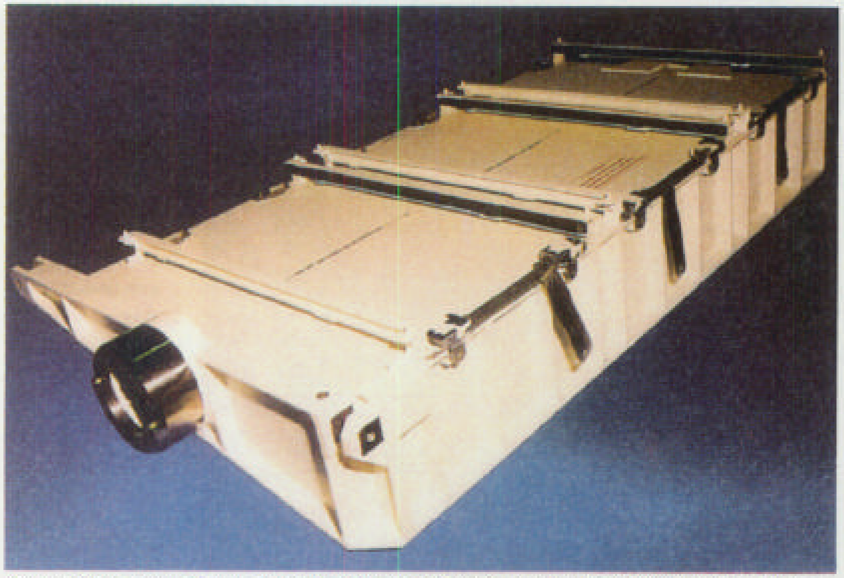
The result of such damage, if not removed, is a dramatic decrease in the fracture strength and elongation characteristics of the metal. Yield strength may not be affected. Machine damage is controlled by adherence to accepted machining practice followed by etching to remove 0.002 - 0.004″ (0.051 - 0.102 mm) per side or by heat treatments designed to anneal out the disturbed layer and twins.

In summary, beryllium can be readily and successfully machined into intricate and very precise tolerance components using standard metal cutting and finishing techniques with slight adaptations.

Drilling of Wrought Products

The key to successful drilling of wrought products involves control of feed rate, and selection of drill points which minimize tool pressure.

Improper control of any factor in this process can result in laminar breakout or delamination within the product. To prevent the occurrence of such a problem, Brush recommends the use of computerized "Tornetic Drilling Unit" produced by Dyna Systems, Inc. of Torrence, California. This drill utilizes an automatic torque-sensing device which varies the speed and feed in order to maintain the cutting force within the safe limits for both the drill and beryllium. A straight two-fluted modified master drill is recommended and commercially available. This device was successfully utilized in the production of the Minuteman Spacers.



Shuttle orbiter navigation base assembly ready for installation in crew module. All detail parts except honey comb core, external fittings and rails are beryllium.

Sheet Cutting

Straight cuts are made in sheet by an abrasive sawing technique. This operation is performed wet using a resin-bonded, semi-friable aluminum oxide wheel rotating to give a surface speed of 7000 to 9000 fpm (35.6 to 45.7 meters per second). Brush recommends using a wheel with an abrasive grain size of 80 grit and a relatively soft "L" bond grade.

Chemical Milling

Chemical milling techniques have been successfully used in the fabrication of parts made from beryllium block, sheet extrusions and forgings. Metal removal may be over the entire surface or it may be restricted to selected areas by masking.

The important steps in the chemical milling operations are clean, mask, scribe and strip mask before milling, mill, and mask removal after milling. Material removal rates vary from 0.001″ (0.025 mm) to 0.002″ (0.051 mm) per minute. Tolerances on the final part are very close to those of the original and can be held to ± 0.005″ (± 0.127 mm) for a material removal of approximately 0.100″ (2.54 mm). Tolerances can be expected to vary in complex configurations. Surface finishes are generally rougher after chemical milling and depend to a great extent on starting material surface quality.

Electrochemical Machining

Successful trepanning, contouring and drilling of complex beryllium parts have been carried out using electrochemical machining. This process is attractive due to the fact that it produces a relatively small degree of surface damage. For beryllium, NaCl and $NaNO_3$ are two electrolytes which have been reported to work successfully.

Electric Discharge Machining

EDM is very effective on beryllium and is used to machine intricate and irregular forms at good production rates. The process is generally carried out using brass or graphite cathode tools, which enhance metal removal rates, and a dielectric oil that acts as a coolant. This method is very practical for the machining of complex shapes of beryllium. Beryllium can also successfully be cut to precise tolerance by using a wire EDM machine.

Joining

Adhesive Bonding

Adhesive bonding is a very desirable way to join beryllium to itself and to other metals. The method of joining permits the utilization of the desirable mechanical and physical properties of the metal, while minimizing notch sensitivity. Depending on the application of the part to be joined, specific adhesives ranging from low temperature to high temperature are available.

Of all the steps involved in producing a good bonded joint, surface preparation is by far the most important. Once the adherents have been acid cleaned and neutralized, the adhesive is applied. The joint is then exposed to heat and pressure, characteristic for each specific adhesive, for about one hour. If for any reason the parts must be taken apart, the adhesive must be removed and the procedure repeated with a clean surface.

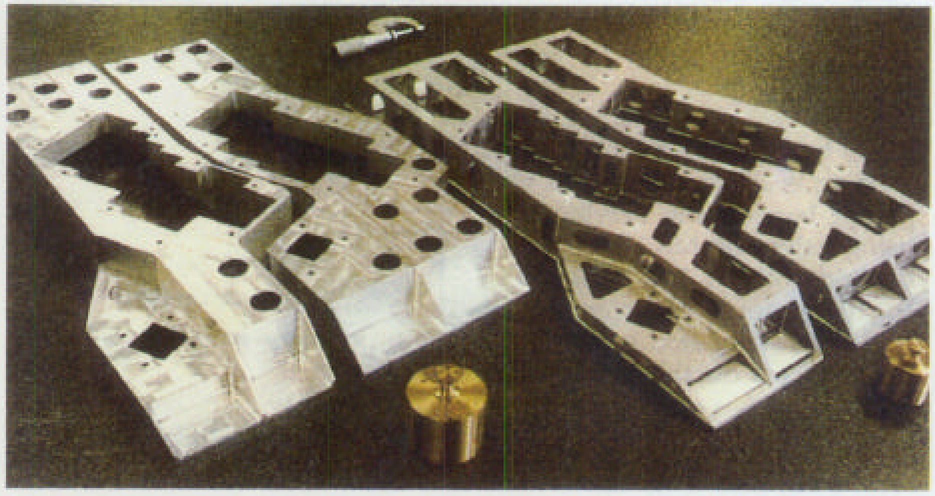
Rockwell International used adhesive bonding on the navigation base of the Shuttle Orbiter, an operation which required bonding 36 detail parts in six different stages using five different adhesives. The navigation base is approximately 44″ (112 cm) long, 22″ (56 cm) wide and 7″ (18 cm) high. The base is required for mounting inertial measurement units and two star trackers as sensors for navigation of the Shuttle Orbiter in earth orbit.

Brazing

Brazing is another means of joining beryllium to itself and other metals. There are several brazing techniques in use, the choice depending on the specific application of the beryllium part itself. Typically a silver base, zinc base or aluminum base alloy is used providing the designer with varied strength and thermal capabilities. The shear strength of joints prepared with several braze alloys are shown in Table XIII. Brazing is considered to be the most reliable method of metallurgically joining beryllium.

The technique of furnace brazing has been used successfully with beryllium using a silver with 0.50% lithium content braze alloy. This technique involves preplacing the braze alloy between two halves of the assembly. The joint is then subjected to a static load and high temperature. The brazing is done in a vacuum to prevent oxidation of the beryllium at the elevated temperature.

Dip brazing was used in the production of the beryllium spacer for the USAF Minuteman ICBM Missile. Brush Wellman fabricated over 2,000 spacers each containing four zinc-brazed joints. Each joint was proof tested with a force of 8,000 lbs. (35,586 N). The shear strength as a function of zinc braze thickness is illustrated in Figure 32. Figure 33 illustrates the effect of test temperature on braze strength. This method of brazing beryllium offers many advantages because zinc has no undesirable reactions with beryllium.



This horn assembly for a commercial communications satellite is a brazed assembly of machined beryllium sections. It was converted from aluminum at 50% savings in weight. (Courtesy, Electrofusion Corporation, a Brush Wellman Company)

TABLE XII - STRENGTH OF ADHESIVE BONDED BERYLLIUM JOINTS

Adhesive System	Average Strength			Type/Test
EA-9309–BR127 Primer	4700	psi	(32.4 MPa)	Lap Shear
HT-424–BR127 Primer	2500	psi	(17.2 MPa)	Lap Shear
FM-123–BR127 Primer	3500	psi	(24.1 MPa)	Lap Shear
FM-123–BR127 Primer	55	lb./in.	(985 kg/m)	Honeycomb Peel
EA-934–BR127 Primer	75	Shore D		Hardness
Epoxy Np. 206–Grade A	3500	psi	(24.1 MPa)	Lap Shear
BR127 Primer	40	lb./in.	(716 kg/m)	90° Peel

Figure 32

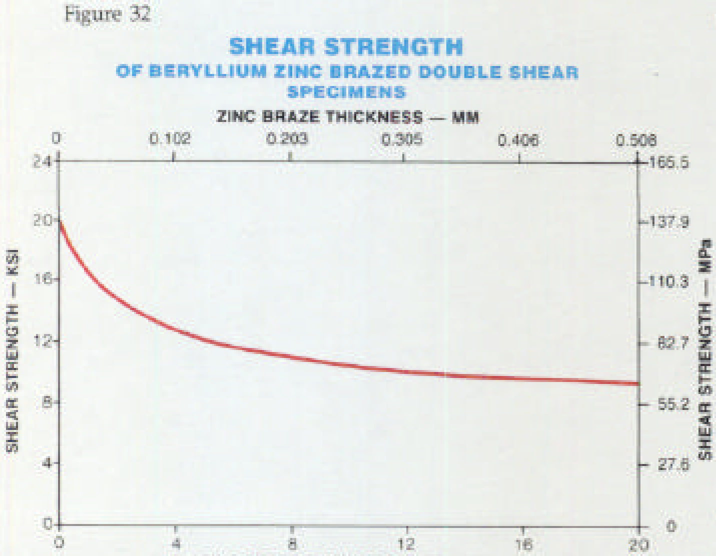
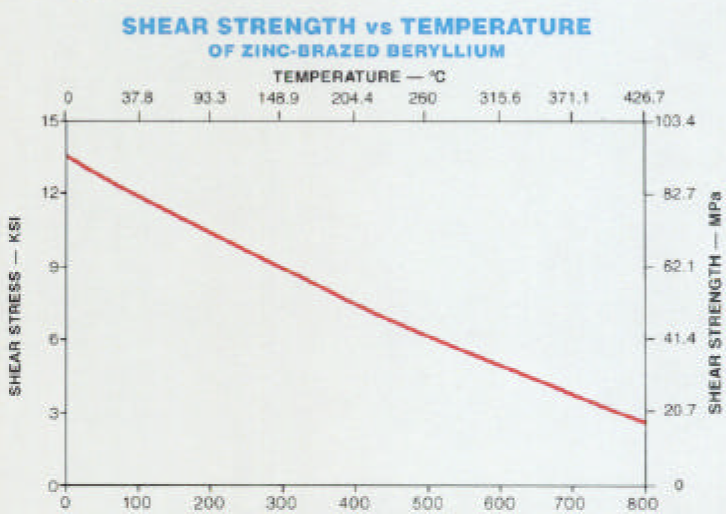


Figure 33



It has been shown that braze welding is a feasible method for joining beryllium to beryllium using either the MIG or TIG method with an AISI filler rod. For this process, however, a great deal of operator skill is required to produce a durable weld.

Other Joining Methods

Fusion welding is not recommended for beryllium because of the cast grain structure developed in the fusion zone. Electron beam welding is successfully carried out, particularly in instrumentation assemblies, where severe structural requirements are not present.

Diffusion bonding can be carried out with beryllium and has been used for assemblies. Such techniques are usually held proprietary by the fabricator.

TABLE XIII - STRENGTH OF BERYLLIUM BRAZED JOINTS

Braze Alloy Composition	Average Shear Strength, ksi (MPa)
Silver—Lithium (0.2%)	30.0 (206.8)
Silver—Copper (28%)	35.0 (241.3)
Easy—F10 (50 Ag, 15.5 Cu, 16.5 Zn, 18 Cd)	44.0 (303.4)
Zinc	12.0 (82.7)
Aluminum-Silicon (12%)	15.0 (103.4)

Coatings

An extensive amount of work has been carried out to develop coatings and protective systems for beryllium operating in hostile environments. Coatings are also used to develop surfaces on beryllium which have characteristics other than that of beryllium itself. A few of these coatings are described below.

Passivation

A beryllium surface exposed to chromate solutions will become passive and relatively stable. Adherence of strain gauges to such a surface or deposition and adherence of electroplated metal is extremely difficult. Berylcoat D is marketed by Brush Wellman Inc., as one treatment of this type which will aid in the prevention of "on the shelf" corrosion problems with the precise instrumentation. No measurable change in dimension nor appearance results with the use of this treatment.

Anodizing

Chromic acid or "black" anodizing of beryllium is employed extensively to provide corrosion protection to beryllium surfaces, to increase emissivity and to depress light reflectivity in optical systems. As deposited the anodized coating is electrically conductive but after proper curing is non-conductive. Excellent resistance to salt spray and high temperature oxidation has been reported for anodized beryllium. The surface finish of an anodized beryllium part is the same as that of the part prior to anodizing. In other words, it can be either highly reflective or matte in nature.

An excellent example of a black anodized beryllium part is this flight optical bench. Beryllium contributes four essential properties for this application: high strength, high stiffness, low weight and decreased emissivity. This optical system will be used to assess the feasibility of using optical sensors to detect and track long-range ballistic missiles. (Courtesy, Hughes Aircraft Co.)

Chromate Conversion Coating

Enhanced resistance to salt spray and high temperature oxidation is provided to beryllium by chromate conversion coatings developed for aluminum (e.g., Iridite Allodyne).. These coatings are formulated and applied following the instructions for use on aluminum.

Plating

A number of metals may be and have been electroplated on beryllium as reported in the literature. Such systems are generally not in extensive use today.

Electroless nickel plating, however, is extensively applied to beryllium, especially in the optics field where the nickel plate is utilized in developing the optical figure and final polish of beryllium mirrors.

Corrosion Resistance

Beryllium, much like aluminum, develops an adherent, protective oxide coating in air. Due to this coating, corrosion and oxidation in air is minimal up to temperatures of about 1400° (760°C). However, in other environments, the protec- tion is not adequate and care must be exercised to avoid corrosion.

Beryllium that is clean and free of surface contamination has good corrosion resistance in low temperature, high purity water. However, beryllium is highly susceptible to localized pitting when in contact with the chloride and sulfate ions contained in ordinary water. Therefore, exposure to tap water should be kept at a minimum and always followed by a rinse with dionized water, followed by drying, to insure against damage. Sea water is very corrosive to beryllium.

The handling of beryllium parts with a finished surface should also be done with care. A fingerprint left on the surface will disrupt the effectiveness of the final etch or coating. When corrosive conditions are anticipated in service, the use of a protective coating is advised.

An interesting corrosion protection system operating when both sea water corrosion and high temperature oxidation are potential problems was developed by Brush Wellman Inc. for use on the brakes of the F-14 fighter air craft of the U.S. Navy. This system involves high temperature paint as a primary protection backed up by manganese metal as a sacrificial anode. Manganese is the only metal more active in the electromotive series than beryllium which has a melting point sufficiently high for this application.

Health and Safety

Handling beryllium metal in solid form poses no special health risk. Like many industrial materials, beryllium-containing materials may pose a health risk if recommended safe handling practices are not followed. Inhalation of airborne beryllium may cause a serious lung disorder in susceptible individuals.

The Occupational Safety and Health Administration (OSHA) has set mandatory limits on occupational respiratory exposures. Read and follow the guidance in the Material Safety Data Sheet (MSDS) before working with this material.

For additional information on safe handling practices or technical data on beryllium metal, contact Brush Wellman Inc., Beryllium Products Division, at 1-800-862-4118.

Availability

Brush Wellman Inc. owns and operates a commercial mine and extraction mill for beryllium in the state of Utah. The beryllium is obtained from a deposit of the mineral bertrandite in the Spor Mountain region. The extraction facility is at the nearby town of Delta. This ore deposit has proven reserves that will assure the continued availability of beryllium well into the 21st century.

Beryllium ore is consumed primarily in beryllium copper alloys, beryllium oxide ceramics and as metallic beryllium. At the Delta facilities, beryllium is extracted from imported beryl ore as well as from bertrandite. In order to further increase the availability of beryllium and to extend the domestic ore reserves, the corporation conducts programs of evaluating other minerals, both domestic and imported, as potential ores for beryllium production.

Process changes have been installed at Delta which will allow the economic processing of beryl ores of significantly lower grades than had been possible previously, again extending the availability of beryllium.

PRODUCT AVAILABILITY

These Beryllium Products	Produced By These Processes	Are Available As	To These Brush Wellman Material Specifications
Standard Mill Products	Vacuum Casting	Ingot Lump Chips	B-26-D
	Attritioning, Impact Grinding and Blending	Powder	SP-200-F SP-65 I P-70
	Vacuum Hot Pressing and Machining	Block, Billet Rod, Bar, Tube	S-200F S-65C, I-70B,I-220C
	Rolling	Foil-Discs and Rect. Sheet Plate	PF-60, IF-1 SR-200 PR-200
Non-Stardard Mill Products	Extruding	Rod, Wire Bar Tube, Shapes	S-200F, S-65C
	Hot Forming	Near Net Shapes	SR-200, PF-60 S-200F S-65S, I-220C
	Cold Pressing	Near Net Shapes	S-200F S-65S-I-220C
	Forging	Shapes	S-200F S-65C, I-220C
	Hot Isostaic Pressing	Near Net Shapes	S-200FH, I-220H S-65H, I-70H
	Cold Isostaic Pressing	Near Net Shapes	S-200FC, I-220C S-65

Technical Services

Brush Wellman maintains a highly skilled staff of materials scientists and manufacturing engineers at our various facilities to work with interested customers in the application of beryllium to specific needs. A call to your local Brush Wellman Sales Engineering Office can focus this capability on your design problem.

Beryllium and Specialty Materials

Cleveland, Ohio

Elmore, Ohio

Reading, Pennsylvania

Delta, Utah

Detroit, Michigan

Fremont, California

Los Angles, California

Fairfield, New Jersey

Elmhurst, Illinois

Tucson, Arizona

Theale, England

Stuttgart, Germany

Tokyo, Japan

Singapore

A sampling of vacuum pressed, hot isostatically pressed, cold isostatically pressed and sintered parts.

BRUSHWELLMAN
ENGINEERED MATERIALS

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