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BERYLLIUM DATA BASE FOR IN-PILE MOCKUP TEST ON BLANKET OF FUSION REACTOR (1)

November 1992

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Beryllium Data Base for In-pile Mockup Test on Blanket of Fusion Reactor (1)

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(Received November 9, 1992)

Beryllium has been used in the fusion blanket designs with ceramic breeder as a neutron multiplier to increase the net tritium breeding ratio (TBR). The properties of beryllium, that is physical properties, chemical properties, thermal properties, mechanical properties, nuclear properties, radiation effects, etc. are necessary for the fusion blanket design. However, the properties of beryllium have not been arranged for the fusion blanket design. Therefore, it is indispensable to check and examine the material data of beryllium reported previously.

This paper is the first one of the series of papers on beryllium data base, which summarizes the reported material data of beryllium.

Keywords: Beryllium, Fusion Blanket, Material Data, Blanket Mockup, Tritium, Neutron Multiplier, Tritium Breeding Ratio

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+ Department of Fusion Engineering Research, Naka Fusion Research Establishment

* N.G.K. Insulators, LTD

核融合炉ブランケットのインパイル試験のための ベリリウムデータベース(1)

日本原子力研究所大洗研究所材料試験炉部
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(1992年11月9日受理)

核融合炉ブランケットにおいて，ベリリウムはトリチウム増殖比を増すための中性子増倍材としてセラミック増殖材とともに使用されようとしている。ベリリウムの特性，例えば物理的特性，化学的特性，熱的特性，核的特性等は，核融合炉ブランケットの設計はいうに及ばず，同ブランケット構造を模擬した照射試験体の設計や照射試験結果の解析に必須となる。しかしながら，現在，ベリリウムの特性は利用しやすいように整理されていない。

本報告書は，ベリリウムのデータベースに関する報告書の第一報であり，これまでに報告された各種特性データをまとめたものである。

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Contents

目　　次

1. Introduction

Beryllium has been used in the fusion blanket designs with ceramic breeder as a neutron multiplier to increase the net tritium breeding ratio (TBR). Data on its irradiation behavior are insufficient and also show rather big scattering. These data are necessary not only for the blanket design but also for the design of blanket mockups to be tested by means of fission reactors.

Therefore, to improve the accuracy of the designs of blanket mockup, it is indispensable to check and examine the material data of beryllium reported previously, to set-up a "reference data set" to be used in the design and to identify the items of material properties to be obtained.

This paper is the first one of the series of papers on beryllium data base, which summarizes the reported material data of beryllium.

2. Resources and Application

"Be-containing minerals(1001)" shows beryllium contents and properties of four beryllium-containing minerals. Bertrandite and beryl are used for industrial beryllium production, their beryllium contents are 15.1% and 3.0-3.5%, respectively. "Distribution of principal mines(1002)" shows the location of principal promising mines in the world. "Beryllium resources by countries(1003)" and "Beryllium reserves by countries(1004)" show that Brazil is ranked top on the world in both cases.

"Solid breeder/multiplier materials and properties considered(1005)" shows considerable properties as neutron multiplier. "Desirable characteristics for neutron multipliers(1006)" shows various properties required as neutron multiplier from a technical point of view. And "Properties of candidates for multiplier(1007)" shows various properties on neutron multiplier candidate. "Upper temperature limits for fusion blanket materials(1008)" shows upper temperature limits in blanket.

1. Introduction

Beryllium has been used in the fusion blanket designs with ceramic breeder as a neutron multiplier to increase the net tritium breeding ratio (TBR). Data on its irradiation behavior are insufficient and also show rather big scattering. These data are necessary not only for the blanket design but also for the design of blanket mockups to be tested by means of fission reactors.

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1001

Be-containing minerals

item / mineral	chemical fomura	content (%) (theoretical value)	specific gravity	hardness (Mohs' scale)
Bertrandite	$4BeO \cdot SiO_2 \cdot H_2O$	15.1	2.6	6
Beryl	$3BeO \cdot Al_2O_3 \cdot 6H_2O$	3.0 ~ 3.5	2.66 ~ 2.83	7.5 ~ 8
Chrysoberyl	$BeO \cdot Al_2O_3$	7.1	3.75	8.5
Phenacite	$2BeO \cdot SiO_2$	46.4	3.0	7.5

(1/1)

【Reference】
M. Ikematsu et al. : "Kishou Kinzoku Data Book <Beryllium>" (Rare Metal Data Book <Beryllium>), Metal Mining Agency of Japan, Tokyo (1985) [in Japanese].

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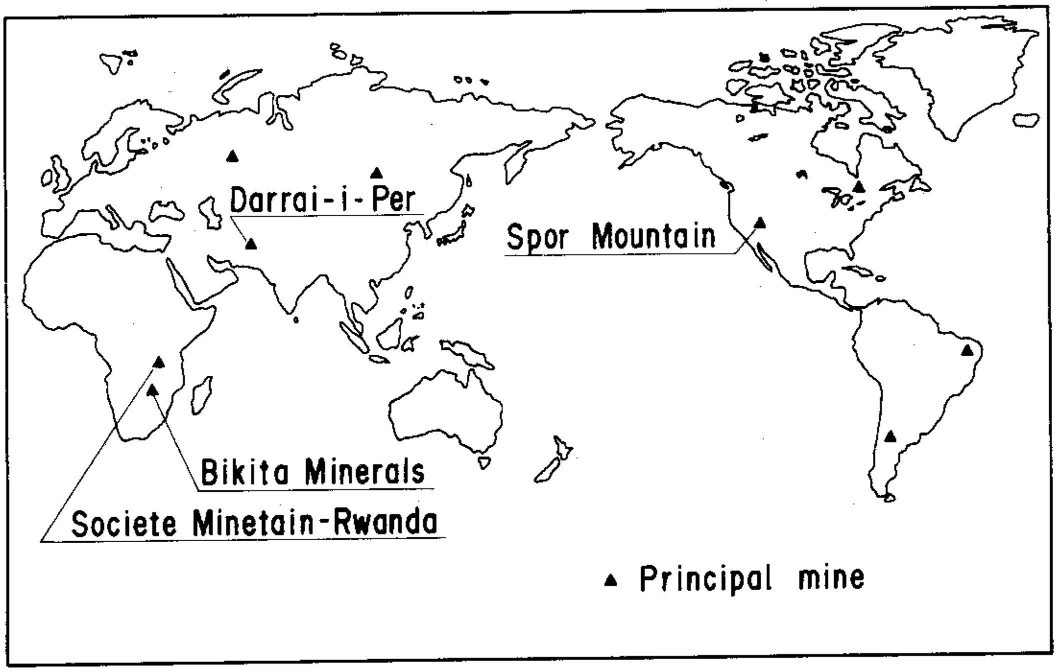
1002

Distribution of principal mines



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【Reference】
M. Ikematsu et al. : "Kishou Kinzoku Data Book〈Beryllium〉" (Rare Metal Data Book〈Beryllium〉), Metal Mining Agency of Japan, Tokyo(1985) [in Japanese].

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1003

Beryllium resources by countries

country	quantity ($\times 10^3$ short ton)	ratio (%)
1. Brazil	397	35.9
2. Soviet Union	173	15.7
3. America	72	6.5
4. Argentine	71	6.4
5. South Africa	44	4.0
6. Uganda	41	3.7
7. Rwanda	31	2.8
8. Australia	30	2.7
9. Canada	23	2.1
10. Zaire	21	1.9
total	903	81.7
Japan	—	—
total all over the world	1,105	

source : M.F.P. 1980

(1／1)

【Reference】

M. Ikematsu et al. : "Kishou Kinzoku Data Book ⟨Beryllium⟩" (Rare Metal Data Book ⟨Beryllium⟩). Metal Mining Agency of Japan, Tokyo (1985) [in Japanese].

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1004

Beryllium reserves by countries

country	quantity ($\times 10^3$ short ton)	ratio (%)
1. Brazil	154	36.8
2. India	71	16.9
3. Soviet Union	67	16.0
4. America	28	6.7
5. Argentine	28	6.7
6. South Africa	17	4.1
7. Uganda	16	3.8
8. Australia	12	2.9
9. Rwanda	12	2.9
10. Zaire	8	1.9
total	413	98.6
Japan	—	—
total all over the world	419	

source : M.F.P. 1980

(1/1)

【Reference】

M. Ikematsu et al. : "Kishou Kinzoku Data Book ⟨Beryllium⟩" (Rare Metal Data Book ⟨Beryllium⟩). Metal Mining Agency of Japan, Tokyo (1985) [in Japanese].

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1005

Solid breeder/multiplier materials and properties considered

Materials	Properties
Li_2O	Density
$LiAlO_2$	Thermal conductivity
Li_5AlO_4	Specific heat
Li_2SiO_3	Temperature limits
Li_4SiO_4	Tritium diffusivity
Li_2ZrO_3	Tritium solubility
Li_8ZrO_6	Tritium surface adsorption
Li_2TiO_3	Elastic modulus
$Li_2Be_2O_3$	Thermal expansion
Li_7Pb_2	Poisson's ratio
Be	Fracture strength
BeO	Material cost
	Grain size
	Impurities

(1／1)

【Reference】
E.C. Bell et al. : UCLA-ENG-86-44, "Modeling, analysis and experiments for fusion nuclear technology" (1987).

1006

Desirable characteristics for neutron multipliers

Property	Desirable Value	Remarks
Physical Properties		
Thermal Conductivity	High	Thermo-mechanical design
Melting Point	High	is easy.
Electric Resistivity	Low	if used as passive shell conductor
Mechanical Property		
Tensile Property	High	Fabrication is easy
Chemical Properties		
Corrosion	Low	Compatibility with structural material
Tritium Adsorption	Low	Tritium inventory
Irradiation Properties		
Swelling	Low	
Embrittlement	Low	

(1/1)

【Reference】
T. Tone et al. : JAERI-M 87-017, "Technical evaluation of major candidate blanket systems for fusion power reactor" (1987).

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1007

Properties of candidates for multiplier

Material	Density (g/cm^3)	Specific Heat* (J/kg/K)	Thermal Conductivity* (W/m/K)	Thermal Expansion x10^{-6} (°C)	Melting Point (°C)
Be	1.8	1923	188	13	1284
BeO	3.0	1042	200	8	2520
Pb	11.3	127	35	29	327
PbO	9.5	209	2.8	50	888
Bi	9.8	56.4	6.0	13	271
Zr	6.5	275	21	6	1852
Zr_5Pb_3	8.9	220	21	20	~1400
PbBi	10.5	125	10	27	125

(*) 25°C

(1/1)

【Reference】
C. C. Baker, et al. : ANL / FPP-80-1, "Starfire - A commercial tokamak fusion power plant study" (1980).

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1008

Upper temperature limits for fusion blanket materials

(Temperature : °C)

Material	Melting	Sinter [a]	Other	Limit [b]	Range [c]
Li_2O	1433	850 800	500 creep	800	500−900
$LiAlO_2$	1610	970 >1000	−	970	850−1200
Li_5AlO_4	1047	600	−	600	520−800
LiAl	717	380	−	380	320−520
$LiAl_5O_8$	1950	1190	−	1190	1060−1500
Li_2SiO_3	1200	700	1150 at 30% BU	700	610−900
Li_4SiO_4	1250	730 950	665 phase chnge 1250 at 30% BU	730	640−950
Li_2TiO_3	1540	920	1430 at 30% BU	920	820−1200
Li_2ZrO_3	1610	970	−	970	860−1200
Li_8ZrO_6	1295	760	660 phase chnge	760	670−980
Li_7Pb_2	726	390 > 600	600−1000 swell. 570 at 30% BU	420	330−530
$Li_2Be_2O_3$	1150	670	−	670	580−870
Be	1285	750	500−600 swell. 700 helium comp	650	500−970
BeO	2540	1580	−	1580	1400−2000
Li_2O / Be	(Be)	−	Compatibility	(Be)	
Li_2O / BeO	(Li_2O)	−	Compatibility	(Li_2O)	
$LiAlO_2$/ Be	(Be)	−	Compatibility	(Be)	
$LiAlO_2$/BeO	($LiAlO_2$)	−	Compatibility	($LiAlO_2$)	

a 0.66 T_{melt} for onset of radiation-induced sintering

b Suggested upper temperature limit set by sintering, except for Li_2O and Be where vapor pressure and swelling influence limit

c Lowest temperature limit or 0.6 T_{melt}, to 0.8 T_{melt}

(1/1)

【Reference】

E.C. Bell et al. : UCLA-ENG-86-44, "Modeling, analysis and experiments for fusion nuclear technology" (1987).

3. Fabrication

"Production of beryllium metal and alloys(2001)" shows the production process of a beryllium-copper alloy and a vacuum hot pressed beryllium metal from beryl. As the extraction method of beryllium, the reduction method of beryllium fluorite by magnesium is shown. "CIP/HIP process (2002)" shows CIP/HIP process with their conditions. "Vacuum hot press (2003,2004)" shows concept and operational conditions of vacuum hot press. Temperature and pressure in vacuum hot press are about 1050°C and 2000psi, respectively. "Effect of powder size on densities of CIP billets(2005)" and "Effect of heat-treatment of powders on densities of CIP/HIP billets (2006)" show the effects of powder size and heat-treatment on densities of beryllium compacts, respectively. "Canned extrusion(2007)" shows the concept of canned extrusion. Generally, the beryllium are worked with compressive stress without tensile stress because it is a brittle material. In this case, beryllium is covered with mild steel and extruded to protect from oxidation of beryllium and damage of die. "Extrusion constant(2008)" shows extrusion constants on the metals containing beryllium on various temperature conditions. It is clear that the extrusion constant of beryllium is higher than other materials. "Deformation(2009) shows the effects of temperature on stress in (0001) and (1010) slip plane. It is clear that the slip in (0001) plane take place according to priority at the temperature range of 0-600°C. Then, "Recrystallization of cast beryllium(2010)" shows that the annealing useful condition for recrystallization on casted beryllium is about one hour at 800°C.

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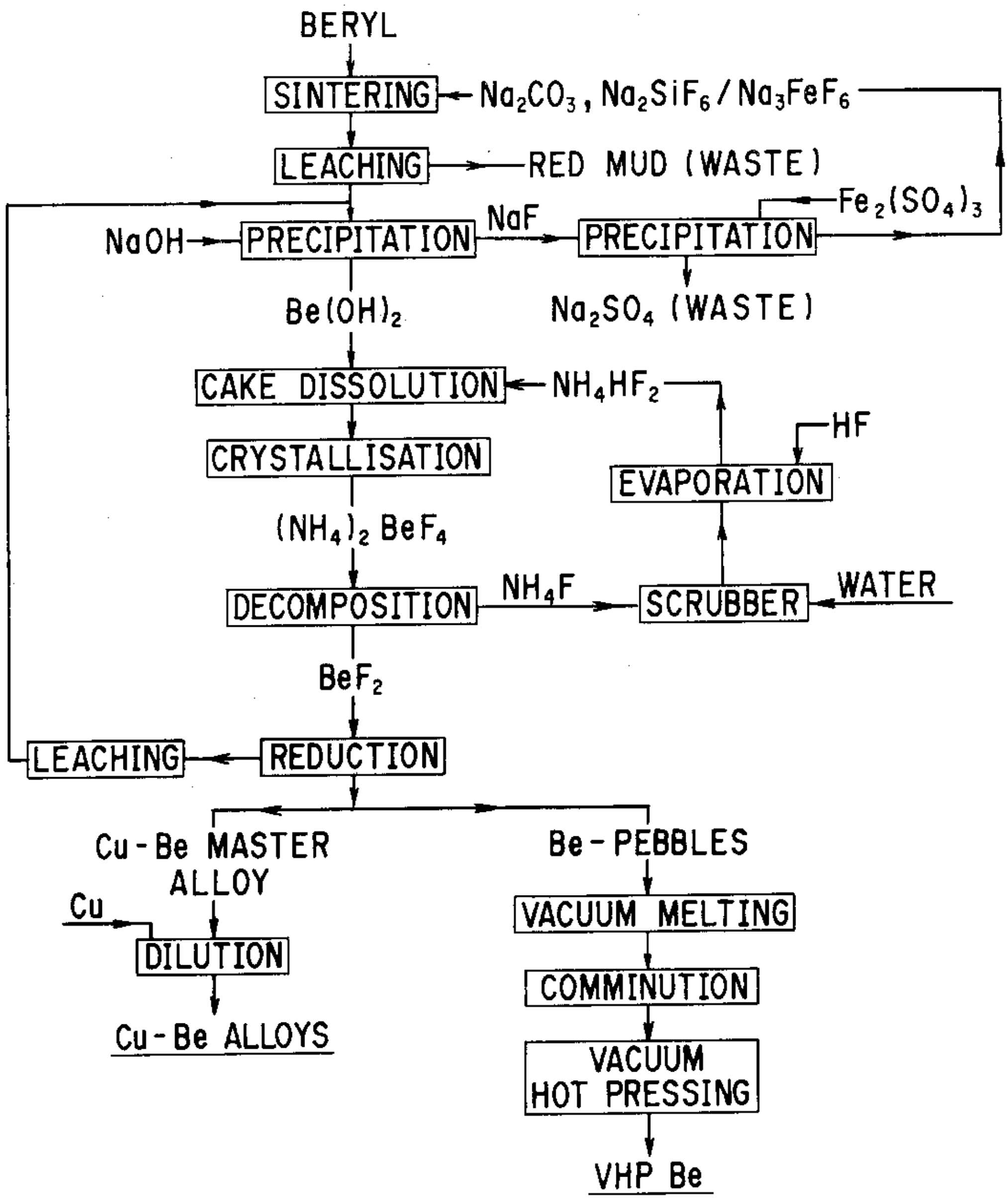
2001

Production of beryllium metal and alloys



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【Reference】

K. S. Subbarao et al. : "Beryllium 1977/Proc. of Fourth International Conference on Beryllium , The Metals Society, The Royal Society, London (1977) 43.

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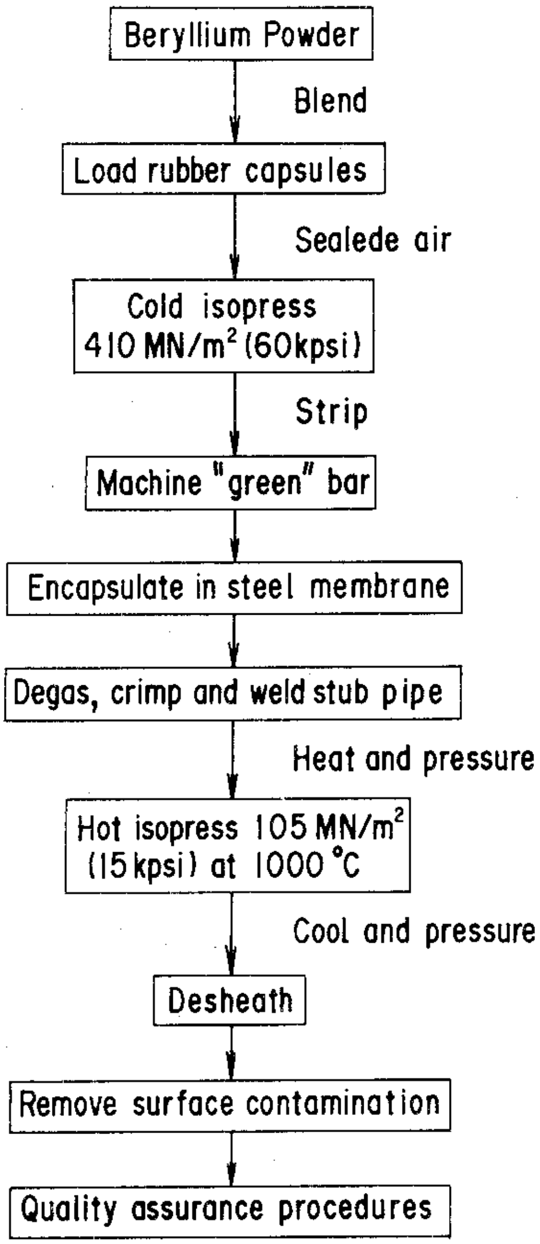
2002

CIP/HIP process



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【Reference】
J.N.Lowe et al.: "Beryllium 1977/Proc. of Fourth International Conference on Beryllium", The Metals Society, The Royal Society, London (1977) 33.

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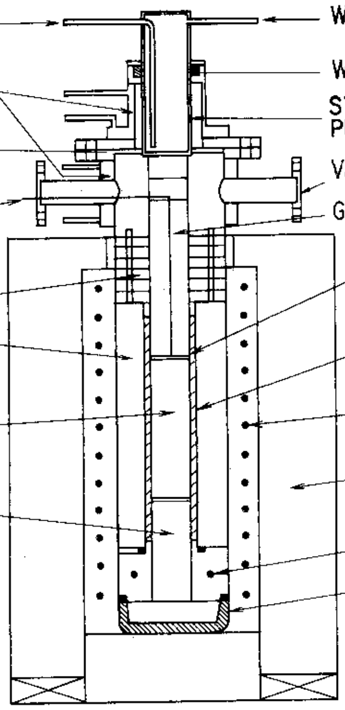
2003

Vacuum hot press (1)

(1) Pressing temperature : ~ 1050℃
(2) Pressure : up to 2000 lb/in^2
(3) Density : greater than 99% of theoretical



Vacuum hot - pressing assembly

(1／1)

【Reference】
T. W. Farthing et al.: "The Metallurgy of Beryllium / Proc. of an International Conference organized by the Institute of Metals in London", Chapman & Hall Ltd., London (1963) 466.

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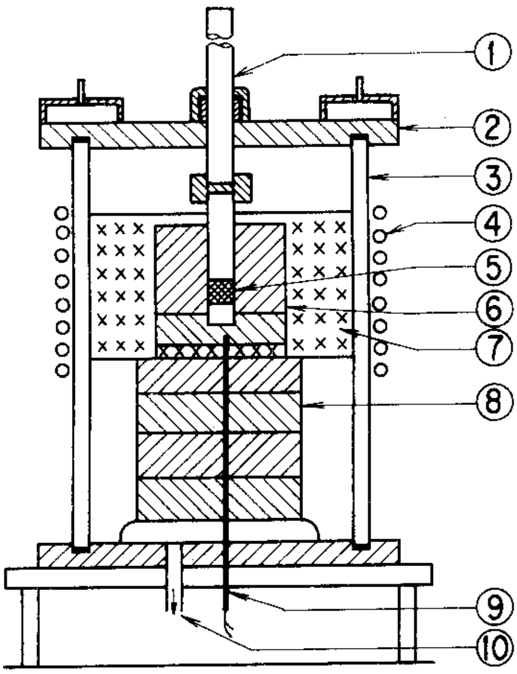
2004

Vacuum hot press (2)

(1) System pressure : 13.32 N/m^2
(2) Precompaction : at 873K and $7 \times 10^6 N/m^2$
(3) Final compaction : at 1423K and $10\text{-}14 \times 10^6 N/m^2$ for 1800s
(4) Density of the theoretical : 99.8%



1. S.S. PLUNGER ROD.
2. GASKETTED BRASS TOP FLANGE.
3. SILICA TUBE.
4. INDUCTION COIL.
5. Be COMPACT.
6. HIGH DENSITY GRAPHITE DIE.
7. CARBON FELT.
8. INSULATION BRICKS.
9. THERMOCOUPLE WELL.
10. EVACUATION LINE.

Vacuum hot-pressing assembly

(1/1)

【Reference】
K.S. Subbarao et al.: "Beryllium 1977/Proc. of Fourth International Conference on Beryllium", The Metals Society, The Royal Society, London (1977) 43.

JMTR

2005

Effect of powder size on densities of CIP billets

Powder size, μm	CIP density Average	(minimum-maximum)
-74	80.0%	(79.3-80.5%)
-44	78.5%	(77.6-79.2%)
-37	77.3%	(76.8-77.8%)

CIP pressure : 415 MPa

(1／1)

【Reference】
Norman P. Pinto et al.: "Beryllium 1977/Proc. of Fourth International Conference on Beryllium", The Metals Society, The Royal Society, London (1977) 31.

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2006

Effect of heat-treatment of powders on densities of CIP/HIP billets

Powder size, μm	Anneal, °C/hrs	CIP MPa	ρ(%)	Δρ(%)	HIP °C/MPa/hrs	ρ(%)	Δρ(%)
-44	925/3	415	83.9	5.2	605/41/3	87.6	3.1
-44	none	415	78.9		605/41/3	84.6	
-44	none	415	78.6		605/41/3	84.4	
-74	925/3	415	85.5	5.2	605/41/3	90.0	1.7
-74	none	415	80.5		605/41/3	88.4	
-74	none	415	80.1		605/41/3	88.2	
-74	925/3	550	88.6				
-44	925/3	550	88.4				

(1／1)

【Reference】
Norman P. Pinto et al.: Beryllium 1977/ Proc. of Fourth International conference on Beryllium", The Metals Society, The Royal Society, London (1977) 31.

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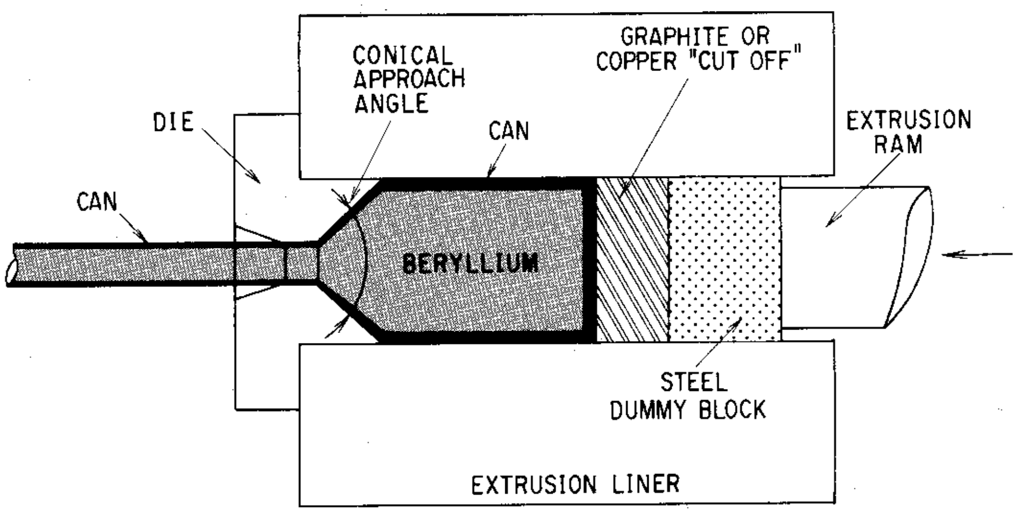
2007

Canned extrusion

(1) Canning material : carbon steel



Schematic for canned extusion

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【Reference】

D.R. Floyd and J.N. Lowe : "Beryllium Science and Technology / Volume 2", Plenum Press, New York (1979) 69.

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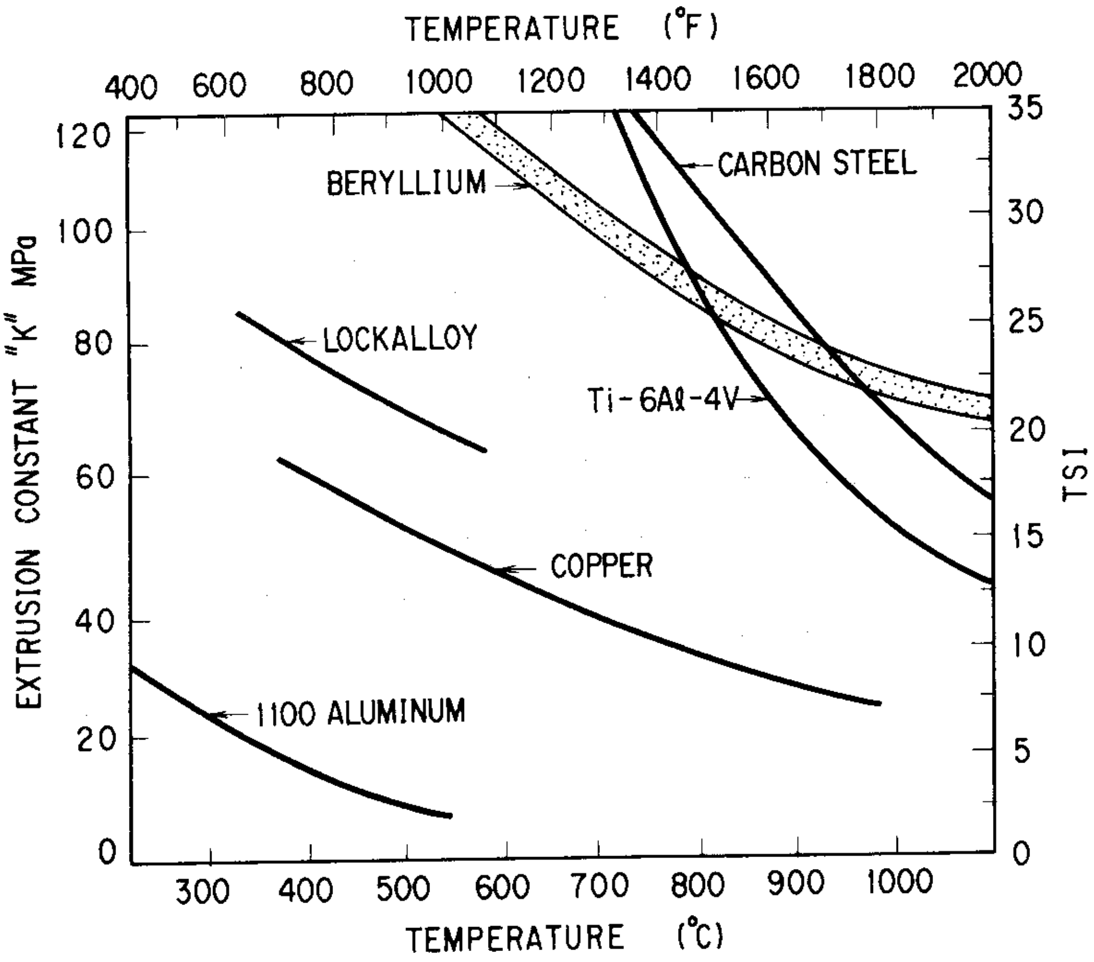
2008

Extrusion constant



(1／1)

【Reference】

D.R. Floyd and J.N. Lowe : "Beryllium Science and Technology / Volume 2", Plenum Press, New York (1979) 74.

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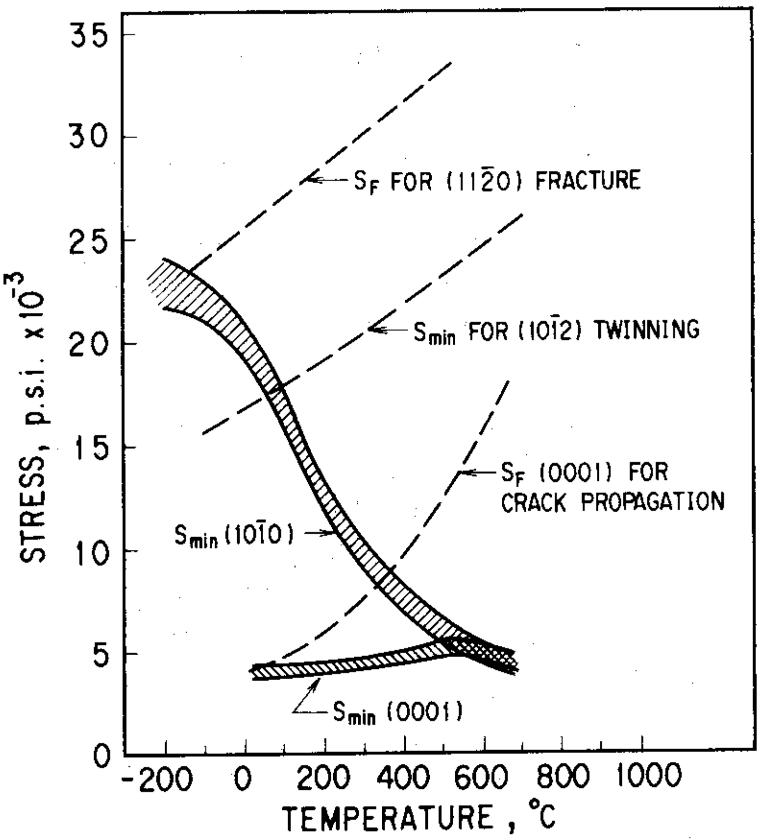
2009

Deformation



[1]

Effect of temperature on the critical stresses for (0001) and (10$\bar{1}$0) slip

[1] G.L. Tuer and A.R. Kaufmann : "The metal beryllium", Amer. Soc. Metals, Cleveland, O. (1955).

(1／1)

【Reference】
A.J. Martin and G.C. Ellis : "The Metallurgy of Beryllium / Proc. of an International Conference organized by the Institute of Metals in London", Chapman & Hall Ltd., London (1963) 4.

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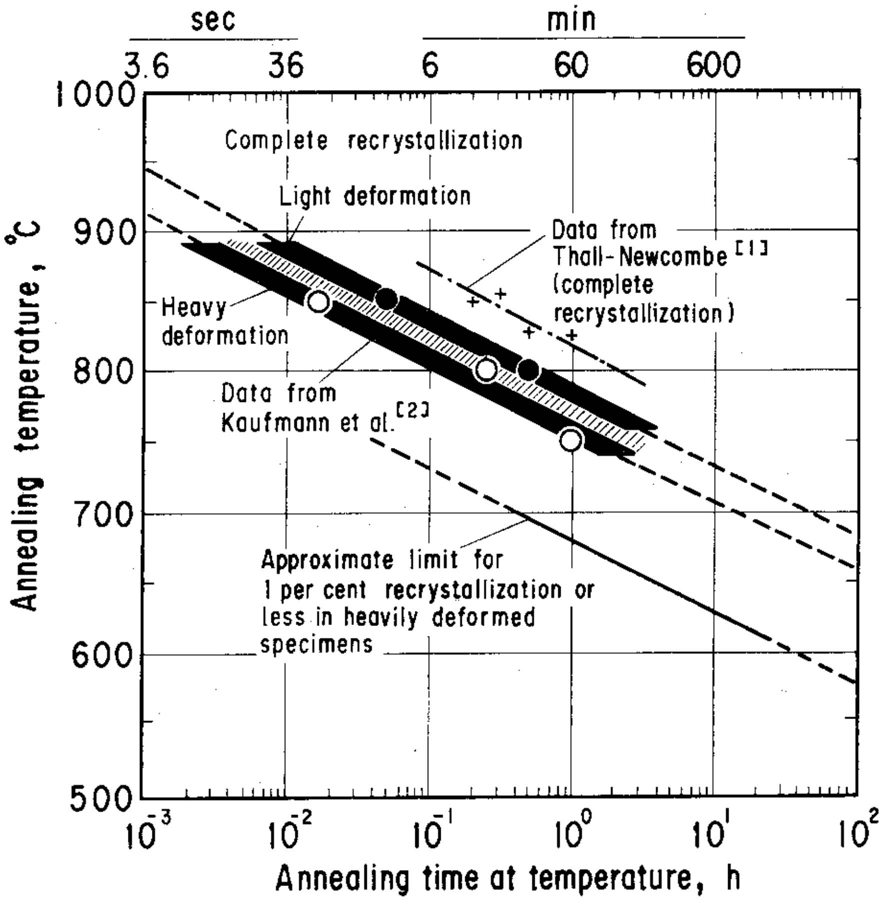
JMTR

2010

Recrystallization of cast beryllium

(1) Practical annealing condition for cast beryllium

: 1h at 800 °C



Recrystallization of cast beryllium

[1] Thall, B.M et al. : Trans. Canad. Min. Inst., 51 (1948) 223.
[2] Kaufmann, A.R. : Trans. Amer. Soc. Metals, 42 (1950) 785.

(1／1)

【Reference】

G.E. Darwin and J.H. Buddery : "Metallugy of the rarer metals - 7 Beryllium", Butterworths Scientific Publications, London (1960) 156.

4. Nuclear Properties and Radiation Effects

"Tritium production by neutron irradiation(3001)" shows that the amount of tritium production on beryllium irradiated up to 5×10^{22} n/cm^2 (E>1MeV) in ATR is 8.23Ci/g. "Cross section of (n,2n) reaction in beryllium(3002)" shows that the threshold energy on (n,2n) reaction in beryllium is about 1.85MeV. "Swelling(1)(3003)" shows swelling data of beryllium irradiated in ETR. From these data, it became clear that the swelling per 10^{22} n/cm^2 is 0.2-0.3%. "Swelling(2)(3004)" shows the length change by swelling of beryllium annealed for one hour at various temperatures after irradiation at ETR. Their data have large scatter. Generally, swelling has a tendency to increase evidently above 700°C. "Swelling(3)(3005)" shows that the swellings of beryllium irradiated in EBR-II and ATR are formularized as follows.

$$\Delta V/V_0=(0.086\pm0.031)G\alpha^{1.035}[1+22.2G\alpha^{0.5}T^{1.5}\exp(-9322/T)],\ (\%).$$

"Swelling(4)(3006)" shows the photographs on cross section of beryllium annealed up to 1180°C after irradiation up to 3.8×10^{20} n/cm^2 (E>1MeV) at 200°C in JMTR. From these photographs, it is clear that swelling takes place with growth of blister and pore by annealing. "Effect of irradiation on tensile properties(3007)" shows the results of surveillance tests on beryllium reflector in JMTR. From these results, it is clear that the elongation on irradiated beryllium evidently decreases as a result of irradiation hardening. "Effect of irradiation on hardness and density (3008)" shows the effects of annealing on the changes of hardness and density on irradiated extrusion beryllium. It is clear that the decreasing of hardness and increasing of density are evidence at about 600°C. "γ-ray spectrum of irradiated beryllium(3009)" shows γ-ray spectrum of irradiated beryllium disk machined from hot pressed block. In this case, γ-ray peak of ^{60}Co is recognized evidently. "Fusion blanket beryllium data needs compared to existing data(3010)" shows the needs of irradiation tests beryllium. Now, we have not the data of high neutron fluence above 1×10^{-3} appm He at the temperature range of 350-700°C.

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3001

Tritium production by neutron irradiation

(1) Specimen

① hot pressed beryllium disk
② purity : 98.26wt % (BeO : 1.7 wt %)

(2) Irradiation condition.

① fluence : 5×10^{22} n/cm^2 (at ATR, E > 1 MeV)

(3) Method of tritium assay : vacuum fusion

Sample	result (Ci/g)
Total tritium assay on as-irradiated material	8.23
Be*1 Test (tritium release test)	
- released tritium (mol sieve analysis)	7.61
- residual tritium (vacuum fusion)	0.46
- totaled tritium	8.07

(1／1)

【Reference】

D.L. Baldwin et al. : PNL-SA-16998, "Tritium release from irradiated beryllium at elevated temperature" (1990).

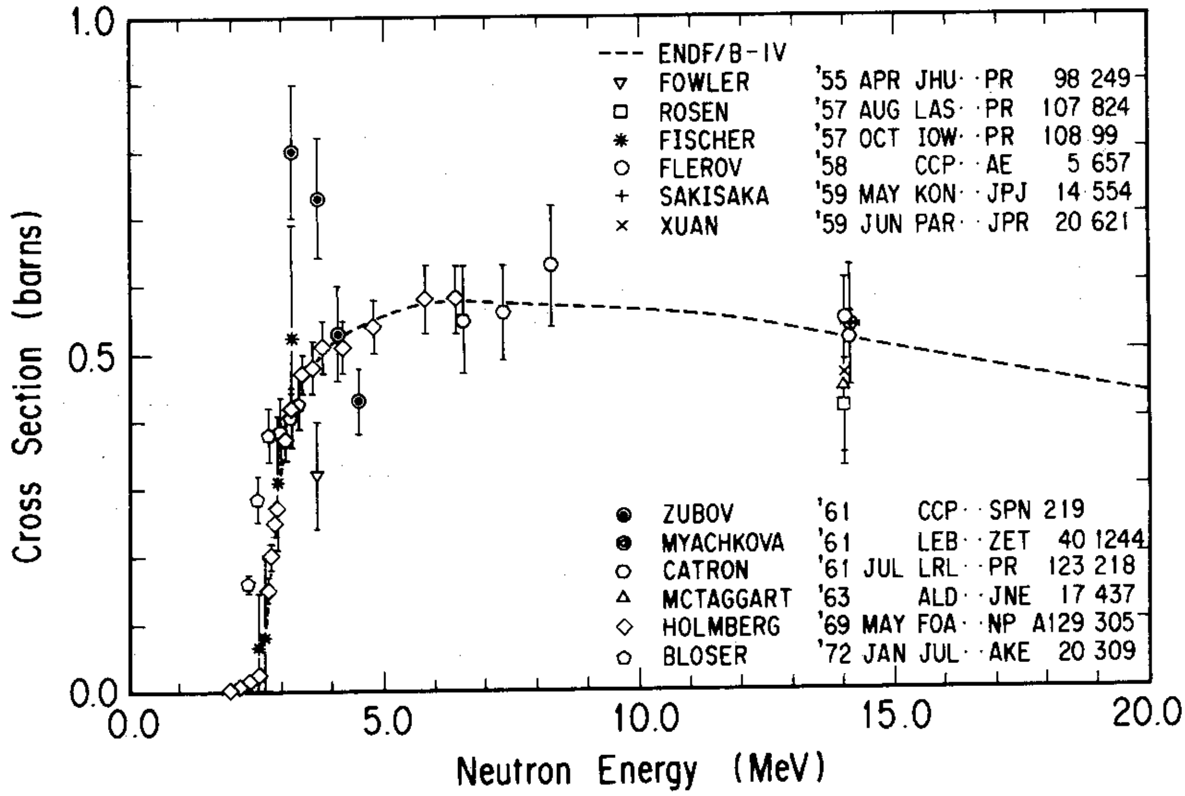
JMTR

3002

Cross section of (n, 2n) reaction in beryllium

① Neutron energy threshold of (n, 2n) reaction

: about 1.85 MeV



Cross section of (n, 2n) reaction in beryllium

(1／1)

【Reference】

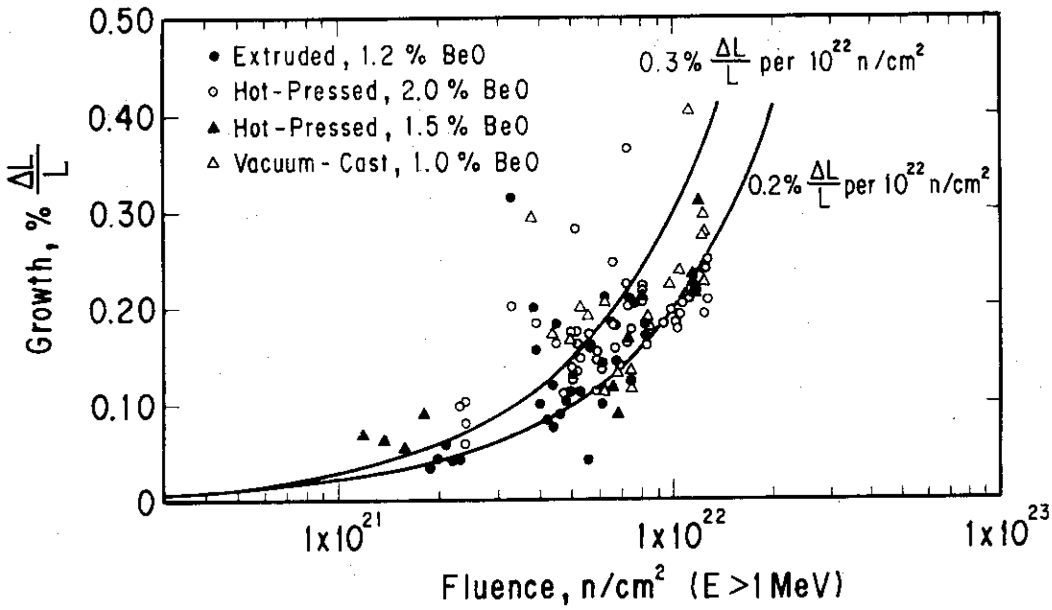
T. Asami and S. Tanaka : JAERI-M 8136, "Graphs of neutron cross section data for fusion reactor development" (1979).

JMTR

3003

Swelling (1)

(1) Irradiation reactor : ETR



Growth of beryllium vs fast neutron exposure

(1／1)

【Reference】

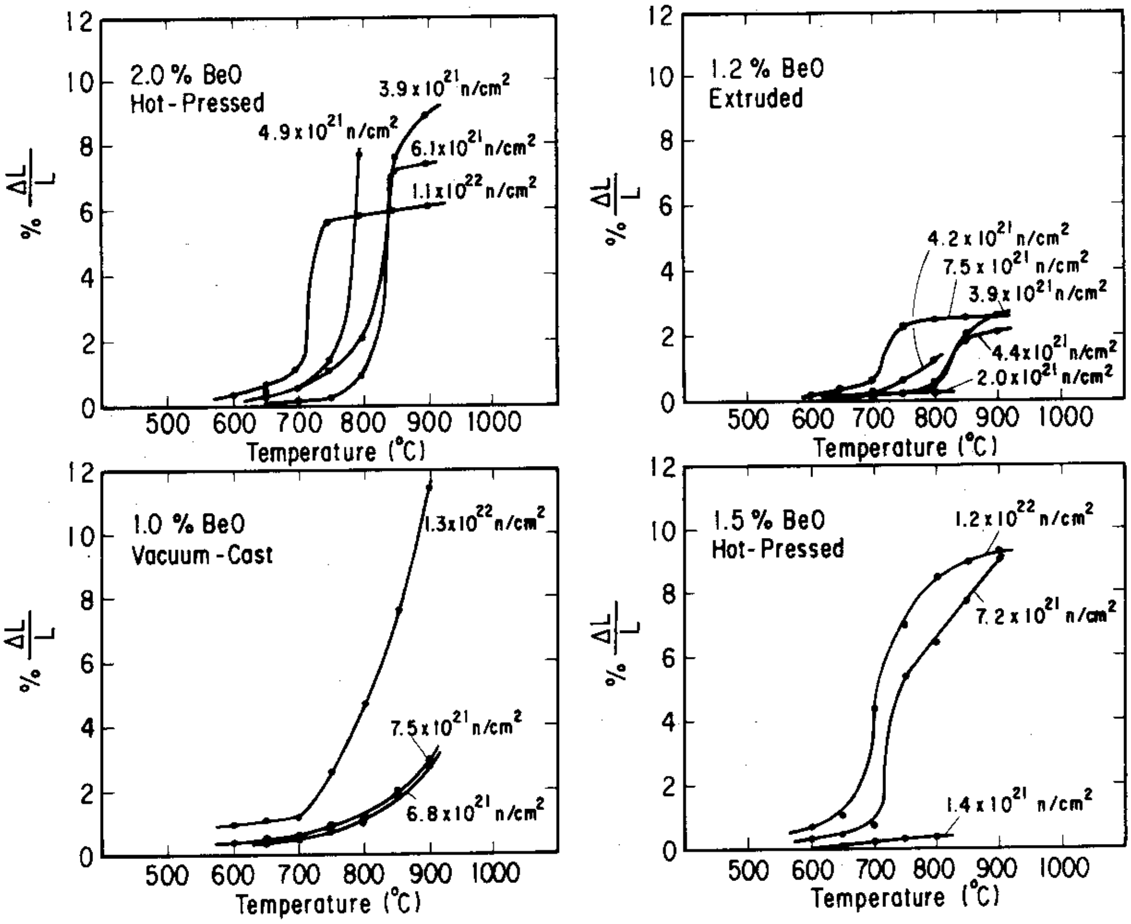
R. M. Brugger et al. : "Metallurgy and materials science branch annual report fiscal year 1970" (1970).

JMTR

3004

Swelling (2)

(1) Irradiation reactor : ETR



Length changes in various types of irradiated beryllium after annealing on hour at each temperature

(1/1)

【Reference】

R.M. Brugger et al. : "Metallurgy and materials science branch annual report fiscal year 1970" (1970).

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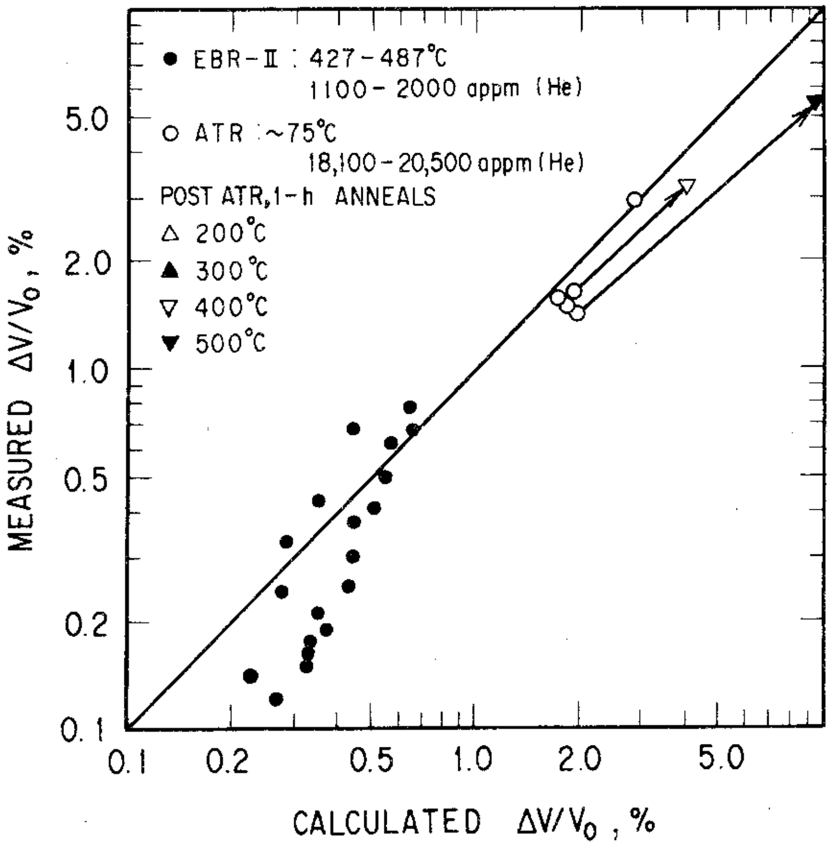
3005

Swelling (3)

(1) $\Delta V/V_0 = (0.086 \pm 0.031)\, G_a^{1.035}\, [1 + 22.2\, G_a^{0.5}\, T^{1.5} \cdot \exp(-9322/T)]$, (%)

G_a : generated He ($\times 10^3$ appm)

T : temperature (K)



(1／1)

【Reference】

M.C. Billone et al. : PNL-SA-18966, "Tritium and helium behavior in irradiated beryllium" (1990).

JMTR

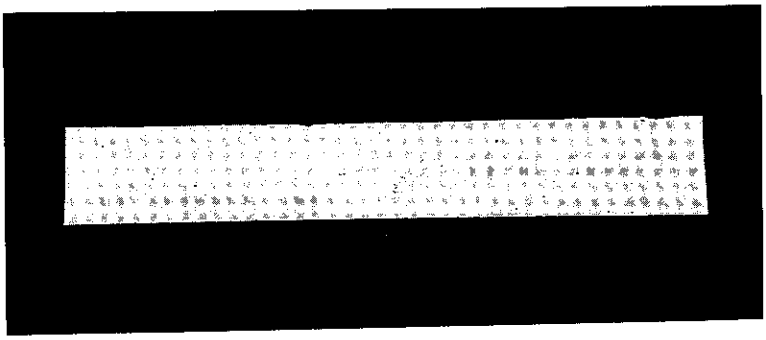
3006

Swelling (4)

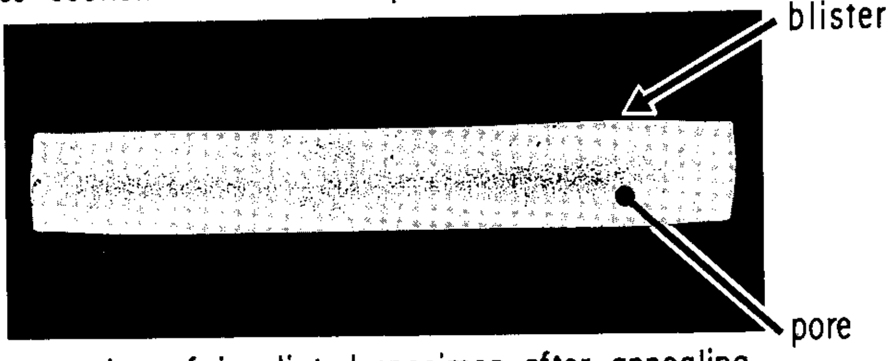
(1) Specimen
① hot pressed beryllium disk (ø10 x ^{t}1.4mm)
② main impurity : 1.28 wt. % BeO

(2) Irradiation condition
① irradiation temperature : 200℃
② first neutron fluence : 3.8×10^{20} n/cm^2
③ thermal neutron fluence : 6×10^{20} n/cm^2
④ reactor : JMTR

(3) Annealing condition
① annealing temperature : up to 1180°C



Cross section of irradiated specimen before annealing



Cross section of irradiated specimen after annealing

(1/1)

【Reference】
E. Ishitsuka, H. Kawamura et al. : JAERI-M 90-013,
"Experiments on tritium behavior in beryllium (2)
-Tritium released by recoil and diffusion-" (1990).

JMTR

3007

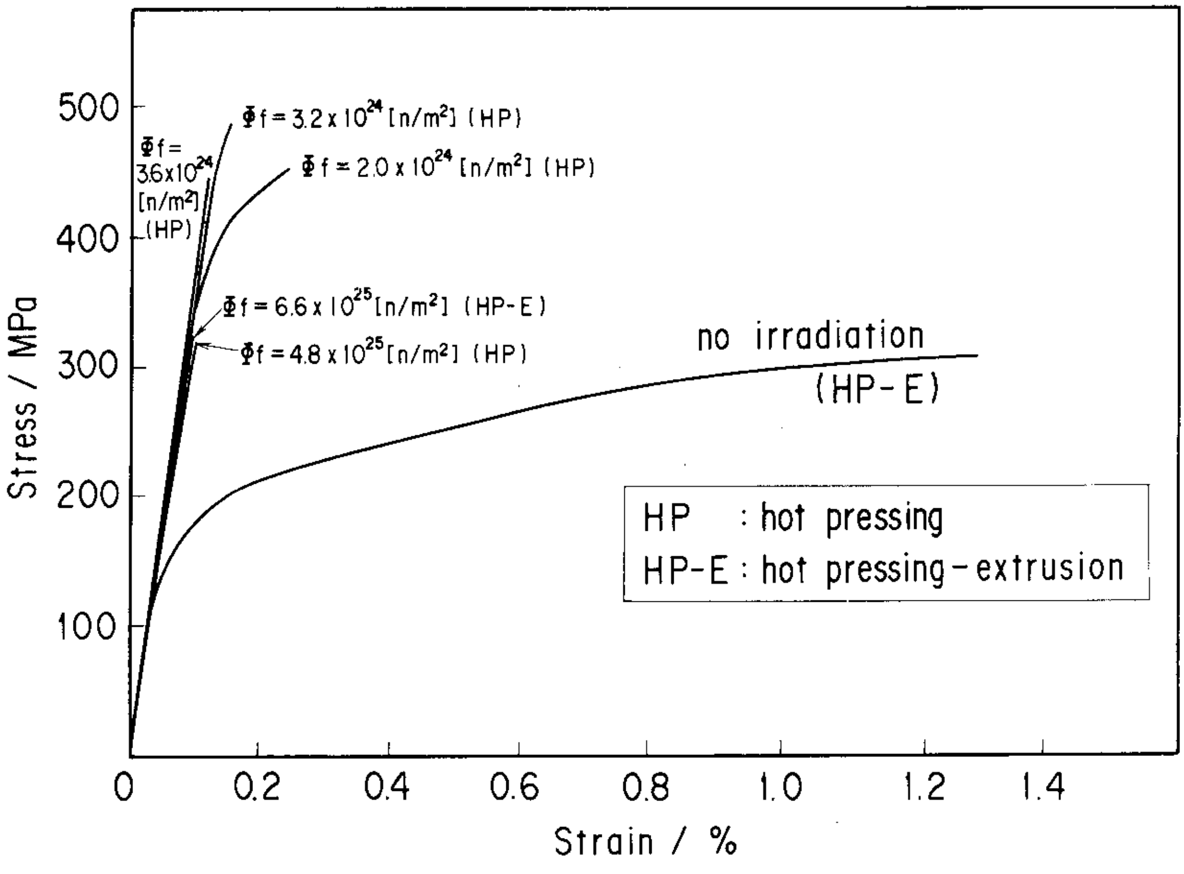
Effect of irradiation on tensile properties

(1) Irradiation condition

① irradiation reactor : JMTR

② irradiation temperature : 45℃

③ testing temperature : room temperature



(1／1)

【Reference】

T. Takeda et al. : JAERI-M 86-007, "Surveillance test of the JMTR core components" (1986).

JMTR

3008

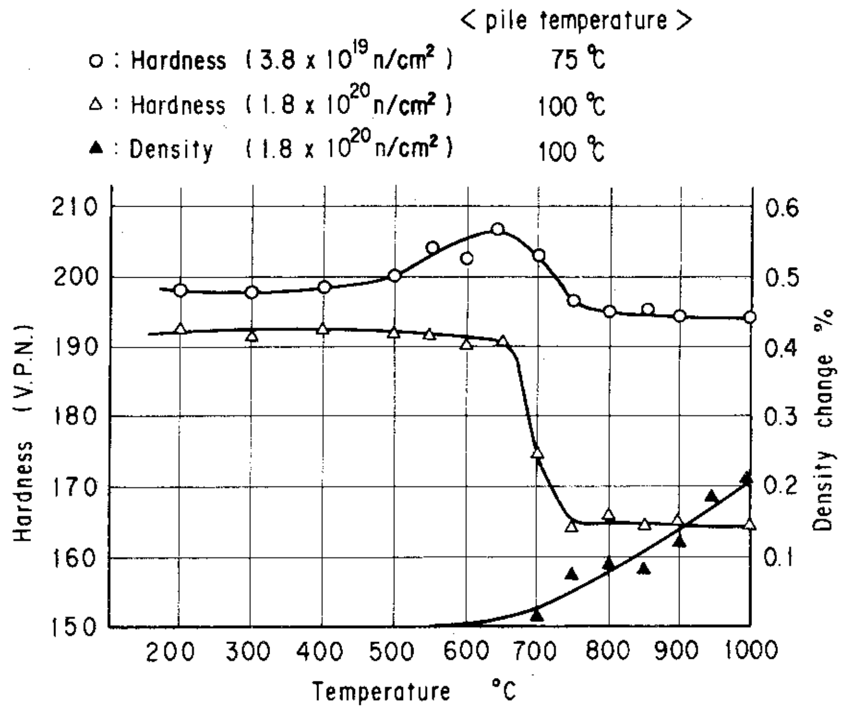
Effect of irradiation on hardness and density

(1) Specimen

① production method : sheath extrusion at 1050 ℃

② dimension

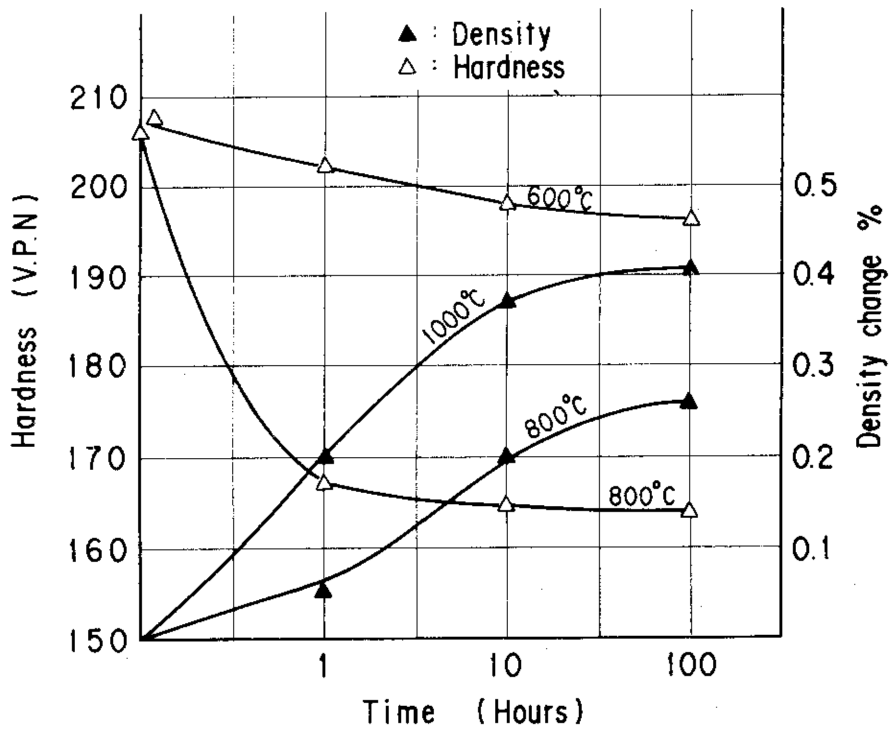
- density and hardness measurement ;
  0.3 or 0.4 inch in diameter x 0.8 inch long
- tensile test ;
  0.15 inch gauge diameter and 1 inch gauge - length



Density and hardness changes on isochromal annealing of specimens irradiated at pile temperature

(1／2)

JMTR



Density and hardness changes on isochromal annealing of specimens irradiated at pile temperature* to 1.8×10^{20} n/cm^2

∗ pile temperature : 100℃

(2／2)

【Reference】
B.S. Hickman : "The Metallurgy of Beryllium / Proc. of an International Conference organized by the Institute of Metals in London", Chapman & Hall Ltd., London (1963) 413.

JMTR

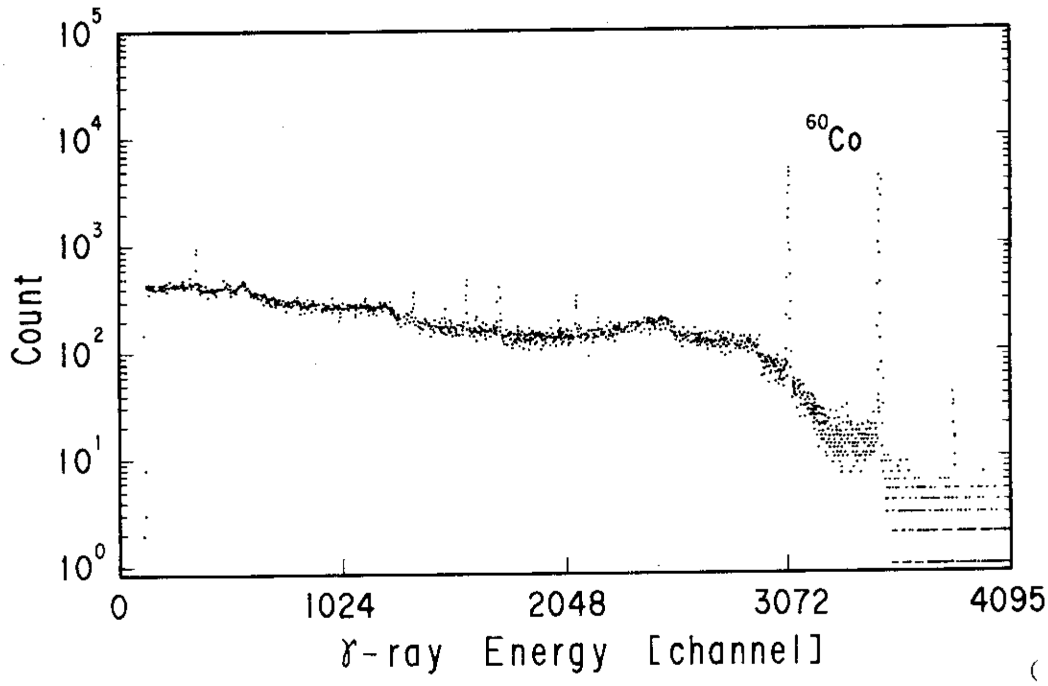
3009

γ-ray spectrum of irradiated beryllium

(1) Specimen
① hot pressed beryllium disk (ø10 x ᵗ1.4 mm)
② main impurities : BeO 1.28 wt.%
Fe 0.0610 wt.%
Co 0.0007 wt.%

(2) Irradiation conditions
① irradiation temperature : 200 °C
② fast neutron fluence : 3.8×10^{20} n/cm^2
③ thermal neutron fluence : 6×10^{20} n/cm^2

(3) Analysis conditions
① cooling time : 52 days
② equipment : High-Purity-Ge Gamma-Ray detector



(1/1)

【Reference】
E. Ishitsuka, H. Kawamura et al. : JAERI-M 90-013, "Experiments on tritium behavior in beryllium (2) -Tritium released by recoil and diffusion-" (1990).

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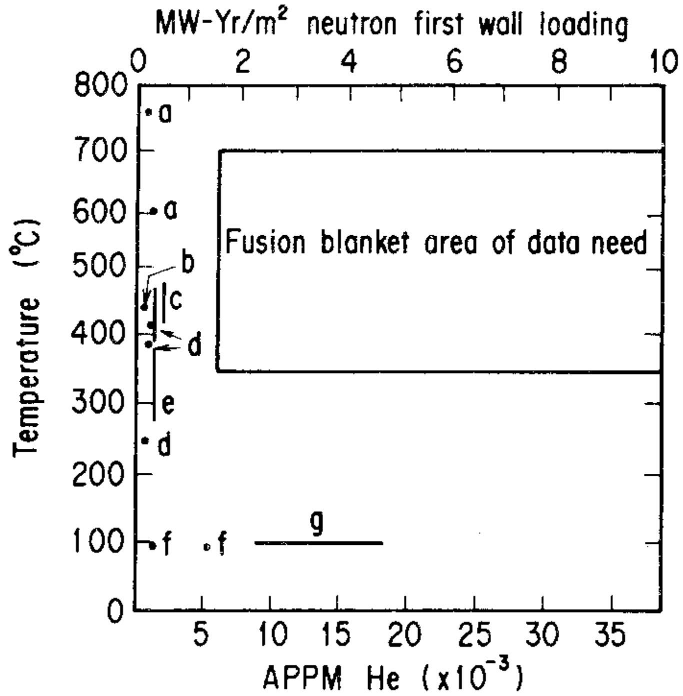
3010

Fusion blanket beryllium data needs compared to existing data



a. J.M. Beeston : ASTM STP 426, "Gas release and compression properties in beryllium irradiated at 600 and 750°C" (1967) 135.
b. S.Morozumi et al. : "Effects of distribution of helium bubbles on the tensile properties and swelling of neutron irradiated and annealed beryllium", J. Nucl. Mater., 68 (1977) 82.
c. J.M. Beeston et al. : "Comparison of compression properties and swelling of beryllium irradiated at various temperature", J. Nucl. Mater., 122-123 (1984) 802.
d. C.E. Ells et al. : J. Nucl. Mater., 13 (1964) 49.
e. J.B. Rich et al. : "The mechanical properties of some highly irradiated beryllium", J. Nucl. Mater., 4, 3 (1961) 287.
f. C.E. Ells et al. : "Effects of neutron-induced gas formation on beryllim", J. Nucl. Mater., 1 (1959) 73.
g. J.M. Beeston : TREE-1063, "Properties of irradiated beryllium statistical evaluation" (1976).

(1/1)

【Reference】

L.G. Miller et al. : "Radiation damage experiments and lifetime estimates for beryllium components in fusion system", Fusion Technology, 8 (1985) 1152.

5. Mechanical Properties

"Summary of mechanical properties(4001)" shows the summary of mechanical properties on breeder and multiplier. "Tensile properties(1)(4002)" shows the tensile strength, elongation and drawing property on hot pressed beryllium at various temperatures. Tensile strength has a flat region at the temperature range of 400-600°C. The elongation and drawing property has a peak at about 400°C. "Tensile properties(2)(4003)" shows tensile strength and elongation on extruded beryllium before and after annealing at various temperatures.

The ultimate strength has a tendency to decrease with increasing the testing temperature and the elongation has two peaks at 400 and 800°C. "Tensile properties(3)(4004)" shows the stress-strain curves of HIP beryllium. "Tensile properties(4)(4005)" shows tensile properties of cold press/sinter/HIP beryllium. Tensile strength at room temperature is larger than hot pressed beryllium, and decreases with increasing testing temperature. The elongation becomes maximum value 50% at 400°C. "Tensile properties(5)(4006)" shows the effects of beryllium oxide content on tensile properties of hot pressed beryllium. Tensile strength and 0.2% yield strength decrease with increasing the temperature. The elongation has a peak at 800°C, and decreases with increasing the beryllium oxide content. "Tensile properties(6)(4007)" shows the effects of grain size on tensile strength and yield strength of high purity beryllium. "Tensile properties(7)(4008)" shows the effect of beryllium oxide content on the elongation. The elongation has a tendency to decrease with increasing beryllium oxide content. "Tensile properties(8)(4009)" shows S-S curve on CIP/HIP beryllium. Generally, the beryllium S-S curve does not show yield phenomenon. "Tensile properties(9)(4010)" shows the mechanical properties on cold press/extrusion beryllium after heat treatment at various conditions. "Tensile properties(10)(4011)" shows the mechanical properties on CIP/HIP and HIP beryllium. The tensile strength and 0.2% yield strength of HIP beryllium is higher by about 20ksi. "Tensile properties(11)(4012)" shows the relation between strain rate and strain at fracture on CIP/HIP and HIP beryllium.

On both materials, the strain at fracture has a tendency to decrease as the strain rate rises. "Tensile properties(12)(4013)" shows S-S curve on CIP/HIP and HIP beryllium. Tensile stress of HIP beryllium is larger than that of CIP/HIP beryllium and yield phenomenon is recognized in HIP beryllium. "Tensile properties(13)(4014)" shows mechanical properties of beryllium produced by the different method. "Ductility correlation(4015)" shows elongation coefficient on various metal materials. The elongation coefficient of beryllium, 0.87 shows that beryllium is a brittle material.

"Ductility(4016)" shows the elongation on hot pressed beryllium at various temperatures. The elongation has a peak at the temperature range of about 300-400°C, and the elongation is about 27%. "Young's modulus(1)(4017)" formularized Young's modulus with parameter of porosity and temperature as follows.

$$E=297\exp(-3.5P)[1-1.9\times10^{-4}(T-293)].$$

"Young's modulus(2)(4018)" shows Young's modulus for various breeder and multiplier materials as a function of density. Young's modulus of beryllium oxide is higher than all of Li-containing ceramics, and similar to zirconia. "Young's modulus(3)(4019)" shows Young's modulus with parameter of porosity in S200 grade hot pressed beryllium. "Vickers hardness vs yield strength(4020)" shows the relation between vickers hardness and yield strength on high purity hot pressed beryllium. "Effect of grain size on the strength(4021)" shows that strength of beryllium related to grain size by the Hall-Petch relationship. "Effect of porosity on mechanical properties(4022)" shows effect of porosity on fracture strain for various grades of beryllium compact.

4001

Summary of mechanical properties

Material	Thermal Expansion α (10^{-6}/K)	Poisson's Ratio ν	Fracture Strength[b] σ_c/σ_t (MPa)
Li_2O	23	0.19	(250) / 50
Al_2O_3	−	0.13−0.32	1200 / 100
$LiAlO_2$	12	(0.23)	400 / (80)
$LiAl_5O_8$	8	(0.25)	(400 / 80)
SiO_2	−	0.16	(200 / 50)
Li_2SiO_3	13	(0.23)	300 / 60
Li_4SiO_4	22	(0.20)	(300 / 60)
ZrO_2	8	0.26−0.29	1000 / 100
Li_2ZrO_3	10	(0.25)	(200 / 50)
Li_8ZrO_6	20	(0.25)	(200 / 50)
TiO_2	9	−	300 / 30
Li_2TiO_3	16	(0.25)	(300 / 30)
Be	16	(0.1)	300 / 300
BeO	8	0.34	400 / 50
$Li_2Be_2O_3$	(20)	(0.2)	(400 / 50)
Li_7Pb_2	(30)	(0.4)	(10 / 10)
Pb	30	0.44	10 / 10

[a] Values in parentheses are suggested in the absence of data. At the given conditions, these results are uncertain by about 10% for thermal expansion, 20% for Poisson's ratio, and a factor of 3 for fracture strength.

[b] Grain diameter on the order of 0.5 - 2 μm ; 85% dense sintered meterial

Summary of mechanical properties at 300 K for candidate solid breeder and multiplier materials

(1/1)

【Reference】

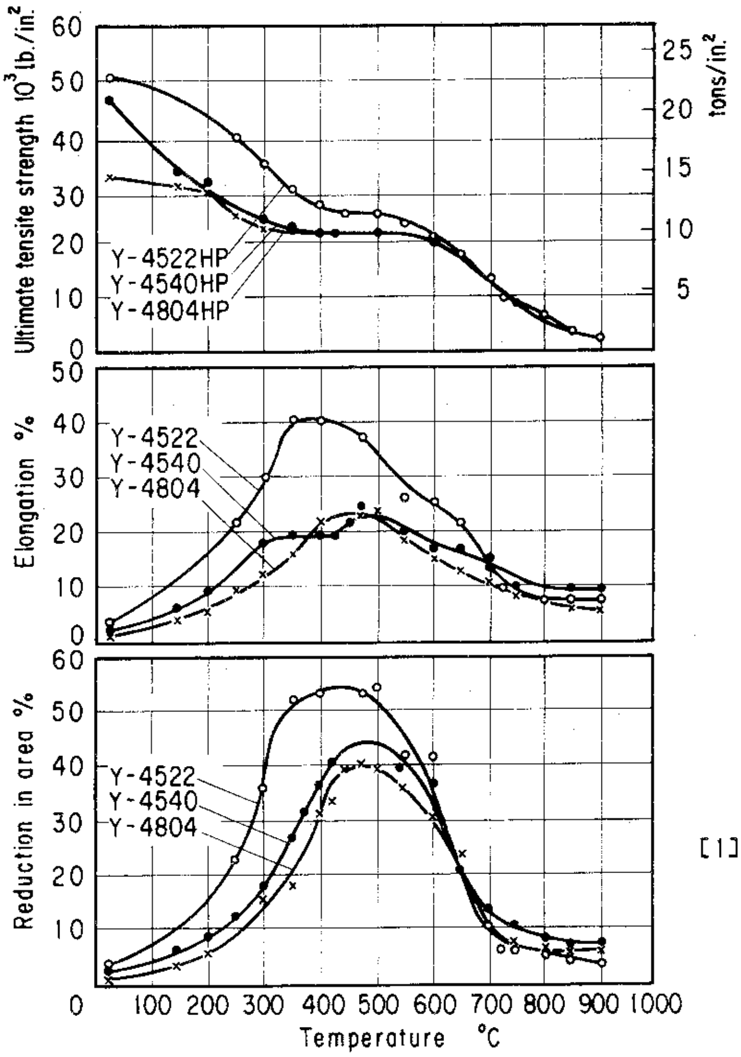
E.C. Bell et al. : UCLA-ENG-86-44, "Modeling, analysis and experiments for fusion nuclear technology" (1987).

JMTR

4002

Tensile properties (I)

(I) Specimen : vacuum hot pressed beryllium
(Y-4522, Y-4540, Y-4804 : Lot. No.)



[1]

[1] Beaver, W. W. et al. : Trans. Amer. Inst. min. Engrs, 200 (1954) 559

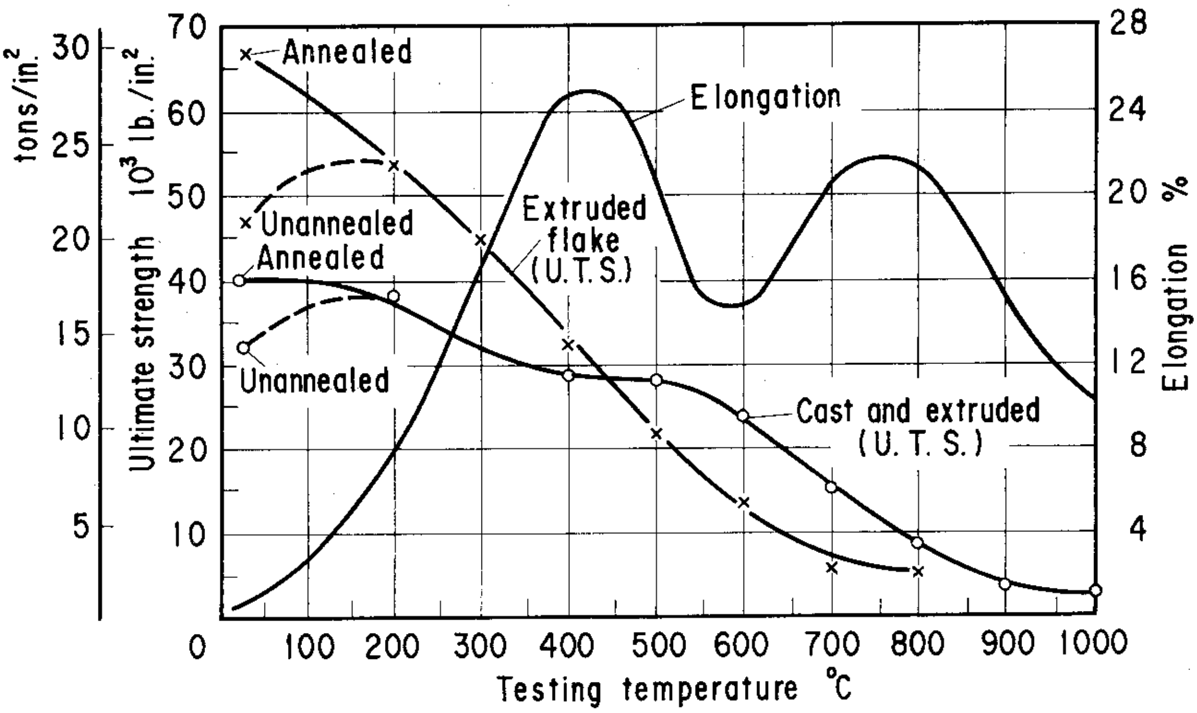
(1/1)

【Reference】
G. E. Darwin and J. H. Buddery : "Metallugy of the rarer metals - 7 Beryllium", Butterworths Scientific Publications, London (1960) 187.

4003

Tensile properties (2)

(1) Specimen : extruded beryllium



Elevated temperature tensile properties of extruded beryllium, before and after annealing [1]

[1] Kaufmann, A.R. et al. : Trans. Amer. Soc. Metals, 42 (1950) 785.

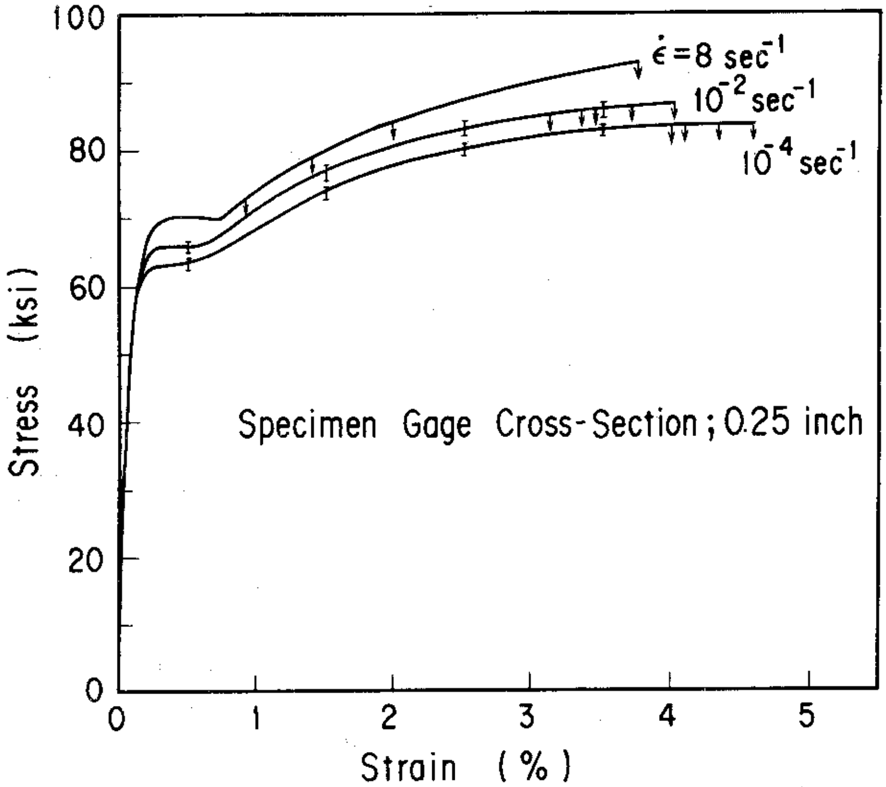
(1/1)

【Reference】
G.E. Darwin and J.H. Buddery: "Metallugy of the rarer metals-7 Beryllium", Butterworths Scientific Publications, London (1960) 187.

JMTR

4004

Tensile properties (3)



Tensile stress-strain curves for HIP beryllium at various strain rates

(1/1)

【Reference】

L.R. Aronin et al.: "Betyllium 1977/ Proc. of Fourth International Conference on Beryllium", The Metals Society, The Royal Society, London (1977) 19.

4005

Tensile properties (4)

Tensile properties of beryllium (S-65B) fabricated by cold pressing-sinter-hot isostatic pressing[a]

Test temperature	Ultimate tensile strength (ksi)	Yield strength 0.2% offset (ksi)	% Elongation	% Reduction in area
Room	49.6	30.6	5.2	...
370°C	33.0	19.3	49.4	66.9
650°C	17.8	11.7	38.5	29.5

a: Average of four or more tests. Tests made under contract to JET, Abingdon, England. All tests transverse to cold pressing direction.

Tensile test results for vacuum hot-pressed S-65B beryllium

Temperature (°C)		Ultimate strength (MPa)	Ultimate strength (ksi)	Yield strength (MPa)	Yield strength (ksi)	Elongation %
20	L[a]	421	61.1	270	39.1	3.0
20	T[b]	454	65.8	273	39.6	5.4
200	L	382	55.4	232	33.6	10.2
200	T	389	56.4	234	34.0	23.4
400	L	270	39.2	179	25.9	50.0
400	T	268	38.8	177	25.6	49.5
600	L	160	23.2	119	17.2	25.2
600	T	167	24.2	122	17.7	31.9

a: Longitudinal direction (parallel to molding pressure).
b: Transverse direction (perpendicular to molding pressure).

(1/1)

【Reference】

A. James Stonehouse : "Physics and chemistry of beryllium",
J. Vac. Sci. Techrol. A, 4, 3 (1986) 1163.

JMTR

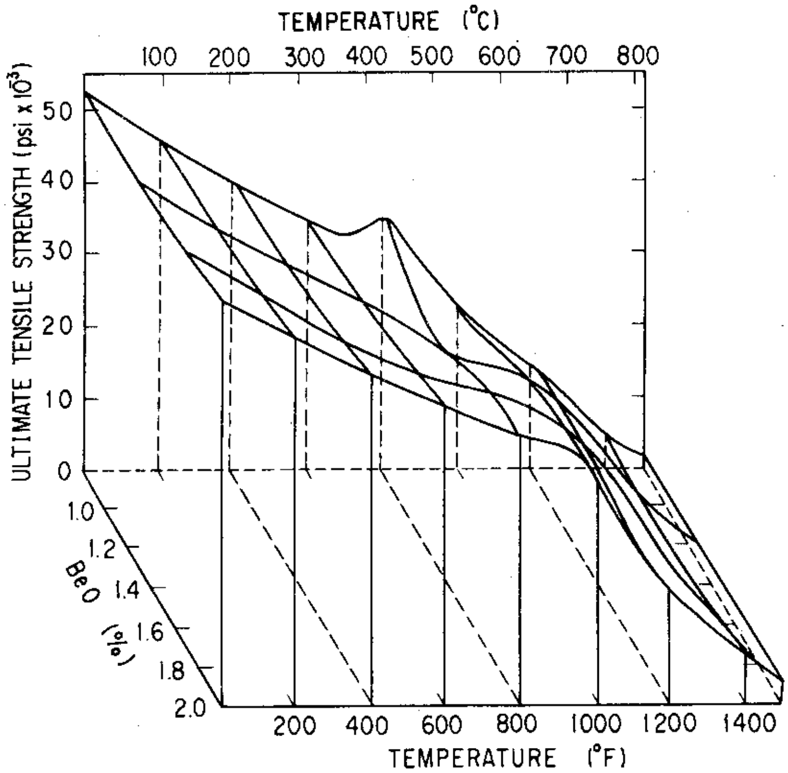
4006

Tensile properties (5)

(1) Specimen : hot-pressed beryllium

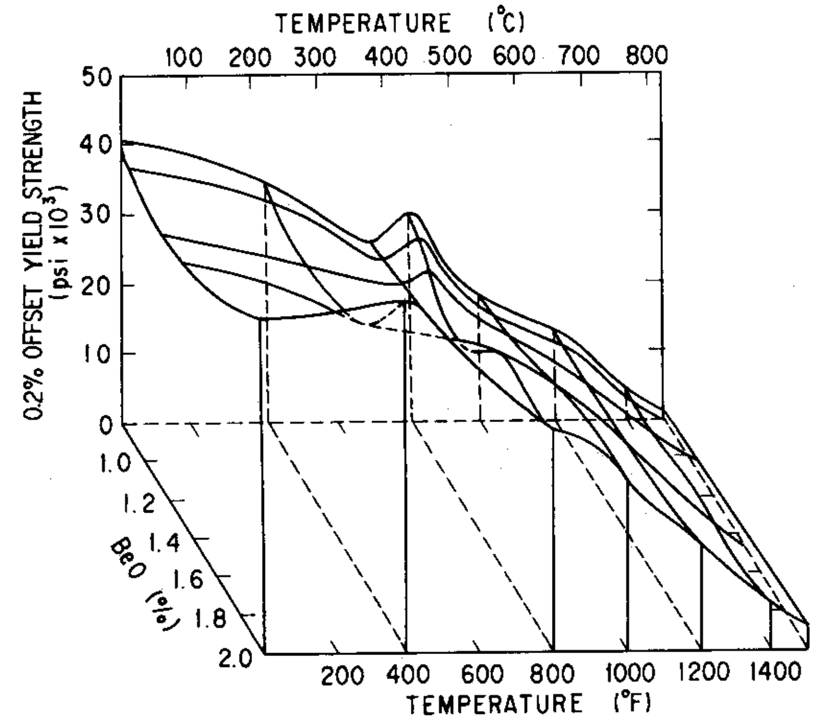
(2) Impurities of specimen :

- 0.85 -2.0% BeO
- 0.025-0.100% Al
- 0.022-0.060% Si
- 0.11 -0.19% Fe
- 0.005-0.090% Mg
- 0.060-0.140% C



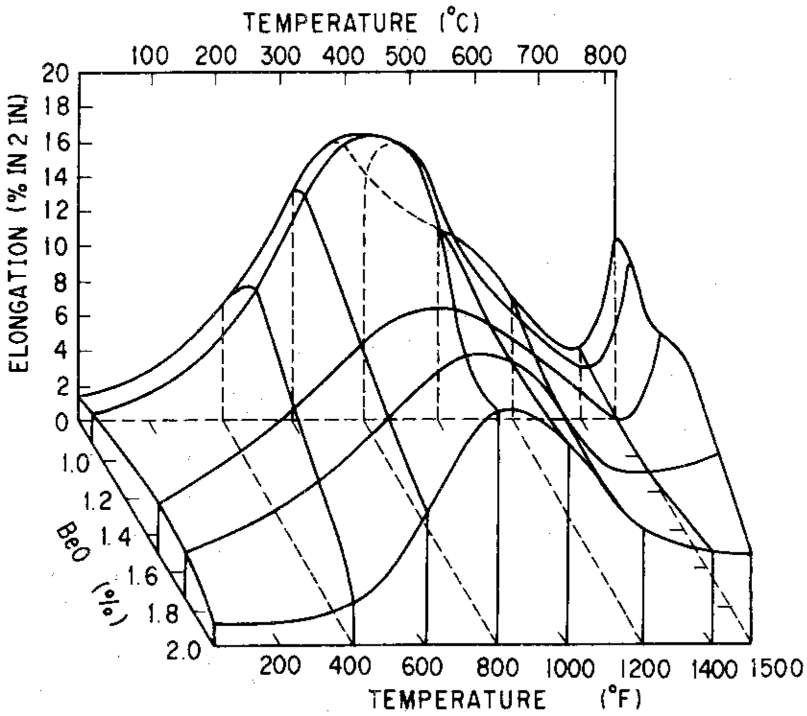
Ultimate tensile strength as a function of temperature and BeO content

JMTR



Yield strength as a function of temperature and BeO content

(2／3)



Elongation as a function of temperature and BeO content

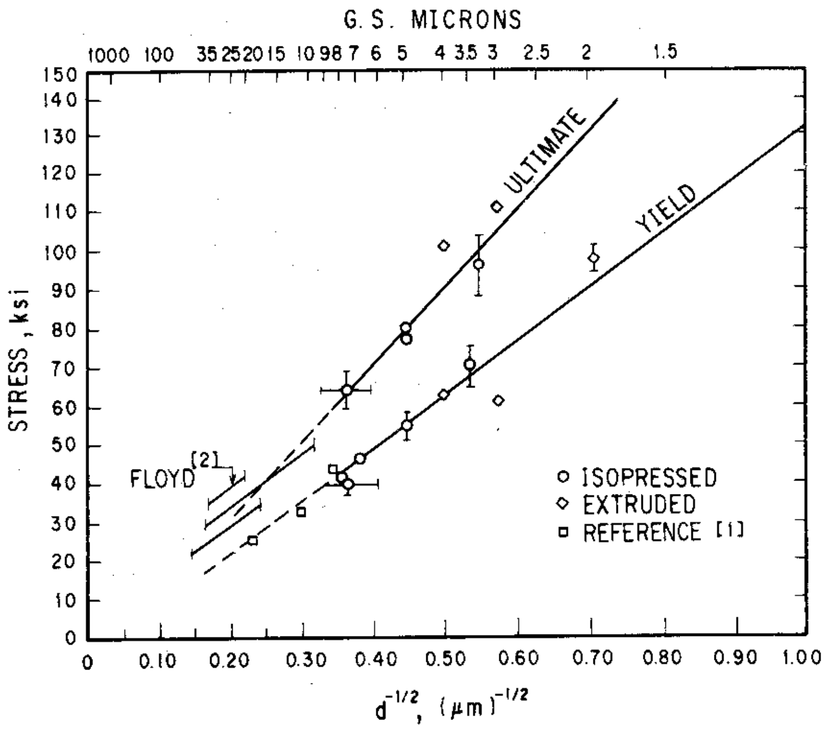
(3/3)

【Reference】
M.I.Jacobson et al.: "The Metallurgy of Beryllium / Proc. of an International Conference organized by the Institute of Metals in London", Chapman & Hall Ltd., London (1963) 100.

JMTR

4007

Tensile properties (6)



Yield and ultimate strength vs grain size for high-purity beryllium

[1] A. J. Stonehouse, Brush-Wellman Co., Cleveland, Ohio, personal communication.

[2] D. R. Floyd : RFP-2061, "Causes of the Yield-point Phenomenon in Commercial Beryllium Products", Dow Chemical Co., Goden, Colorado (1974).

(1／1)

【Reference】

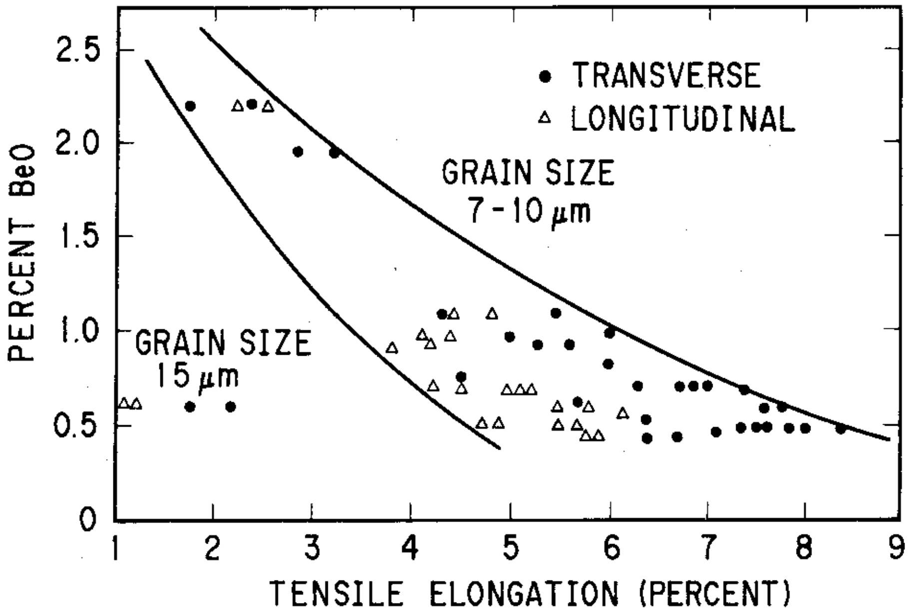
D. Webster and G. J. London : "Beryllium Science and Technology / Volume 1", Plenum Press, New York (1979) 133.

JMTR

4008

Tensile properties (7)

(1) Specimen : hot isostatically pressed beryllium



[1]

The effect of BeO content upon the tensile elongation

[1] D. Webster et al. : "Factors affecting the tensile strength, elongation and impact resistance of low oxide, hot isostatically pressed beryllium block", Met. Trans., 7A (1976) 851.

(1／1)

【Reference】

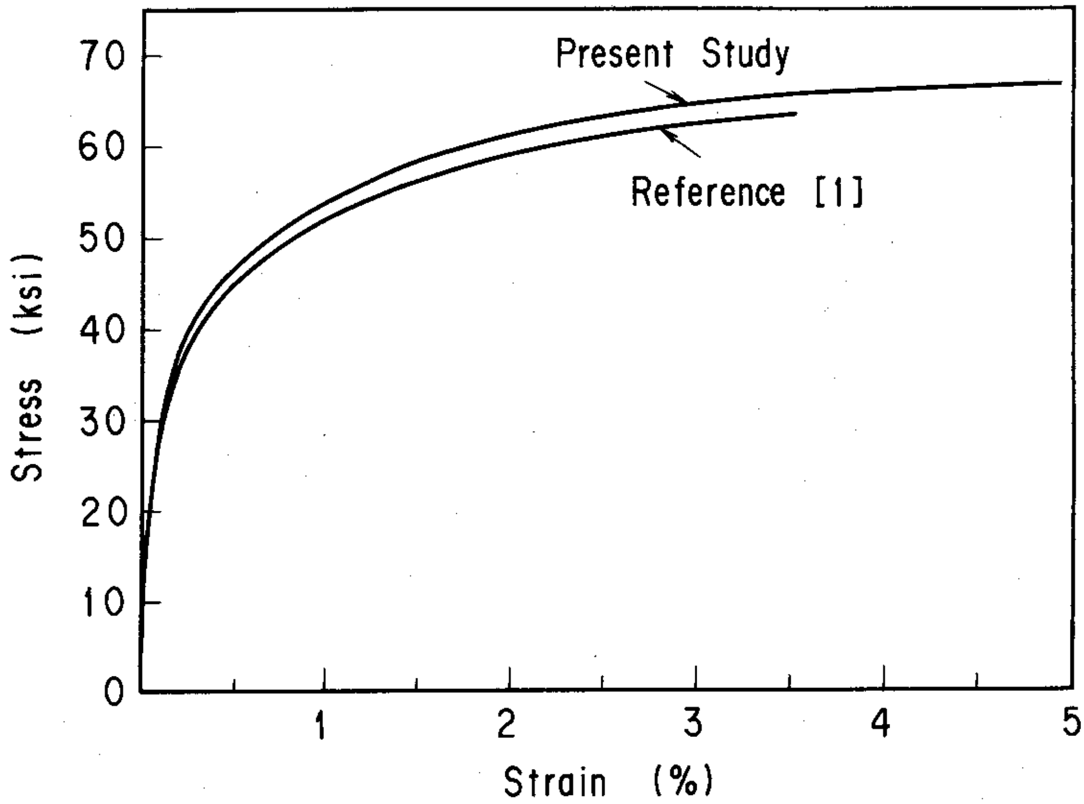
D. Webster and G.J. London : "Beryllium Science and Technology / Volume 1", Plenum Press, New York (1979) 133.

JMTR

4009

Tensile properties (8)

(1) Specimen : CIP / HIP beryllium
~1.09 % BeO



[1] T. Nicholas : AFML-TR-75-168, "Mechanical properties of structural grades of beryllium at high strain rates" (1975).

(1/1)

【Reference】

S.C. Chou et al.: "Beryllium 1977 / Proc. of Fourth International Conference on Beryllium", The Metals Society, The Royal Society, London (1977) 20.

4010

Tensile properties (9)

(1) Specimen :

① Cold compacted and extruded (at 1950℃)

② ~16ft long, having undergo a reduction in area of~30:1

Heat Treatment*		Yield Strength (0.2% Offset), lb/in² x 10³			Ultimate Tensile Strength, lb/in² x 10³			Percentage Elongation		
		High	Avg.	Low	High	Avg.	Low	High	Avg.	Low
As−extruded		50	49	46	100	99	94	19	17	15
Furnace − cooled		46	44	43	93	88	83	17	12	6
Air − cooled		42	41	40	75	69	58	4	3	2
As − quenched		44	43	42	80	67	62	5	3	2
As − quenched		44	44	43	77	74	71	4	3	3
As − quenched		47	46	44	80	76	72	4	3	3
Temp.	Time									
200℃	24 h	45	44	44	71	69	66	3	3	2
	1 week	51	50	48	74	70	61	3	2	1
300 C	24 h	47	45	42	72	70	66	3	3	2
	1 week	52	48	45	70	66	60	2	2	1
400℃	15 min	46	45	43	67	64	59	2	2	1
	2 h	47	46	44	73	64	53	4	2	1
	7 h	48	47	45	86	83	79	6	5	5
	7 h	44	42	41	59	57	56	1	1	1
	16 h	47	46	43	76	66	57	4	2	1
	24 h	46	46	44	71	62	53	3	2	1
	24 h	47	46	45	72	62	48	3	2	0
	24 h	45	44	44	66	62	57	2	2	1
	30 h	46	44	43	69	60	50	3	2	1
	42 h	45	44	43	65	56	44	2	1	0
	60 h	48	47	45	70	66	60	2	2	1
	1 week	45	45	44	71	62	55	3	2	1
	8 days	44	43	42	67	52	48	3	1	0
500℃	15 min	48	47	46	67	62	56	2	2	1
	2 h	48	47	45	73	63	54	3	2	1
	24 h	48	45	43	70	64	51	3	2	1
	1 week	49	47	45	87	82	79	8	6	4
600℃	15 min	44	43	42	74	64	58	3	2	1
	2 h	47	46	45	75	71	64	4	3	2
	24 h	49	48	47	92	80	63	4	3	2
	1 week	44	44	43	94	86	79	18	10	5
700℃	15 min	46	44	43	76	67	57	4	2	1
	2 h	47	46	46	85	81	79	6	5	4
	24 h	46	45	45	92	82	74	16	8	4
	1 week	49	48	48	96	95	92	17	14	9
800℃	15 min	46	43	42	76	70	57	4	3	1
	2 h	44	44	43	86	80	75	9	6	4
	24 h	46	45	45	92	91	90	16	14	12
	1 week	49	47	44	96	94	90	17	14	8

* With the exception of the as-extruded condition. the heat-treatments listed have been preceded by a solution-treatment at 1100 ℃ for 1h.

(1/1)

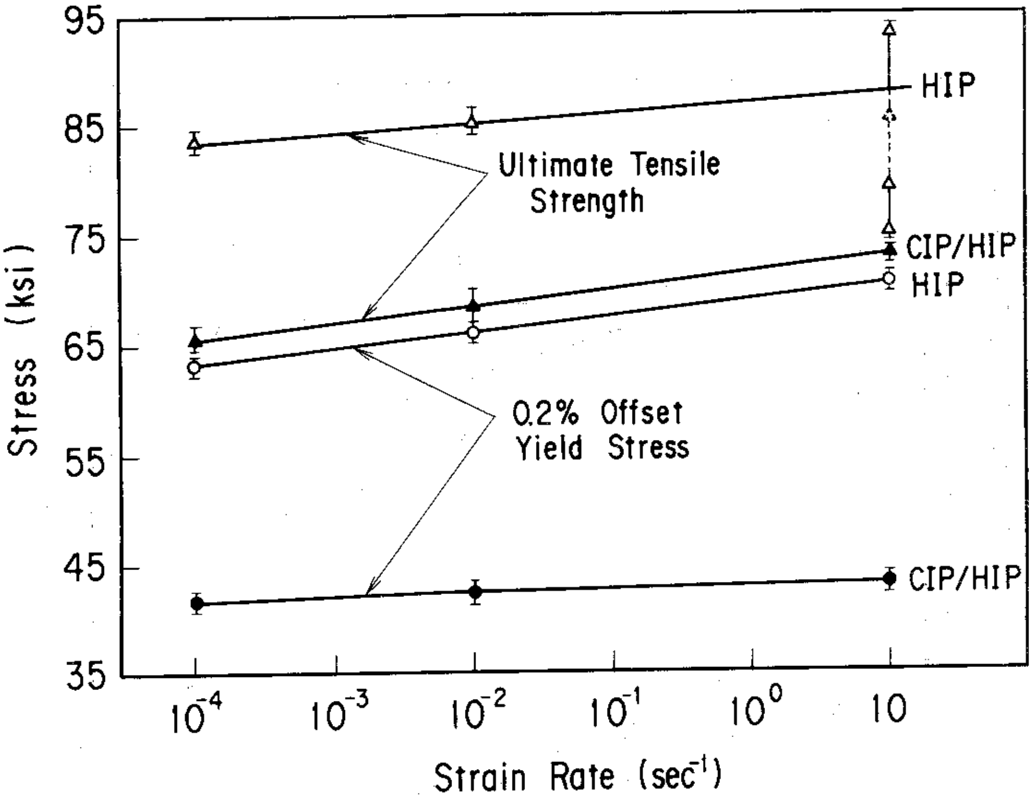
【Reference】

A.K. Wolff et al.: "The Metallurgy of Beryllium / Proc. of an International Conference organized by the Institute of Metals in Londen", Chapman & Hall Ltd., London (1963) 152.

JMTR

4011

Tensile properties (10)



Comparison of ultimate tensile strength and yield stress of CIP/HIP and HIP beryllium

(1／1)

【Reference】

L.R Aronin et al.: "Beryllium 1977 / Proc. of Fourth International Conference on Beryllium", The Metals Society, The Royal Society, London (1977) 19.

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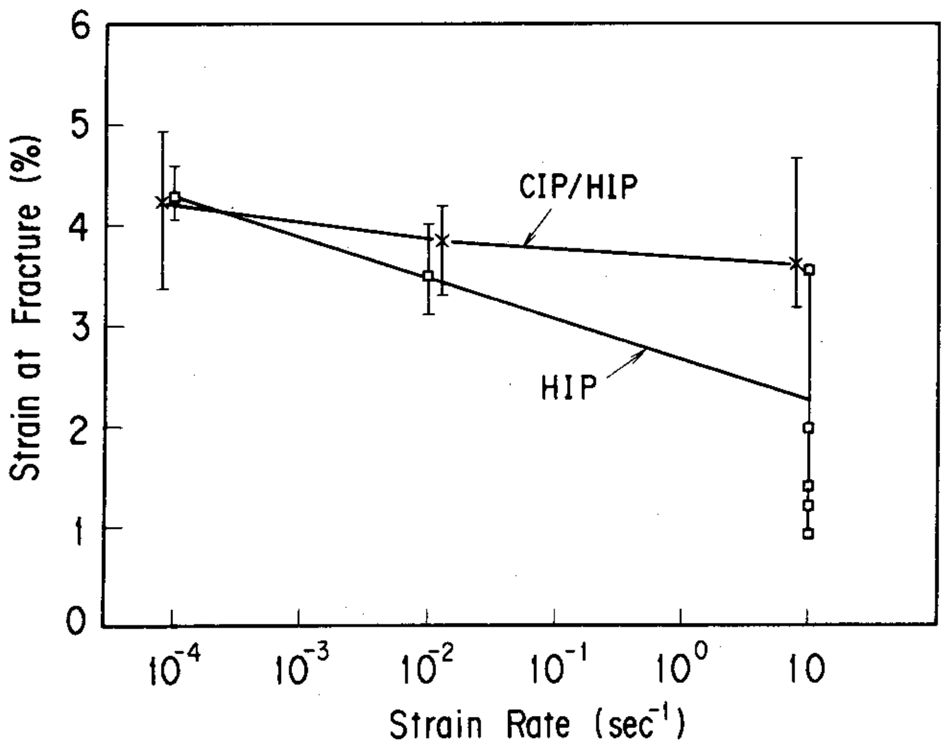
4012

Tensile properties (11)



Comparison of ductility of CIP/HIP and HIP beryllium

(1／1)

【Reference】

L.R. Aronin et al.: "Beryllium 1977/ Proc. of Fourth International Conference on Beryllium", The Metals Society, The Royal Society, London (1977) 19.

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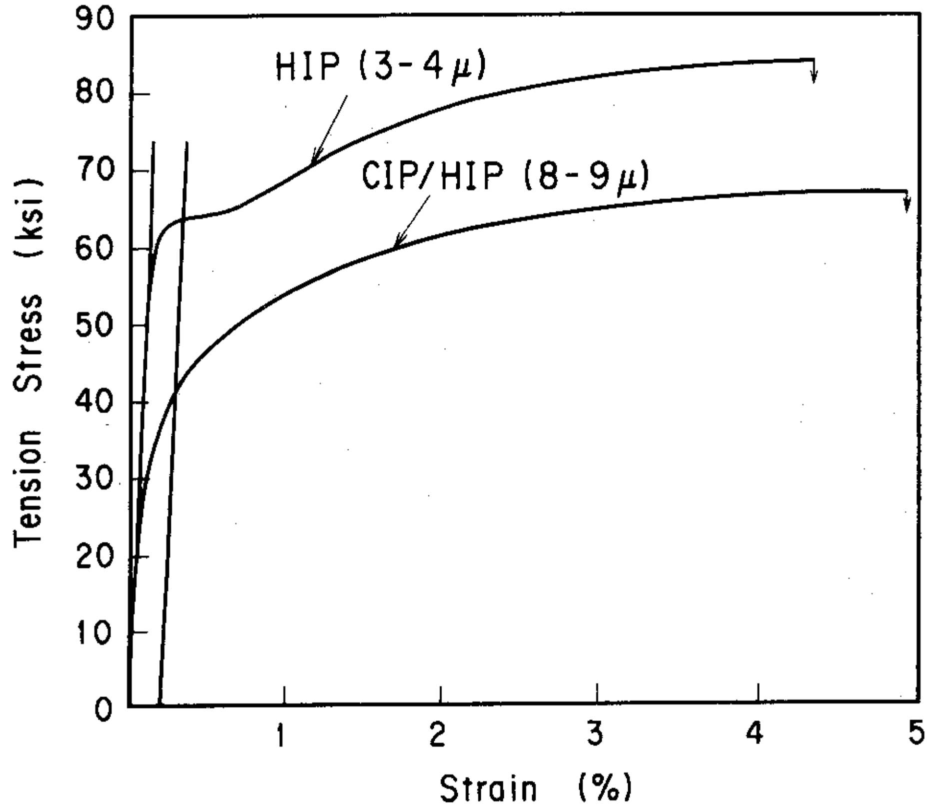
4013

Tensile properties (12)



Comparison of tensile stress－strain curves for CIP/HIP and HIP beryllium at $\dot{\epsilon} = 10^{-4}$/sec

(1／1)

【Reference】

L.R. Aronin et al. : "Beryllium 1977/ Proc. of Fourth International Conference on Beryllium", The Metals Society, The Royal Society, London (1977) 19.

4014

Tensile properties (13)

Billet Condition	Avg. Density, g/c.c.	Avg. Tensile Strength, lb/in^2	Avg. Yield Strength, lb/in^2	Avg. Elong, %	Avg. Contraction, %	Avg. Product Yield, %
Cold-Pressed 70°F (not sintered)	1.22-1.31	90 700	43 900	13.4	13.4	43
Warm-Pressed 850°F (not sintered)	1.58-1.71	87 400	42 200	12.6	13.1	68
Pressureless-Sintered (loose powder)	1.70-1.80	84 600	41 100	10.8	11.1	88
Hot-Pressed	1.84-1.86	83 700	40 900	10.3	10.4	89

Properties of beryllium rod from billets of different origin

(1/1)

【Reference】
The Institute of Metals : "The Metallurgy of Beryllium/Proc. of an International Confererence organized by the Institute of Metals in London", Chapman & Hall Ltd., London (1963) 783.

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4015

Ductility correlation

[1], [2]

Element	c/a	Primary slip mode	K/G	Ductility
Cd	1.886	Basal	2.03	Fair
Zn	1.856	Basal	1.59	Brittle
Co	1.623	Basal	2.43	Fair
Mg	1.623	Basal	1.92	Fair
Re	1.615	Both basal and prismatic	1.76	Fair
Zr	1.593	Prismatic	2.58	Ductile
Ti	1.587	Prismatic	3.25	Ductile
Hf	1.581	Prismatic	3.58	Ductile
Os	1.579	—	1.67	Brittle
Be	1.568	Basal	0.87	Brittle

[1] S.F. Pugh : Atomic Energy Research Establishment Report, No. MIR (1953) 1290.

[2] H. Conrad : "Beryllium as a technological material, Proc. Int. Conf. Beryllium Met.", French University Press, Paris (1965).

(1/1)

【Reference】

D. Webster and G. J. London : "Beryllium Science and Technology / Volume 1", Plenum Press, New York (1979) 117.

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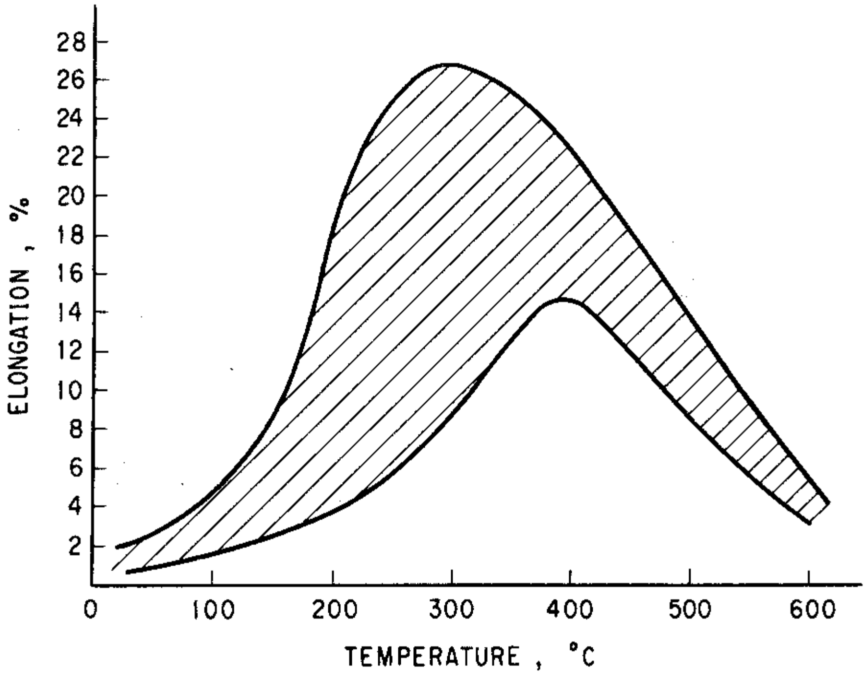
4016

Ductility

(1) Specimen : hot - pressed
(−200 mesh beryllium powder)



Ductility scatter band [1]

[1] B. Goosey (A.W.R.E), private communication.

(1/1)

【Reference】
A.J. Martin et al. : "The Metallurgy of Beryllium / Proc. of an International Conference organized by the Institute of Metals in London", Chapman & Hall Ltd., London (1963) 4.

JMTR

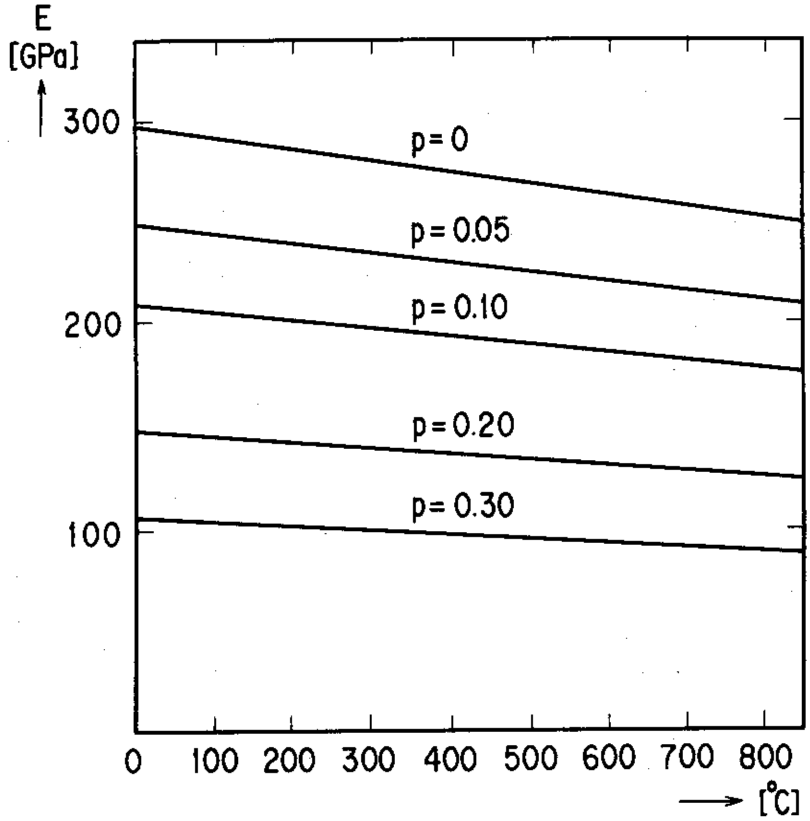
4017

Young's modulus (1)

(1) $E = 297\exp(-3.5P)[1-1.9\times10^{-4}(T-293)]$

$P=0$, $293 \le T \le 1088\,K$

(P : porosity [-] , T : temperature [K])



Young's modulus vs porosity

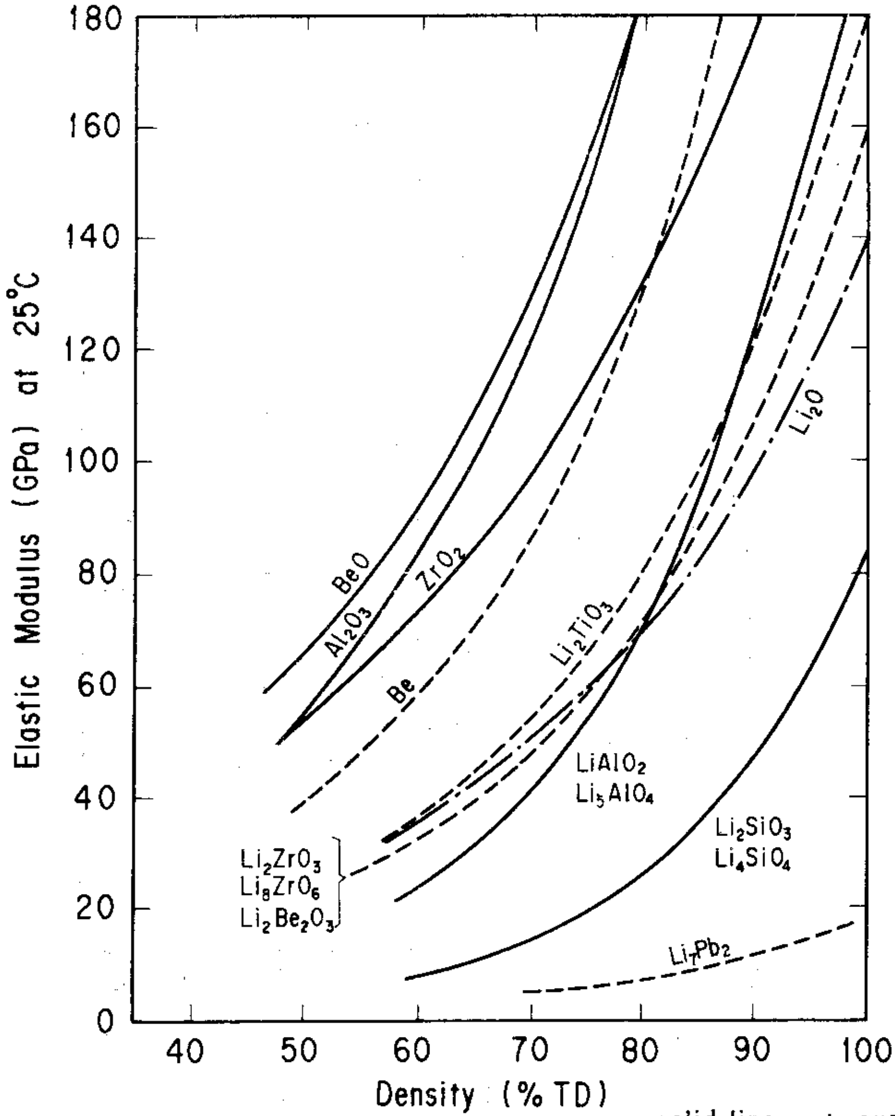
(1/1)

【Reference】
M.C. Billone et al. : ANL/FPP/TM-218, "Summary of mechanical properties data and correlations for Li_2O, Li_4SiO_4 , $LiAlO_2$ and Be" (1988).

JMTR

4018

Young's modulus (2)



solid line : experimental
dashed line : estimated

Young's modulus for various breeder materials as a function of density

(1／1)

【Reference】

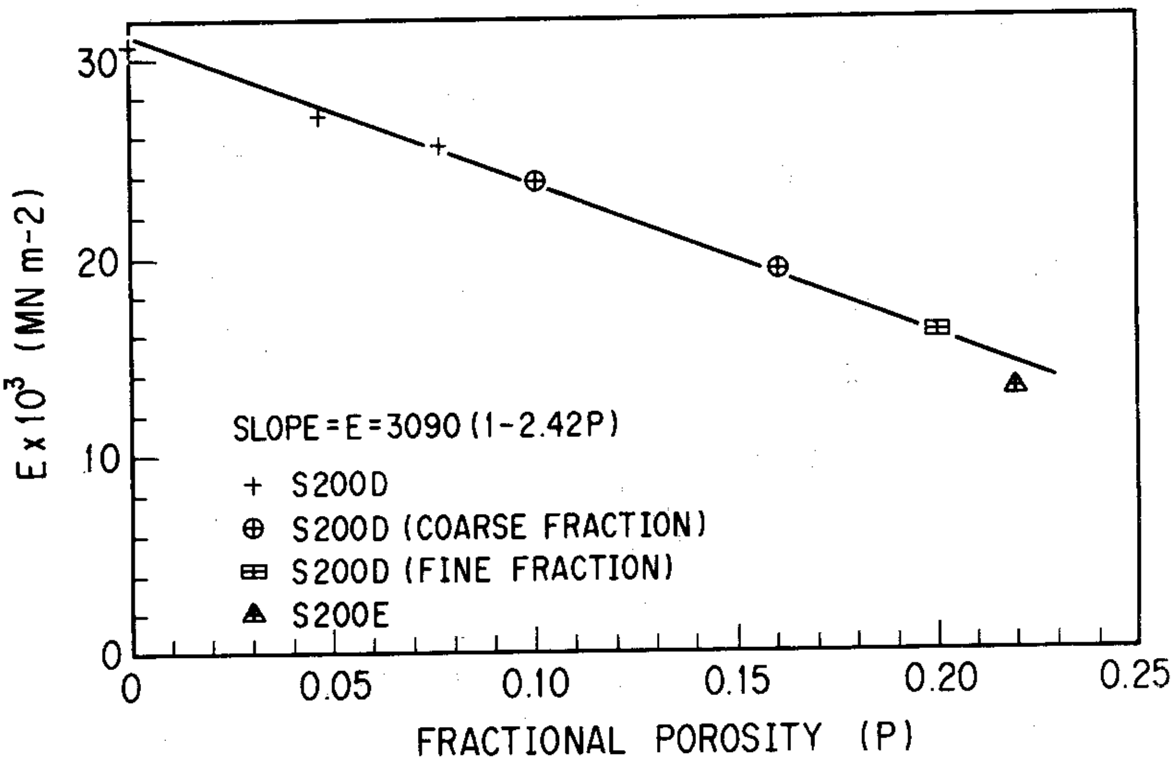
E.C. Bell et al. : UCLA-ENG-86-44, "Modeling, analysis and experiments for fusion nuclear technology" (1987).

4019

Young's modulus (3)

(1) Specimen

① S200 grade hot pressed beryllium



Young's modulus of elasticity on porous beryllium

(1／1)

【Reference】
"Beryllium 1977 / Proc. of Fourth International Conference on Berryllium", The Metals Society, The Royal Society, London (1977) 24.

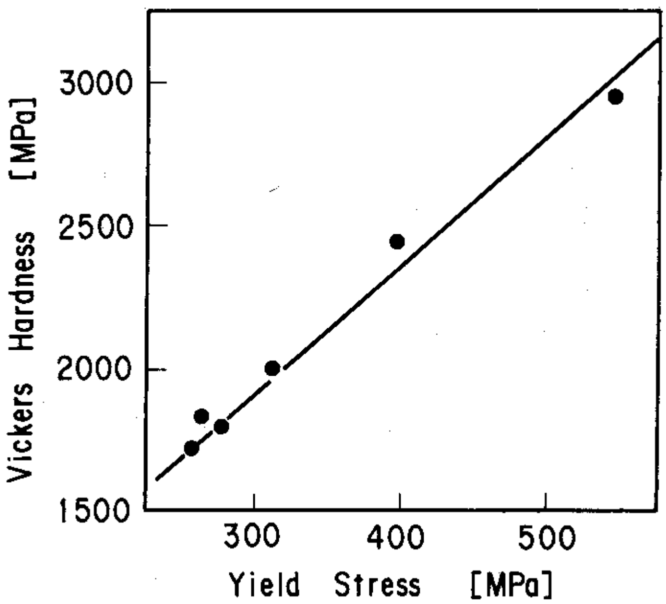
JMTR

4020

Vickers hardness vs yield strength

(1) Specimen :

- hot pressed
- high purity beryllium



(1／1)

【Reference】

F. Aldinger et al. : "Beryllium 1977/ Proc. of Fourth International Conference on Beryllium", The Metals Society, The Royal Society, London (1977) 14.

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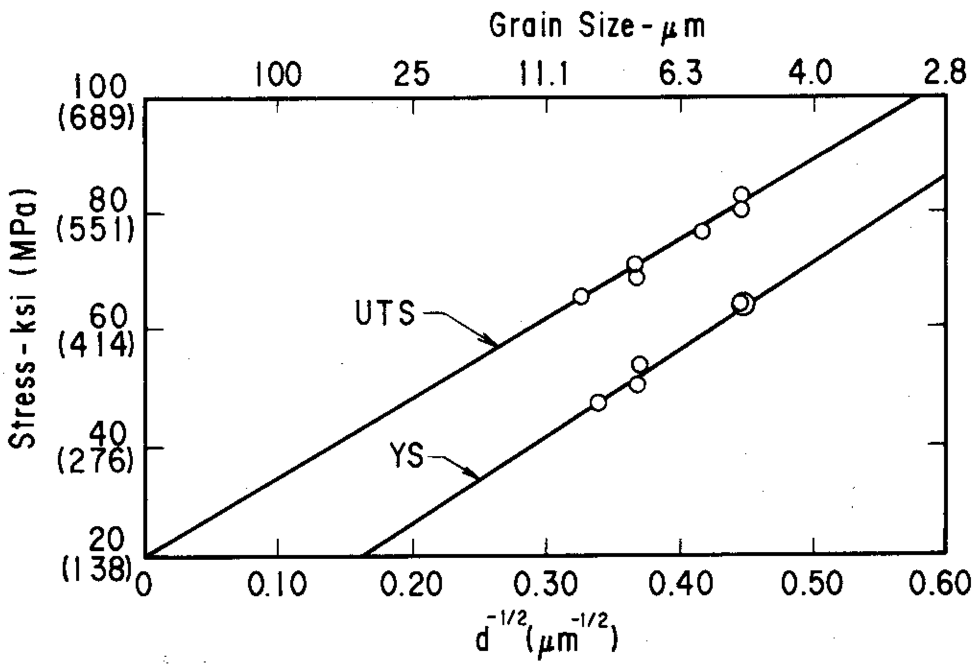
4021

Effect of grain size on the strength

(1) Strength of beryllium : related to grain size by the Hall－Petch relationship.



(1／1)

【Reference】

A. James Stonehouse : "Physics and chemistry of beryllium", J. Vac. Sci. Technol. A, 4, 3 (1986) 1163.

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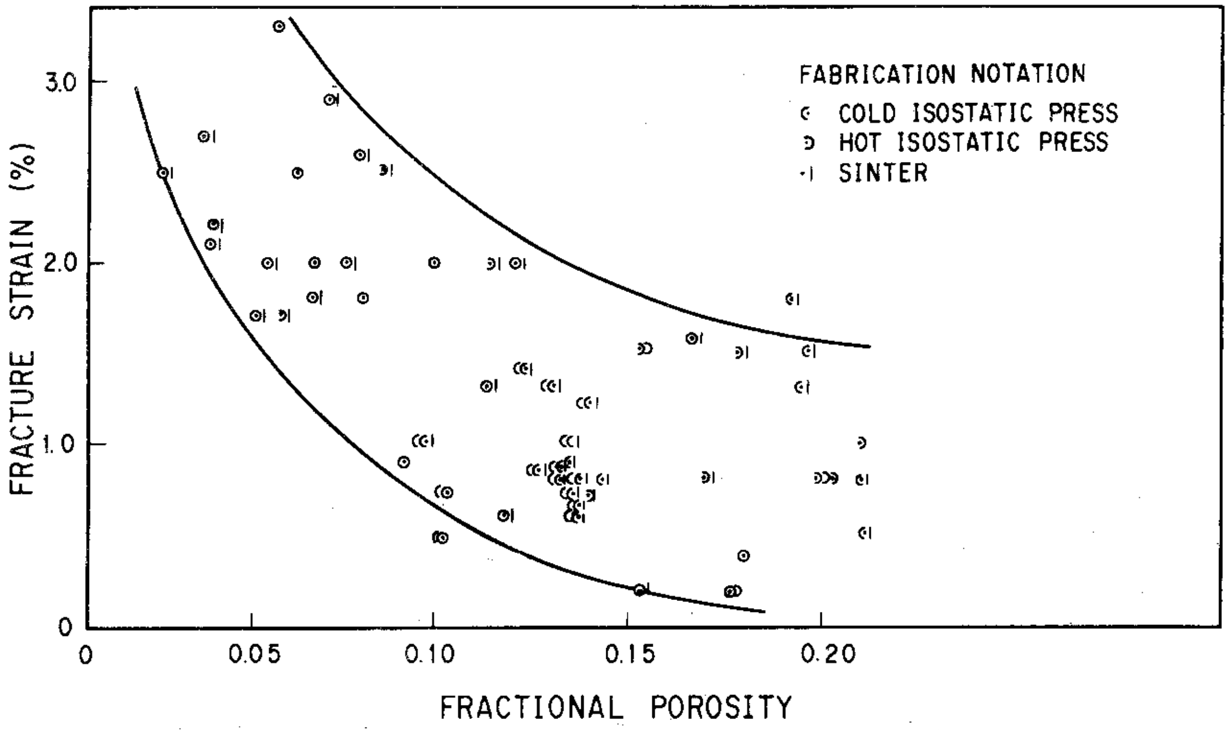
4022

Effect of porosity on mechanical properties



Effect of porosity on fracture strain for various grades of beryllium compact

(1/2)

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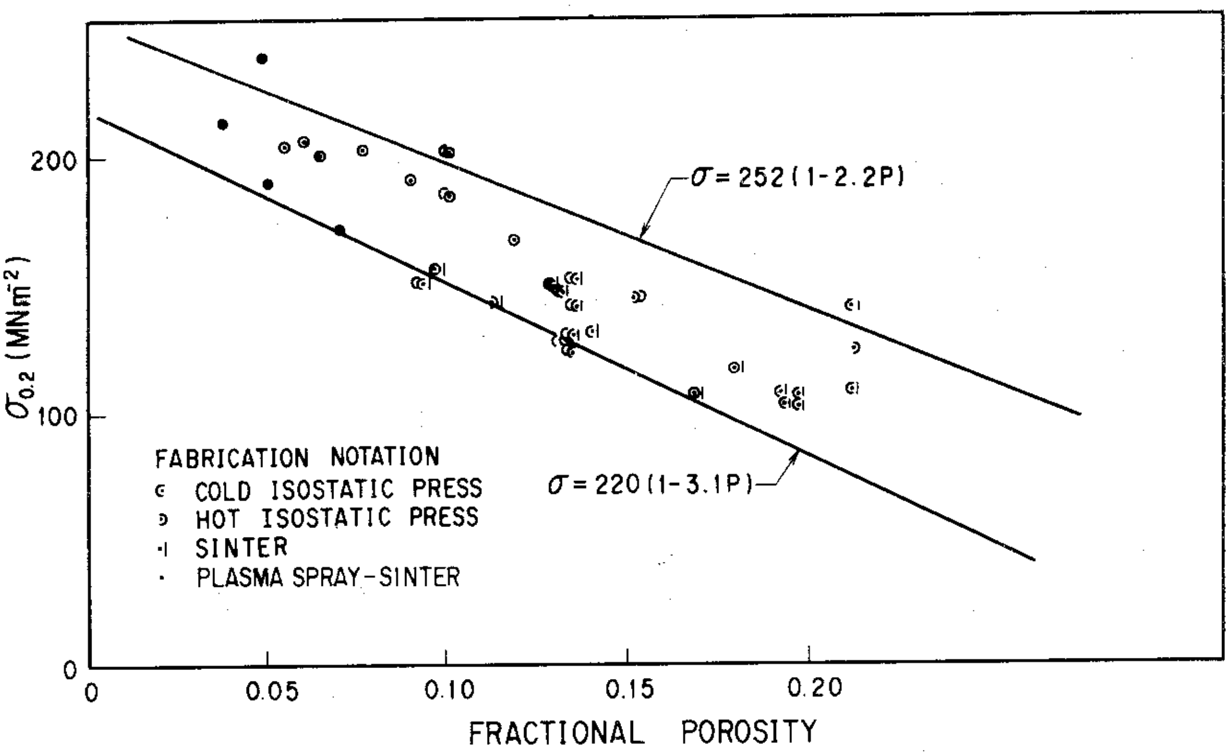

Effect of porosity on $\sigma_{0.2}$ for various grades of beryllium compact

(2／2)

【Reference】

D. Beasley et al. : "Beryllium 1977 / Proc. of Fourth International Conference on Beryllium", The Metals Society , The Royal Society, London (1977) 24.

6. Thermal Properties

"Specific heat(1)(5001)" shows the result of measurement on specific heat of beryllium. From these data, the specific heat of beryllium is formularized as follows.

$$Cp=4.54+2.12\times10^{-3}T-0.82\times10^{5}T^{-2}\ (cal/g/{}^{\circ}C).$$

"Specific heat(2)(5002)" shows specific heat of various breeders and multipliers. Specific heat of beryllium is larger than the other Li-containing ceramics except lithium oxide. "Thermal conductivity(3)(5003)" shows the results of measurement on thermal conductivity of beryllium produced by various methods. "Thermal expansion(5004)" shows that linear expansion and the coefficient of expansion are formularized as follows.

$$\Delta\ell/\ell_0=8.43\times10^{-4}(1+1.36\times10^{-3}T-3.53\times10^{-7}T^2)(T-298) \quad (298\leqq T\leqq1500K)$$

$$\alpha=5.01\times10^{-6}(1+3.451\times10^{-3}T-1.979\times10^{-7}T^2) \quad (298\leqq T\leqq1500K)$$

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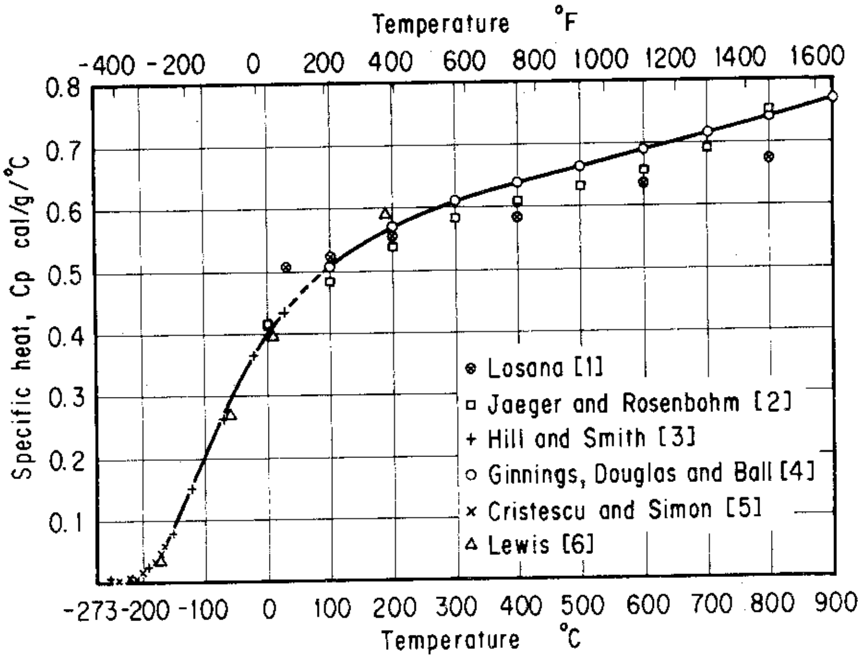
5001

Specific heat(1)

(1) Specific heat (Cp) in cal/K/mol in the range
298 − 1173K :

$$Cp = 4.54 + 2.12 \times 10^{-3} T - 0.82 \times 10^{5} T^{-2}$$

(T : temperature/K)



[1] Losana, L. : Alluminio, 8 (1939) 67.
[2] Jaeger, F. M. and Rosenbohm, E. : Proc. Acad. Sci. Amst., 37 (1934) 67.
[3] Hill, R.W. and Smith, P.L. : Phil. Mag., 44 (1953) 636.
[4] Ginnings, D.G., Douglas, T.B. and Ball, A.F. : J. Amer. Chem. Soc., 73 (1951) 1236.
[5] Cristescu, S. and Simon, F. : Z. phys. Chem., 25 (1934) 273.
[6] Lewis, E.J. : Phys. Rev., 34 (1929) 1575.

(1/1)

【Reference】
G.E. Darwin and J.H. Buddery : "Metallugy of the rarer metals -7 Beryllium", Butterworths Scientific Publications, London (1960) 170.

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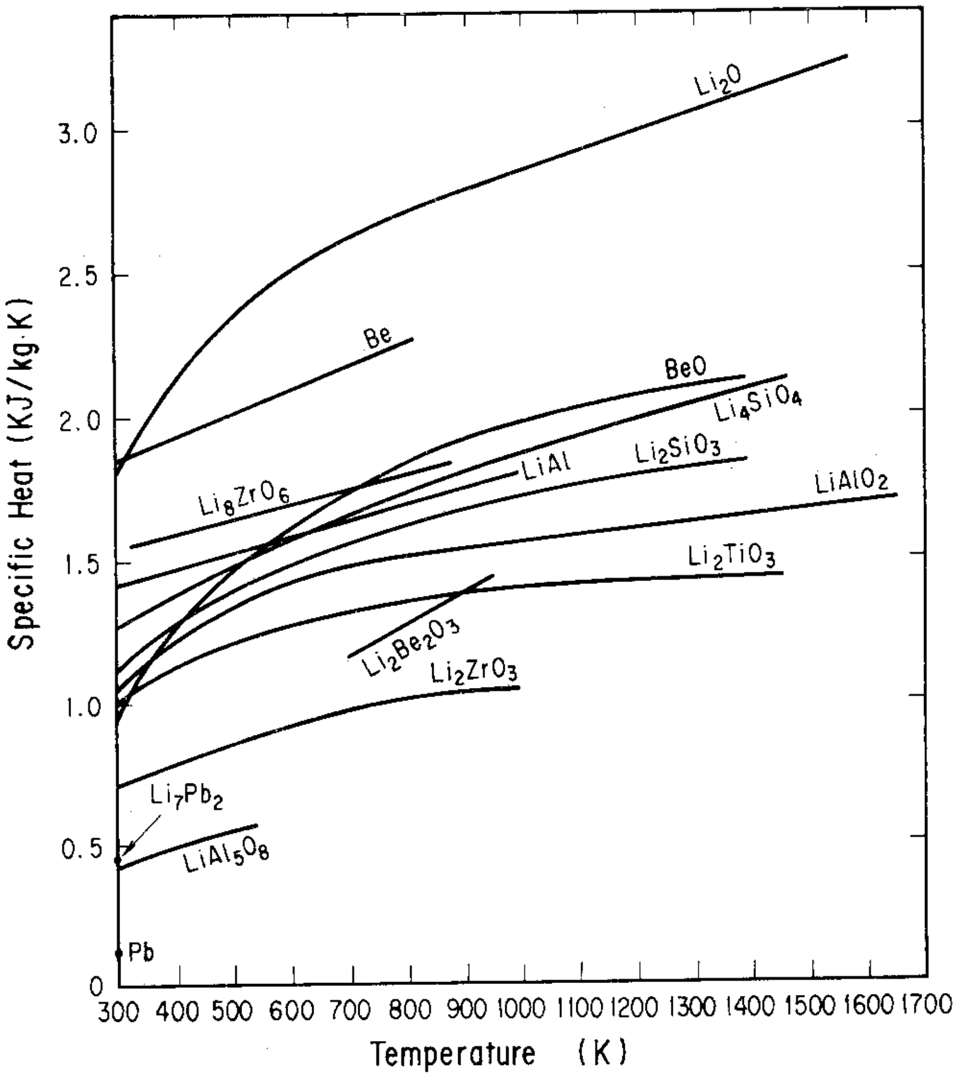
5002

Specific heat (2)



Specific heat for various solid breeder and multiplier materials

(1／1)

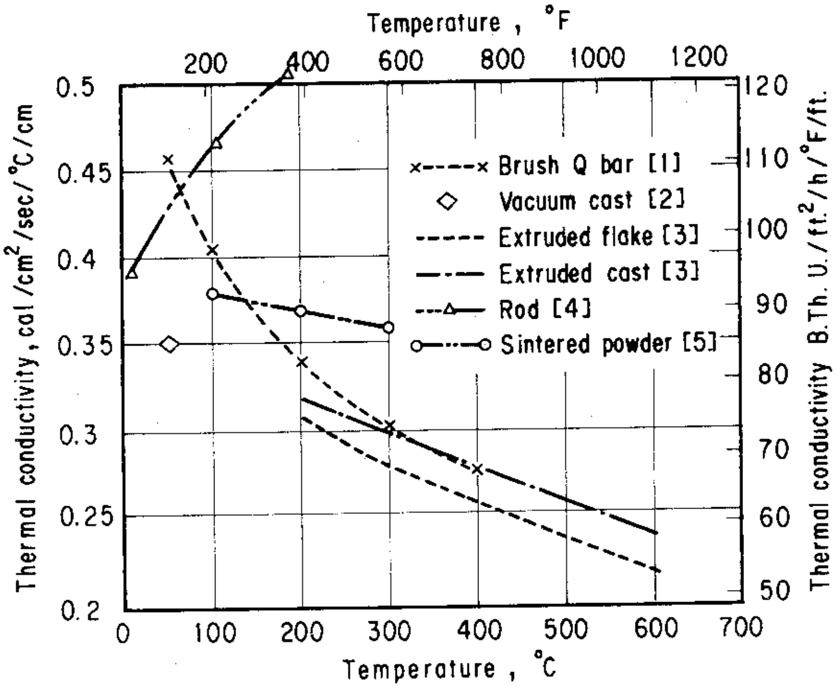
【Reference】

E.C. Bell et al. : UCAL-ENG-86-44, "Modeling, analysis and experiments for fusion nuclear technology", (1987).

JMTR

5003

Thermal conductivity (1)



[1] Powell, R.W. : Phil. Mag., 44 (1953) 645.

[2] Lockart, R. : U.S. Atom. En. Comm. Rep. No. KAPL-75 (1948).

[3] Grenell, L.H. et al. : U.S. atom. En. Comm. Rep. No. BMI-M3476 (1947).

[4] Lewis, E.J. : Phys. Rev., 34 (1929) 1575.

[5] Lillie, D.W. : The metal Beryllium (Ed. by D.W. White, Jr. and J.E. Burke), Chapter VIA : American Society for Metals, Cleveland, 1955.

(1/1)

【Reference】

G.E. Darwin and J.H. Buddery : "Metallugy of the rarer metals -7 Beryllium", Butterworths Scientific Publications, London (1960) 171.

5004

Thermal expansion

(1) Linear expansion (%) :

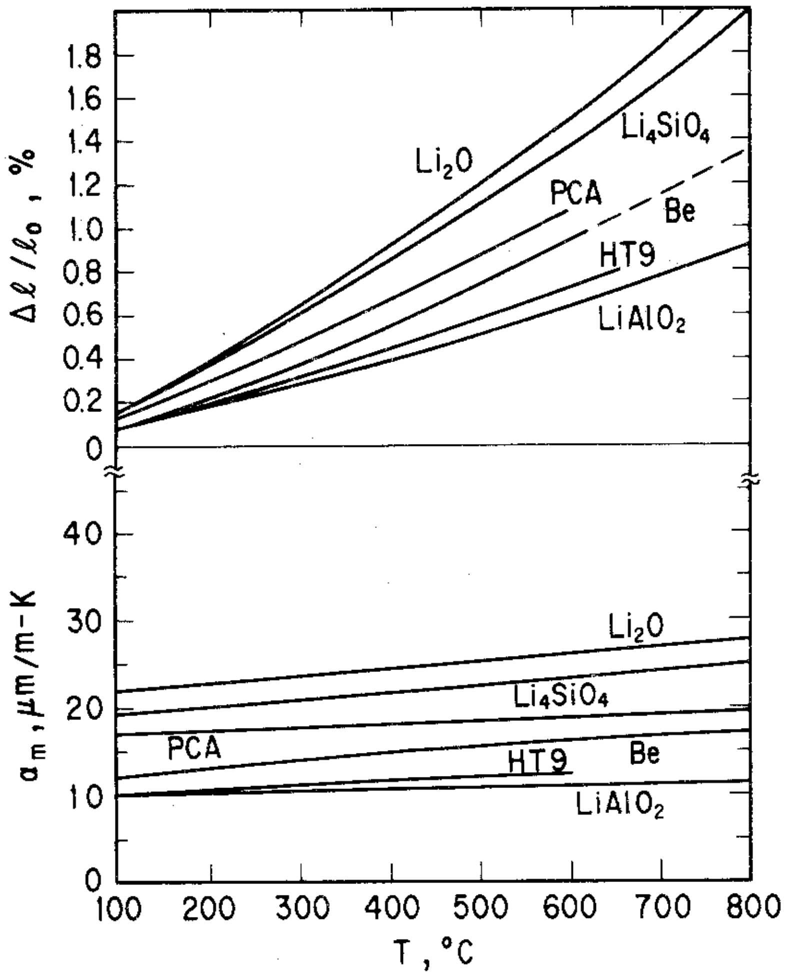
$$\Delta \ell / \ell_0 = 8.43 \times 10^{-4} (1 + 1.36 \times 10^{-3} T - 3.53 \times 10^{-7} T^2)(T - 298)$$

$(298 \leq T \leq 1500\,K)$

(2) Instantaneous coefficient (1/K) :

$$\alpha = 5.01 \times 10^{-6} (1 + 3.451 \times 10^{-3} T - 1.979 \times 10^{-7} T^2)$$

$(298 \leq T \leq 1500\,K)$



(1／1)

【Reference】

Y. S. Touloukian et al. : "Thermal expansion : metallic elements and alloys", Vol. 12 , Thermophysical properties of matter , IFI / Plenum (New York) 1975.

7. Physical Properties

"Physical properties(6001)" shows various physical properties on beryllium. "Properties of isotopes(6002)" shows the properties on beryllium isotopes. "Lattice parameters(6003)" shows lattice parameters of beryllium at various temperatures. "Relative sizes of common hexagonal unit cells(6004)" shows that relative size of common hexagonal unit cells on beryllium is smallest in the other elements. "Density of candidate solid breeder and multiplier materials(6005)" shows the densities of solid breeder and multiplier materials. "Interstitials in the hcp structure(6006)" shows the hcp interstitials into which atoms can be inserted. "Electronegativity plotted versus the atomic radius(6007)" shows the relation between atomic radius and electronegativity on various elements. The atomic radius and electronegativity of beryllium, are smaller than other elements. "Crystallographic planes and directions (6008)" shows crystallographic planes and directions which most influence deformation and fracture at room temperature. "Thermal expansion(6009)" shows the linear expansion and instantaneous coefficient of several kinds of blanket materials. "Vapor pressure(6010)" shows that vapor pressure of beryllium is formularized as follows,

$$\log P(\mathrm{atm})=6.186+1.454\times10^{-4}T-(16734\pm80)T^{-1},$$

$$\log P(\mathrm{Torr})=6.494-11710T^{-1} \quad (1577\text{-}2058^\circ\mathrm{C})$$

"Electrical resistivity(6011)" shows the electrical resistivities of beryllium made by various different production methods. "Effect of vacuum annealing on surface characteristics(6012)" shows the effect of vacuum annealing temperature on surface composition of beryllium. "X-ray diffraction data(6013-6014)" shows X-ray diffraction data on beryllium, beryllium oxide and $Li_2Be_2O_3$.

6001

Physical properties

Physical properties of beryllium

Atomic number	: 4
Atomic weight	: 9.0122
Crystal structure	
Hexagonal close-packed	: σ=2.854, c=3.5829, c/a=1.5677
Body-centered cubic (above 1254°C)	: σ=2.550
Density	: 1.8477 g/cm^3
Melting point	: 1287°C
Boiling point	: 2472°C
Vapor pressure	: $\log P(atm)=6.186+1.454\times10^{-4}T-16734T^{-1}$
Heat of fusion	: 2.8 kcal/g atom
Heat of sublimation	: 76.56 kcal/mol
Heat of evaporation	: 53.55 kcal/mol
Specific heat	: $Cp=4.54+2.12\times10^{-3}T-0.82\times10^{3}T^{-3}$ cal/K/mol
Thermal expansion	: 11.5×10^{-6}/℃ (0−50°C)
Entropy 25°C	: 2.28 cal/℃/mol
Enthalpy 25°C	: 465 cal/mol
Electrical resistivity	: 4.31 μΩ cm
Magnetic suscepubility (293 K)	: -1.00×10^{-9} m^3/kg
Velocity of sound	: 12600 m/s
Volume contraction on solidification	: 3 %

(1/1)

【Reference】

A. James Stonehouse : "Physics and chemistry of beryllium", J. Vac. Sci. Technol. A, 4, 3 (1986) 1163.

JMTR

6002

Properties of isotopes

Properties of Isotopes [1,2]

Isotope	No. of neutrons N	Mass	Packing fraction	Average binding energy per nucleon MeV	Half life	Mode of decay	Energy of radiation MeV	Q value MeV	Method of production
Be^6	2	6.0219	0.00365	4.41	0.4sec	Uncertain	—		
Be^7	3	7.01916	0.00274	5.33	53 days	Electron capture	0.477γ	0.863	$Li^6(d,n)$, $B^{10}(p,\alpha)$
Be^8	4	8.00785	0.00098	7.02	$\sim 10^{-16}$ sec	2α	0.047α	0.094	$Be^9(\gamma,n)$, $Be^9(n,2n)$
Be^9	5	9.01504	0.00167	6.42	Stable	—	—	—	Natural
Be^{10}	6	10.1677	0.00168	6.45	2.5×10^6 years	β^- (no γ)	0.557β	0.557	$Be^9(n,\gamma)$, $Be^9(d,p)$

[1] Strominger D., Hollander J. M. and Seaborg G. T. : Rev. mod. Phys., 30 (1958) 585.
[2] Udy M. C., Shaw H. L. and Boulger F. W. : Nucleonics, 11 (1953) 52.

(1/1)

【Reference】
G. E. Darwin and J. H. Buddery : "Metallugy of the rarer metais − 7 Beryllium", Butterworths Scientific Publications, London (1960) 164.

JMTR

6003

Lattice parameters

(1) Lattice parameters of beryllium[1]

$a_0 = 2.2854$ Å
$C_0 = 3.5829$ Å
$c/a = 1.5677$

Effect of temperature on the lattice parameters and calculated values of the true and the mean coefficients of thermal expansion.[2]

Temperature °C	a_0 Å	C_0 Å	c/a	Coefficient of expansion $\times 10^6$/°C			
				True $\alpha_\perp$	True $\alpha_\parallel$	Mean $\alpha_\perp$	Mean $\alpha_\parallel$
50	2.287	3.585	1.5679	11.7	9.4	10.7	8.7
100	2.288	3.587	1.5676	14.7	10.8	12.6	9.6
200	2.292	3.591	1.5670	16.7	13.1	14.7	11.0
300	2.296	3.596	1.5664	18.2	14.4	15.7	12.1
400	2.300	3.601	1.5658	19.1	14.9	16.5	12.8
500	2.304	3.607	1.5652	20.1	15.6	17.2	13.3
600	2.309	3.613	1.5646	20.6	16.5	17.8	13.8
800	2.319	3.625	1.5633	22.0	18.3	18.7	14.8
1000	2.330	3.639	1.5620	—	—	19.7	15.8

$\alpha_\perp$; coefficient perpendicular to the hexagonal axis
$\alpha_\parallel$; coefficient parallel to the hexagonal axis

[1] Kaufmann A.R., Gordon P. and Lillie D.W. : Trans. Amer. Soc. Metals, 42 (1950) 785.

[2] Gordon P. : J. appl. Phys., 20 (1949) 908.

(1/1)

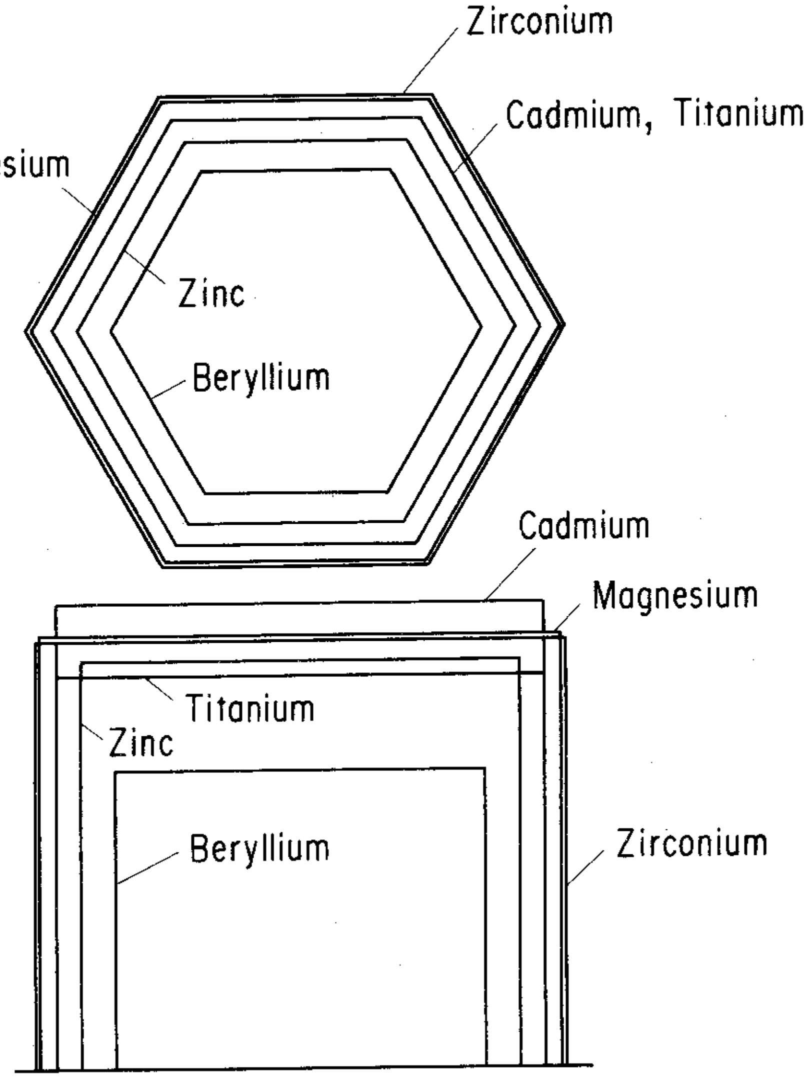
【Reference】

G.E. Darwin and J.H. Buddery : "Metallugy of the rarer metals -7 Beryllium", Butterworths Scientific Publications, London (1960) 165.

JMTR

6004

Relative sizes of common hexagonal unit cells



(1/1)

【Reference】
The Institute of Metals : "The Metallurgy of Beryllium/Proc. of an International Conference organized by the Institute of Metals in London", Chapman & Hall Ltd., London(1963)12.

JMTR

6005

Density of candidate solid breeder and multiplier materials

Material	Phase	Temperature (°C)	Density Total	(g/cm³)[a] Lithium
Li_2O	—	25	2.01	0.94
$LiAlO_2$	γ	25	2.55	0.27
Li_5AlO_4	β	25	2.22	0.61
Li_2SiO_3	—	25	2.52	0.39
Li_4SiO_4	α	25	2.39	0.55
	γ	665	2.21	0.51
Li_2ZrO_3	mono	25	4.15	0.38
Li_8ZrO_6	—	25	3.01	0.69
Li_2TiO_3	β	25	3.43	0.43
	γ	1150	2.57	0.32
$Li_2Be_2O_3$	—	25	2.54	0.43
Li_7Pb_2	—	25	4.59	0.48
BeO	—	25	3.0	0
Be	—	25	1.85	0
Zr_5Pb_3	—	25	9.69	0

[a] 100% theoretical density

(1／1)

【Reference】

E.C. Bell et al. : UCLA-ENG-86-44, "Modeling, analysis and experiments for fusion nuclear technology" (1987).

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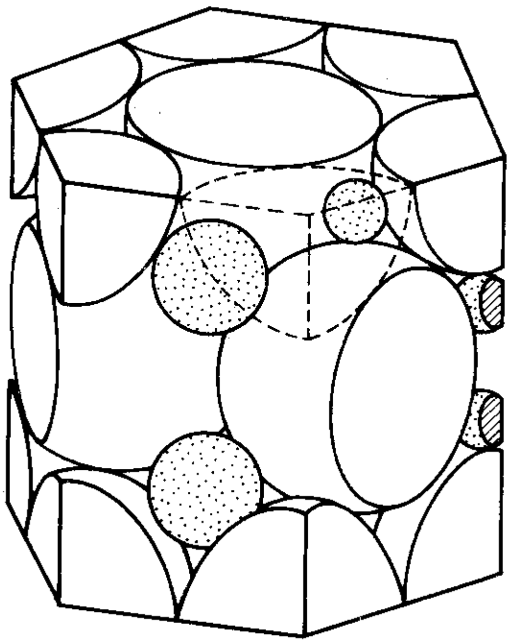
6006

Interstitials in the hcp structure



(1／1)

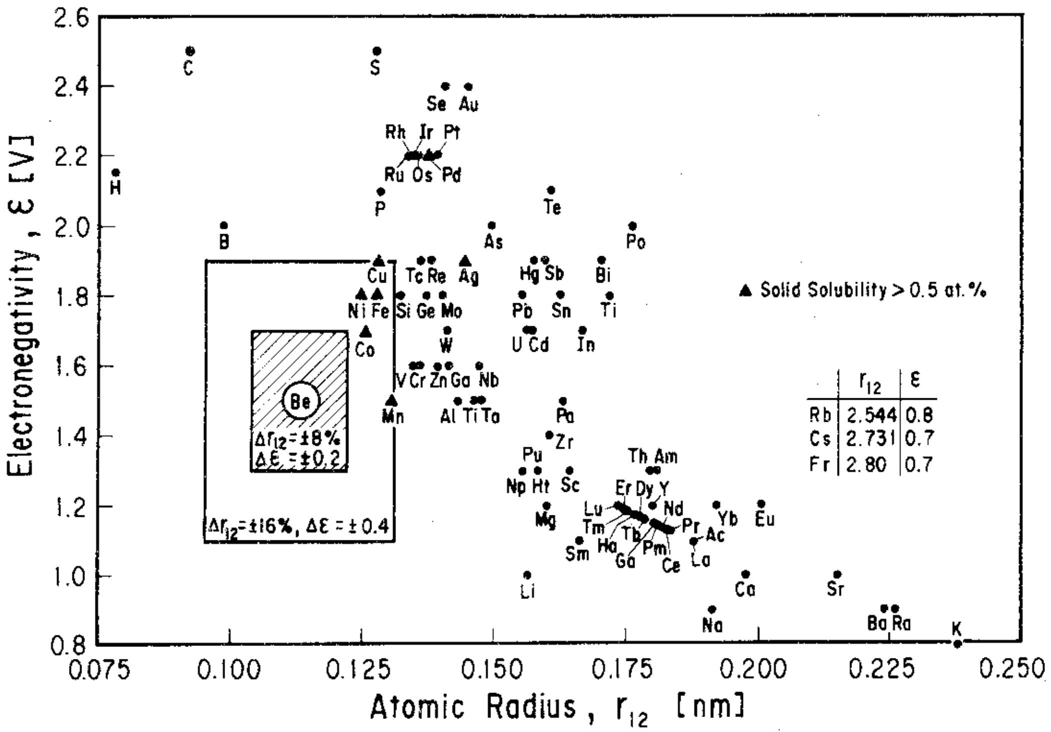
【Reference】

D. Webster and G. J. London : "Beryllium Science and Technology / Volume 1", Plenum Press, New York (1979) 248.

JMTR

6007

Electronegativity plotted versus the atmic radius



(1／1)

【Reference】

D. Webster and G. J. London : "Beryllium Science and Technology / Volume 1", Plenum Press, New York (1979) 248.

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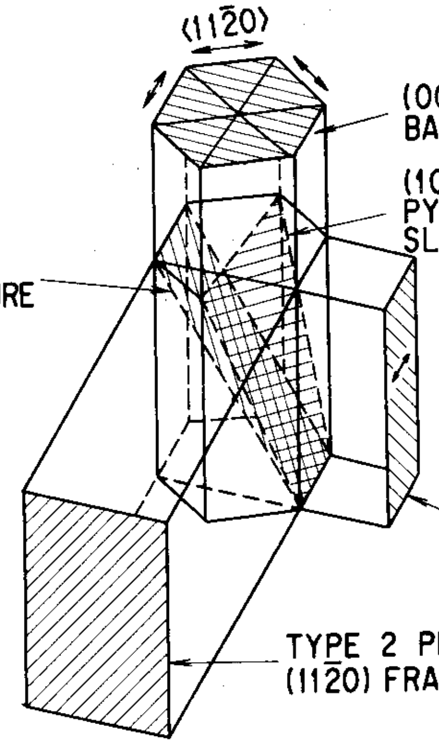
6008

Crystallographic planes and directions



Crystallographic planes and directions that influence most room temperature deformation and failure

(1/1)

【Reference】

D. Webster and G.J. London: "Beryllium Science and Technology / Volume 1", Plenum Press, New York (1979) 119

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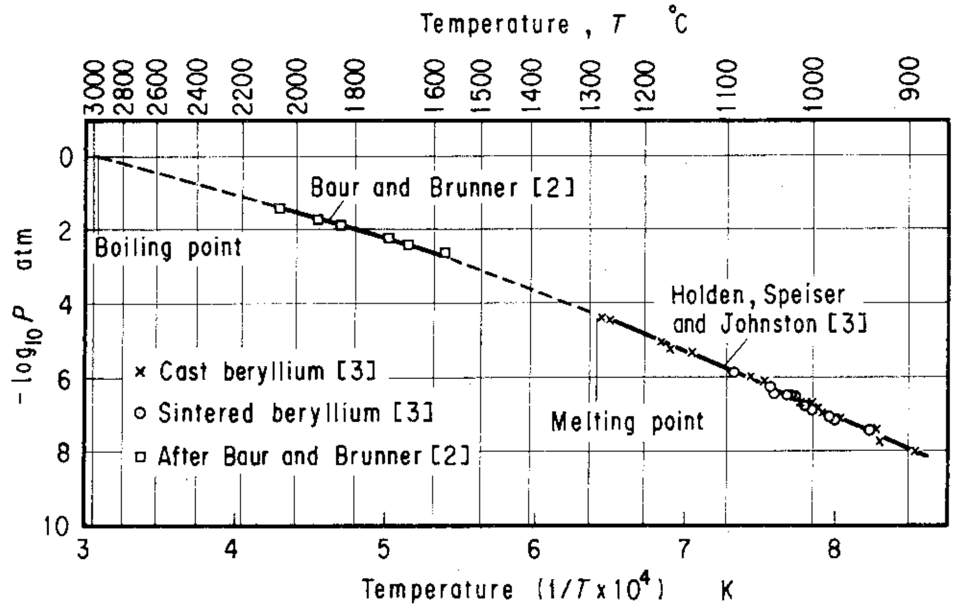
6009

Vapour pressure

(1) Vapour pressure of beryllium below the melting point
$\log P\,(\mathrm{atm}) = 6.186 + 1.454 \times 10^{-4} T - (16734 \pm 80)\, T^{-1}$ [1]

(2) Vapour pressure of beryllium in the region 1577-2058 °C
$\log P\,(\mathrm{Torr}) = 6.494 - 11710\, T^{-1}$ [2]

(T : temperature / K)



[1] Gulbransen E. A. and Andrew K. F. : J. Electrochem. Soc., 97 (1950) 383.
[2] Baur E. and Brunner R. : Helv. Chim. Acta, 17 (1934) 958.
[3] Holden R.B., Speiser R. and Johnston H. L. : J. Amer. Chem. Soc., 70 (1948) 3897.

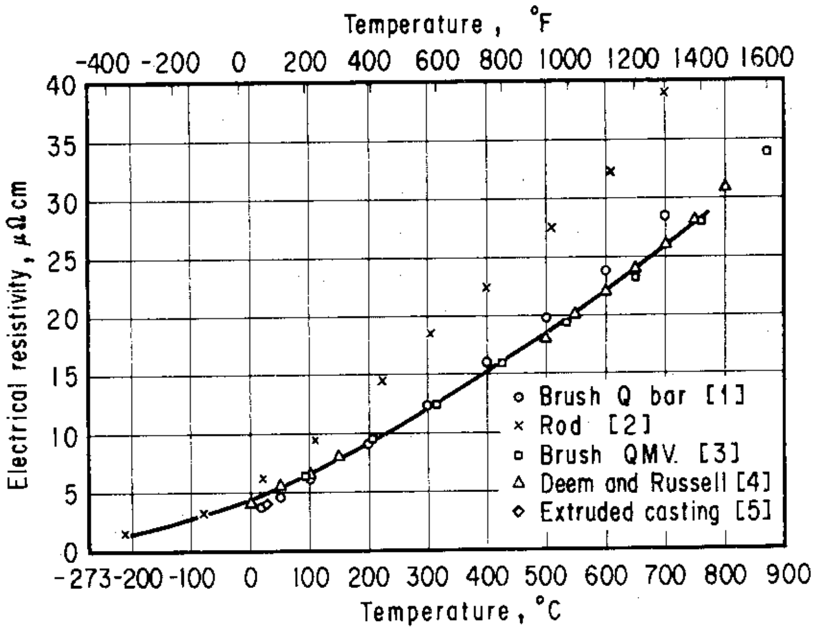
(1／1)

【Reference】
G.E. Darwin and J.H. Buddery : "Metallugy of the rarer metals - 7 Beryllium", Butterworths Scientific Publications, London (1960) 168.

JMTR

6010

Electrical resistivity



[1] Powell, R.W. : Phil. Mag., 44 (1953) 645.
[2] Lewis, E.J. : Phys. Rev., 34 (1929) 1575.
[3] Lampson, F.K. : U.S. Atom. En. Comm. Rep. No. NEPA−1860 (1951).
[4] Udy, M.C. : Nucleonics, 11 (1953) 52.
[5] Gordon, P. : U.S. Atom. En. Comm. Rep. No. NDDC−1370, CT-3315 (1945).

(1/1)

【Reference】
G.E. Darwin and J.H. Buddery : "Metallugy of the rarer metals-7 Beryllium", Butterworths Scientific Publications, London (1960) 172.

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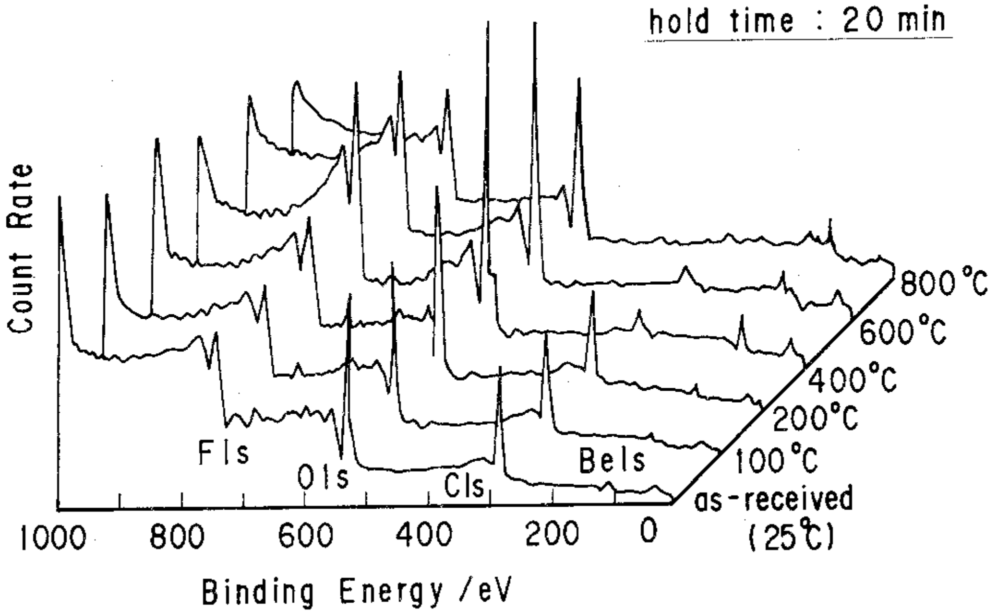
6011

Effect of vacuum annealing on surface characteristic

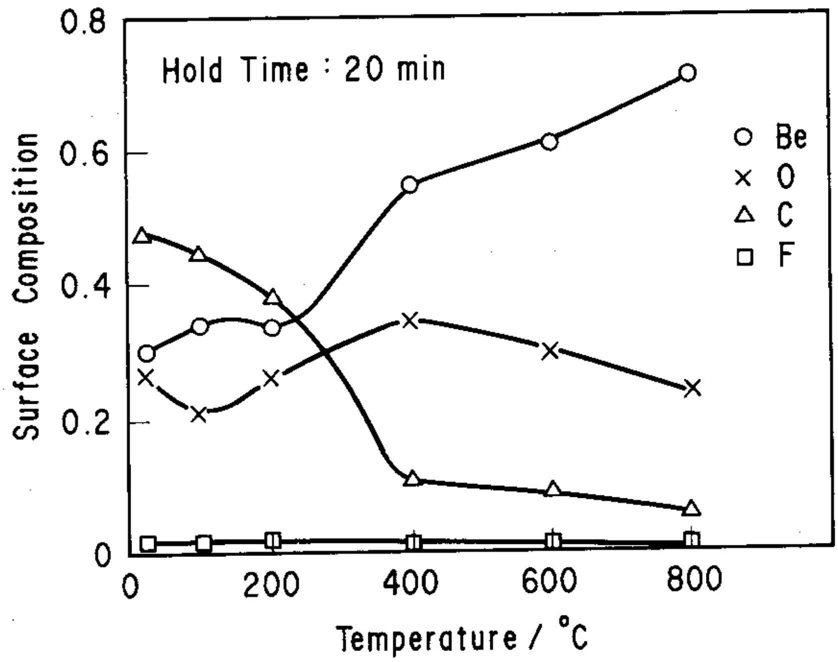


XPS spectra for the as-received hot-pressed beryllium and those after vacuum annealing

XPS conditions

Range	Wide	Narrow
Pass Energy [eV]	100	25
Time Constant [s]	1	1
Full Scale [kcps]	10	1
SEM Voltage [kV]	2.8	2.8
Sweep Rate [eV/s]	2	0.04
Iteration	2	2

(1／2)



Changes in the surface composition of hot-pressed beryllium with vacuum annealing

(2／2)

【Reference】
E. Ishitsuka, H. Kawamura et al. : "Surface characterization of hot-pressed beryllium with X-ray photoelectron spectroscopy", Ann. Rept. Tritium Res. Centr. Toyama Univ., 8 (1988) 61.

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6012

X-ray diffraction data of beryllium

1 − 1291 MAJOR CORRECTION

3762 d 1-1291	1.73	1.97	1.79	1.97	Be
I/I_1 1-1291	100	20	14	20	Berllium

Rad MoKα λ 0.709 Filter ZrO_2
Dia. 16 Inohes Cut off Coll.
I/I_1 Calibrated atrips d corr.abs.? No.
Ref. H

Sys. Hexagonal S.G. D_{6H}^4 − $P6_3/mmc$
a_0 2.2859 b_0 C_0 3.5843 A C 1.5680
α β γ Z 2
Ref. Gordon, J. Appl. Phys. 20, 908 (1949)

εα nωβ εγ Sign
2V D 1.85[20] mp 1280 Color Grayish white
Ref. C.C.

B.P. 2780

d Å	I/I_1	hkl	d Å	I/I_1	hkl
1.97	20	10.0			
1.79	14	00.2			
1.73	100	10.1			
1.33	12	10.2			
1.14	12	11.0			
1.02	12	10.3			
0.98	2	20.0			
.96	8	11.2			
		Indexed by SW			

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(1/3)

JMTR

CALCULATED PATTERN - PEAK HEIGHT C

22 - 111

1.73	1.98	1.79	100	30	25

Be, alpha form

Beryllium

Ref. National Bureau of Standards, Mono. 25, Sec. 9 (1971)

Sys. Hexagonal S.G. $P6_3/mmc$ (194) Dx 1.845 Z 2
a_0 2.2859±0.002* b_0 c_0 3.5844±0.003*
α β γ
Ref. Mckay and Hill, J. Nucl. Mat., 8 263 (1963)
*published values : 2.2858 and 3.5843

Scale factor (Integrated Intensities) 0.0005998 x 10^4
λ 1.54056

d A	I/I_0	h k l	d A	I/I_0	h k l	d Å	I/I_0	h k l
1.9795	30	100	1.0230	8	103	.8664	1	202
1.7925	25	002	0.9898	1	200	.8163	1	104
1.7330	100	101	.9636	8	112			
1.3287	9	102	.9541	6	201			
1.1430	9	110	.8961	1	004			

CALCULATED PATTERN - INTEGRATED C

22 - 111A

1.73	1.98	1.79	100	28	25

Be, alpha form

Beryllium

Ref. National Bureau of Standards, Mono. 25, Sec. 9 (1971)

Sys. Hexagonal S.G. $P6_3/mmc$ (194) Dx 1.845 Z 2
a_0 2.2859±0.002* b_0 c_0 3.5844±0.003*
α β γ
Ref. Mckay and Hill, J. Nucl. Mat., 8 263 (1963)
*published values : 2.2858 and 3.5843

Scale factor (Integrated Intensities) 0.0005998 x 10^4
λ 1.54056

d A	I/I_0	h k l	d A	I/I_0	h k l	d Å	I/I_0	h k l
1.9797	28	100	1.0229	12	103	.8665	3	202
1.7922	25	002	0.9898	2	200	.8164	3	104
1.7329	100	101	.9637	14	112			
1.3286	11	102	.9541	10	201			
1.1429	12	110	.8961	2	004			

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(2/3)

JMTR

38 - 780 ★

Be

Beryllium

Rad. MoK_{α} λ 0.7107 Filter Zr d-sp D.S.-57.3
Cut off Int. $I/I_{cor.}$
Ref. Ming. L., Manghnani, J. Phys. F, 14 L1 (1984)

Sys. Hexagonal S.G.
a 4.328(13) b c 3.416(10) A C 0.7893
α β γ Z 8 mp
Ref. Ibid.

D_x 2.160 D_m SS/FOM F_6 = 537.7 (.0012, 9)

Pattern at 28.3 GPa and ambient temperature. Phase II.

d Å	Int	hkl	d Å	Int	hkl
2.525	5	011			
2.164	5	110			
1.874	30	200			
1.708	15	002			
1.643	100	201			
1.554	70	102			

(3／3)

【Reference】

Powder Diffraction File (Joint Committee on Powder Diffraction Standards) 1990.

JMTR

6013

X-ray diffraction data of beryllium oxide

20 − 164

d	2.38	2.13	1.38	3.35	β- BeO
I/I_1	100	60	30	10	Beryllium Oxide

Rad. CuKα λ 1.5418 Filter Ni Dia.
Cut off I/I_1 Diffractometer
Ref. Smith, Cline and Austerman, Acta Cryst., 18, 3, 393−97 (1965)

Sys. Tetragonal S.G. $P4_2/mnm$ (136)
a_0 4.75 b_0 c_0 2.74 A C
α β γ Z Dx 2.69
Ref. Ibid.

εα nωβ εγ Sign
2V D 2.82 mp Color
Ref. Ibid.

High temperature modification. Data collected at 2100°C.

d Å	I/I_1	hkl	d Å	I/I_1	hkl
3.35	10	110			
2.375	100	101,020			
2.125	60	120,111			
1.676	20	121,220			
1.500	10	130			
1.370	30	031,002			
1.316	6	012,131+			
1.187	10	022,231+			
1.152	2	122,410			
1.118	2	330			
1.062	2	141,240+			
0.897	2	341,013+			
.882	2	151,142+			
.868	2	332			
.840	2	251,123+			

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(1/2)

JMTR

35-818 ★

BeO	d Å	Int	hkl	d Å	Int	hkl
Beryllium Oxide — Bromellite, syn	2.3370	85	100			
	2.1888	56	002			
	2.0615	100	101			
	1.5975	19	102			
Rad. CuK_{α_1} λ 1.540598 Filter Mono. d-sp Diff.	1.3493	28	110			
Cut off 17.7 Int. Diffractometer $I/I_{cor.}$	1.2378	22	103			
Ref. Nat. Bur. Stand. (U.S.) Monogr., 21 (1984)	1.1683	4	200			
	1.1486	14	112			
Sys. Hexagonal S.G. $P6_3mc$ (186)	1.1288	4	201			
a 2.69808(8) b c 4.3785(2) A C 1.6228	1.0948	1	004			
α β γ Z 2	1.0309	2	202			
Ref. Ibid.	0.9913	<1	104			
	0.9120	5	203			
D_x 3.009 D_m 3.020 mp	0.8832	2	210			
εα nωβ 1.719 εγ 1.733 Sign + 2V	0.8657	2	211			
Ref. Dana's System of Mineralogy	0.8500	1	114			
Color Colorless	0.8200	5	105			
The temperature of data collection was approximately 25.0 C. The sample was obtained from Alfa Products, Thiokol/Ventron Division, Danvers, Massachusetts, USA. CAS#: 1304-56-9. $\sigma(I_{obs}) = \pm 1$. Wurtzite group, Zincite subgroup. F_{18} = 138.5 (0.007, 18). Silicon used as internal standard. PSC: hP4. To replace 4-843.	0.8190	2	212			

(2／2)

【Reference】

Powder Diffraction File (Joint Committee on Powder Diffraction Standards) 1990.

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JMTR

6014

X-ray diffraction data of $Be_2Li_2O_3$

20 - 160

d	2.43	7.30	1.44	7.30	$Be_2Li_2O_3$ ★
I/I_1	100	45	25	45	Beryllium Lithium Oxide

Rad. CuK_α λ 1.5418 Filter Ni Dia.
Cut off I/I_1 Diffractometer
Ref. Turner and Bertram, Inorg. Chem., 6, 4, 833-35 (1967)

Sys. Monoclinic S.G.
a_0 14.89 b_0 5.020 c_0 8.547 A C
α β 101.6° γ Z 12 Dx 2.54
Ref. Ibid.

εα nωβ εγ Sign
2V D 2.52 mp Color
Ref. Ibid.

d A	I/I_1	hkl	d A	I/I_1	hkl
7.30	45	200	2.070	6	420
4.31	6	011	2.037	6	611,313
4.02	10	111	2.002	2	222
3.90	10	$21\bar{1}$	1.902	2	$520,61\bar{3}$
3.64	20	400	1.820	20	800
3.55	2	211	1.774	2	$60\bar{4},422$
3.35	2	202	1.746	16	$620,81\bar{1}$+
3.08	10	$40\bar{2},311$	1.722	16	513
2.940	6	$41\bar{1}$	1.614	2	$23\bar{1}$
2.646	6	411	1.602	6	$720,32\bar{4}$+
2.515	10	020	1.587	6	$231,72\bar{2}$
2.481	16	$120,11\bar{3}$	1.560	2	802
2.429	100	600	1.474	6	$100\bar{2}$,911+
2.377	6	220	1.459	2	1000,324+
2.340	6	113	1.443	25	$13\bar{3},23\bar{3}$+
2.231	16	320	1.425	10	$722,20\bar{6}$
2.219	2	$61\bar{1},41\bar{3}$	1.361	10	$101\bar{3}$,920
2.192	16	213	1.348	10	$813,53\bar{3}$
2.170	2	$12\bar{2}$			
2.098	6	004,122			

(1／1)

【Reference】

Powder Diffraction File (Joint Committee on Powder Diffraction Standards) 1990.

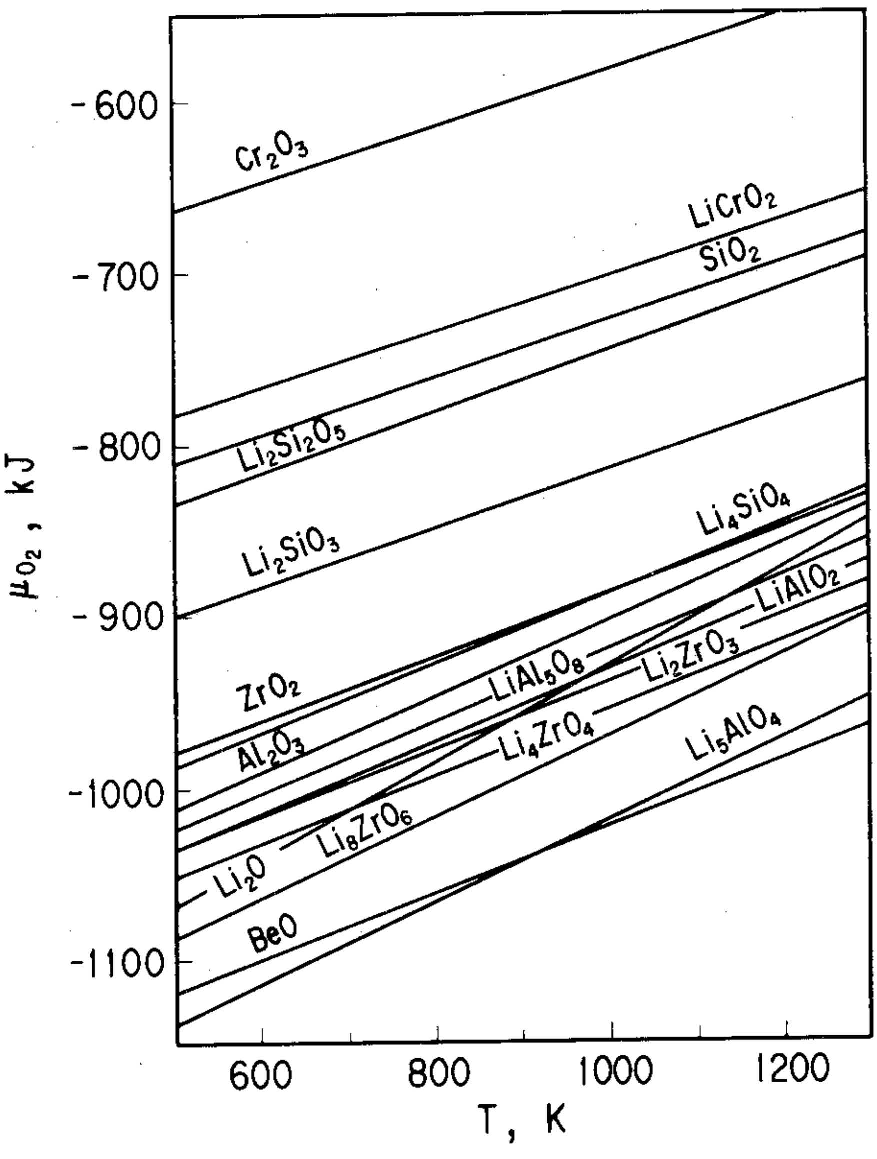
8. Chemical Properties

"Oxygen potential of formation(7001)" shows oxygen potential of formation for Li-containing ceramics and beryllium oxide, etc. From this result, it is clear that the oxygen potential of formation for beryllium oxide is lower than all Li-containing ceramics except Li_5AlO_4. Gibbs free energies of compounds(7002)" shows Gibbs free energies of compounds including beryllium oxide. "Free enthalpy of formation values of breeder and multiplier(7003)" shows free enthalpy of formation values of breeder and multiplier in the temperature range of 600-1200K and 1200-1600K. "Compatibility with SUS316L and 1.4914(7004)" shows that the threshold temperature on reactions between beryllium and SUS316L, and between beryllium and 1.4919 stainless steel are 580°C and 650°C, respectively. "Compatibility with AISI 316(7005)" shows that stratified reaction products were recognized on contacting interface. From this result, it is clear that NiBe is produced on the surface of AISI316L. "Compatibility with Li_2SiO_3(7006)" shows that uniform and localized attack is recognized on contacting interface. Both reactions depend on diffusion. "Compatibility with lithiated ceramics(7007)" shows the compatibility of beryllium and beryllium calcium alloy with Li-containing ceramics. "Compatibility with stainless steel and lithiated ceramics(7008)" shows the results of compatibility test of beryllium with $LiAlO_2$ and Li_2SiO_3, beryllium with 316L, and HT9 and 1.4914. "Thermochemistry in the system Li-Al-Be-O(7009)" shows the possibility of producing $Li_2Be_2O_3$ from BeO and Li_2O below 900°C. "Tentative phase diagram of beryllia-lithia system(7010)" shows that eutectic point, i.e. melting point is about 750°C. "Parabolic oxidation (7011)" shows that the oxidation progresses in accordance with parabolic law at various temperatures. "Catastrophic oxidation(7012)" shows that oxidation rate increase considerably immediate after oxidation.

JMTR

7001

Oxygen potential of formation



(1／1)

【Reference】

O. Götzmann : "Thermodynamics of ceramic breeder materials for fusion reactors", J. Nucl. Mater., 167 (1989) 213.

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JMTR

7002

Gibbs free energies of compounds

(1) ΔG° (kcal/mol) = a + b (T/10^3)
(700-1000 K)

[1]

Compound (crystalline or gaseous)	a	b	Compound (crystalline or gaseous)	a	b
AlF_3	-359.73	51.82	SiF_4	-386.26	34.71
BeF_2	-243.47	31.5	ThF_4	-477.0	65.8
CF_4	-223.30	36.54	UF_4	-452.0	67.4
CaF_2	-291.25	32.83	ZrF_4	-453.7	75.7
CeF_3	-417.83	57.59	BeO	-146.02	24.94
CrF_2	-182.0	34.2	Cr_2O_3	-270.79	61.64
FeF_2	-168.62	32.98	CuO	- 37.73	18.3
HF	- 65.19	-1.01	FeO	- 62.71	15.15
KF	-135.65	20.47	NiO	- 56.26	20.35
LiF	-146.50	23.11	SiO_2	-216.55	42.10
MgF_2	-268.46	41.4	ThO_2	-292.40	44.55
NaF	-137.46	21.11	UO_2	-258.0	40.0
NiF_2	-156.33	37.65	ZrO_2	-260.44	44.44
PuF_3	-370.0	57.5			

(2) ΔG° (kJ/mol)

[2]

T(K)	Li_5AlO_4	$LiAl_5O_8$	Li_9Al_4	Li_3Al_2	LiAl	$Be_3Al_2O_6$	$BeAl_2O_4$	$BeAl_6O_{10}$	$Li_2Be_2O_3$
500	2463	4673	406.7	172.3	64.69	3589.9	2343.3	5775.7	1874
600	2491	4711	444.1	185.1	72.09	3612.5	2358.2	5817.8	1887
700	2523	4750	-	198	79.54	3638.8	2376.2	5856.1	1908
850	2575	4807	-	-	90.63	3684.7	2406.8	5930.8	1942
900	2599	4827	-	-	94.35	3702.0	2418.4	5959.3	1954
1000	2642	4865	-	-	-	3738.2	2442.4	6018.0	1979

(1／1)

【Reference】
[1] C.E. Bamberger : "Advances is molten salt chemistry, Vol. 3", Plenum Press, New York, 177.
[2] H. Migge : "Thermochemistry in the system Li-Aℓ-Be-O", J. Nucl. Mater., 155-157 (1988) 455.

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JMTR

7003

Free enthalpy of formation values of breeder and multiplier

Free enthalpy of formation values for temperatures between 600 and 1200 K [J/mol]

		Ref.
Li_2O	-604000 + 138 T	[1]
SiO_2	-904000 + 173 T	[1]
Al_2O_3	-1680000 + 320 T	[1]
ZrO_2	-1097100 + 187 T	[1]
Li_2SiO_3	-1656500 + 321 T	[2]
$LiAlO_2$	-1196000 + 222 T	[2]
Li_2ZrO_3	-1766500 + 323 T	[3]
Li_4SiO_4	-2328000 + 472 T	[3] a
$Li_2Si_2O_5$	-2578000 + 494 T	[2] a
Li_8SiO_6	-3556000 + 766 T	d
Li_5AlO_4	-2563000 + 500 T	d
$LiAl_5O_8$	-4580000 + 850 T	d
$Li_2Zr_2O_5$	-2878700 + 513 T	d
Li_4ZrO_4	-2385600 + 450 T	d
Li_8ZrO_6	-3608000 + 700 T	d
LiAl	-53400 + 20 T	[3]
Li_2Si	-82000 + 25 T	
Cr_2O_3	-1131000 + 255 T	[1]
$LiCrO_2$	-950000 + 193 T	[4] a
BeO	-608000 + 97 T	[1]
$Li_2Be_2O_3$	-1832000 + 344 T	d
Li_2BeSiO_4	-2290000 + 420 T	d

Note : d = determined ; a = adjusted.

[1] L.B. Pankrarz : "Thermodynamic properties of elements and oxides", US department of the interior, Bureau of mines (1982).
[2] JANAF thermochemical tables, NSRD-NBS-37, 1974 supplement.
[3] I.Barin et al. : Thermochemical propertise of inorganic substances (Springer-Verlag Berlin, Heidelberg, New York, 1973, and supplement 1977).
[4] T.B. Lindemer et al. : J. Nucl. Mater. 100 (1981) 178.

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(1/2)

JMTR

Free enthalpy of formation values for temperatures between 1200 and 1600K [J/mol]

			Ref.
Li_2O	−597 700 + 133T		[1]
Al_2O_3	−1690 000 + 329T		[1]
SiO_2	−901 200 + 171T		[1]
ZrO_2	−1091 000 + 182T		[1]
$LiAlO_2$	−1196 700 + 223T		[2]
Li_5AlO_4	−2548 000 + 490T		
$LiAl_5O_8$	−4604 000 + 870T		
Li_2ZrO_3	−1753 500 + 312T		
$Li_2Zr_2O_5$	−2860 000 + 497T		
Li_4ZrO_4	−2366 600 + 434T		
Li_8ZrO_6	−3577 000 + 647T	$1200 < T <\sim 1400$ K	
Li_2SiO_3 (s)	−1649 600 + 315T	$1200 < T < 1480$ K	[2]
Li_2SiO_3 (ℓ)	−1613 200 + 290T	$1480 \leqslant T \leqslant 1600$ K	[2]
Li_2SiO_3 (ℓ)	−1789 000 + 400T	$1600 < T \leqslant 1700$ K	[2]
Li_4SiO_4	−2313 000 + 462T	$1200 \leqslant T < 1530$ K	
$Li_2Si_2O_5$	−2562 000 + 483T	$1200 \leqslant T \leqslant 1300$ K	

[1] L.B. Pankrarz : "Thermodynamic properties of elements and oxides", US department of the interior, Bureau of mines (1982).

[2] JANAF thermochemical tables, NSRD-NBS-37, 1974 supplement.

(2/2)

【Reference】

O. Götzmann : "Thermodynamics of ceramic breeder materials for fusion reactors", J. Nucl. Mater., 167 (1989) 213.

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7004

Compatibility with 316L and 1.4914

(1) Test method : contact test

(2) Contact pressure : 1.5 x 10^4 Pa

(3) Atmosphere : under dynamic vacuum (0.5 to 1 Pa)

(4) Beryllium specimen : mechanical polished disks (ϕ20 x ^{t}10mm)

impurities 1000 − 5000 wtppm O

500 − 650 wtppm Aℓ

300 − 500 wtppm Fe

Interaction	Temps (°C)	Duration (h)	Material	Observed phenomenon	Thickness (μm)
316L / Be	550	3300	Be 316L	No interaction No interaction	
	580	500	Be 316L	Holes at the surface *1 Discontinuous zones of Be diffusion	0− 25 0− 10
	600	1500	Be 316L	Holes at the surface *1 Discontinuous zones of Be diffusion	0− 100 0− 40
	650	1500	Be 316L	Holes at the surface *1 Discontinuous zones of Be diffusion	0 − 100
	700	500	Be 316L	Holes at the surface *1 Discontinuous zones of Be diffusion	0 − 200 0 − 100
	700	500	Be Ca 316L	Holes at the surface *1 Discontinuous zones of Be diffusion	0 − 65
1.4914 / Be	550	3000	Be 1.4914	No interaction No interaction	
	600	1500	Be 1.4914	No interaction No interaction	
	650	1500	Be 1.4914	Holes at the surface *1 Discontinuous zones of Be diffusion	0 − 20
	700	500	Be 1.4914	Holes at the surface *1 Discontinuous zones of Be diffusion	0 − 20 0 − 30
	700	500	Be Ca 1.4914	Indented surface Discontinuous zones of Be diffusion	0 − 12

*1 Not directly related to affected parts of steel surface

(1／1)

【Reference】

A. Terlain et al. : "Proc. of the 15th symposium fusion technology, Netherlands , 1988", Fusion Technology, 2 (1988) 1179.

JMTR

7005

Compatibility with AISI 316

(1) Test method

① specimen

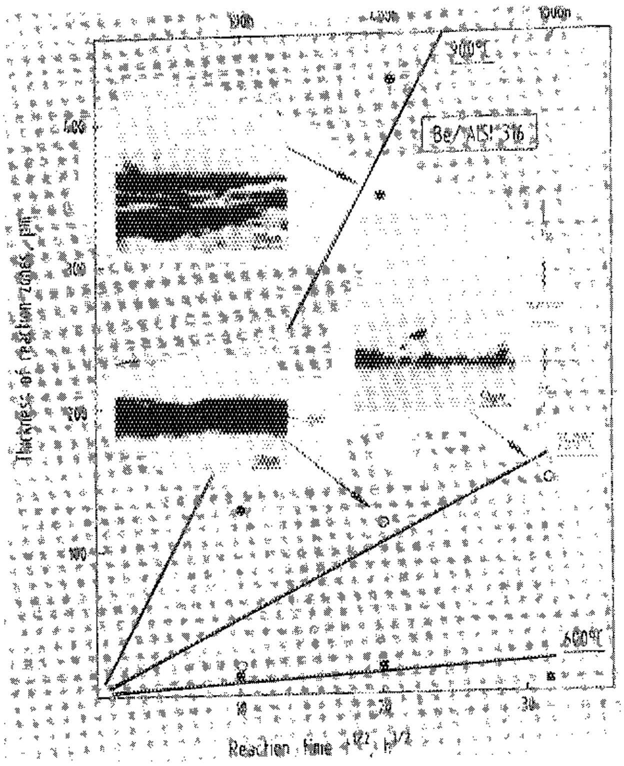
- Be disk : hot-pressed beryllium
- capsule material : AISI 316
- capsule-sealing gas : high purity argon

② annealing condition

- temperature : 600, 750 and 900°C
- time : 100, 400 and 1000h

③ analysis method

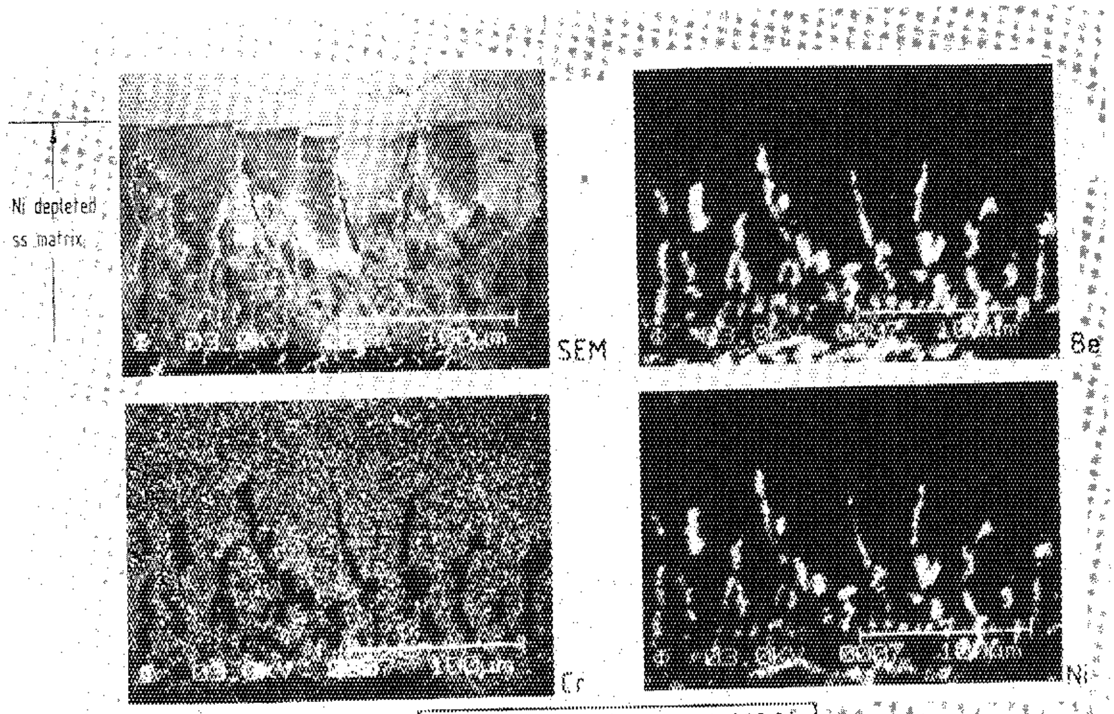
measurements of the layer thickness of the reaction products by the light microscope



Chemical interaction between Be and AISI 316

(1/2)

JMTR



Be/AISI 316, 900°/100h

Chemical interactions between Be and AISI 316 after 100h at 900℃. Auger electron spectroscopy analysis of the reaction zone indicates the formation of a BeNi compound.

(2/2)

【Reference】

P. Hofmann et al. : "Compatibility studies of metallic materials with lithium-based oxide", J. Nucl. Mater., 155-157 (1988) 485.

JMTR

7006

Compatibility with Li_2SiO_3

(1) Test method

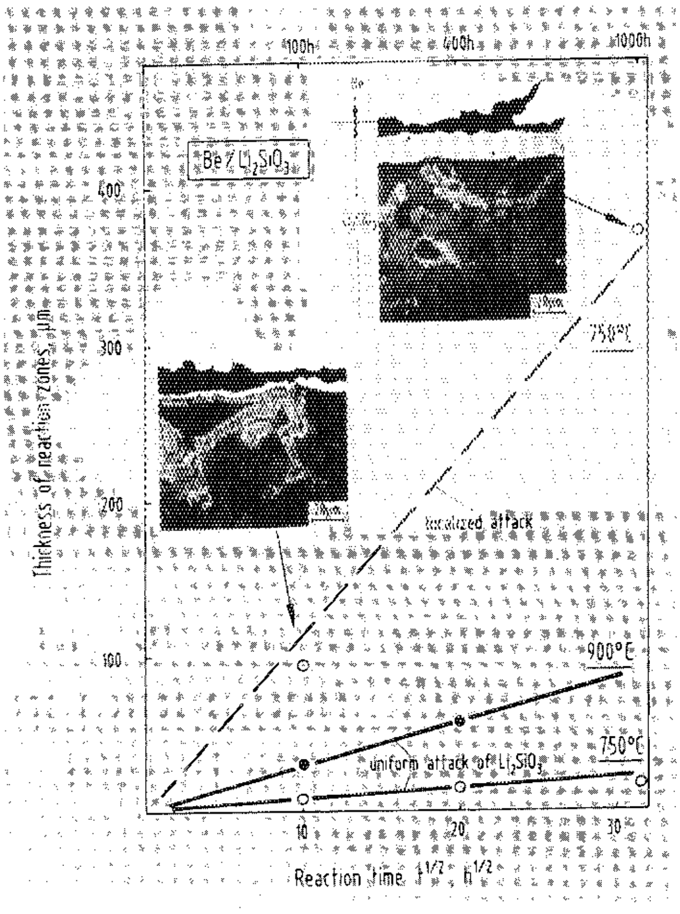
① specimen : Be disk and Li_2SiO_3 in high purity argon

② annealing condition

· temperature : 600, 750 and 900℃

· time : 100, 400 and 1000h

③ analysis method : measurement of the layer thickness of the reaction products by the light microscope



Chemical interaction between Be and Li_2SiO_3 (1／1)

【Reference】

P. Hofmann et al. : "Compatibility studies of metallic materials with lithium - based oxide", J. Nucl. Mater., 155-157 (1988) 485.

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JMTR

7007

Compatibility with lithiated ceramics

(1) Test method : contact test

(2) Contact pressure : 1.5×10^4 Pa

(3) Atmosphere : under dynamic vacuum (0.5 to 1 Pa)

(4) Beryllium specimen : mechanical polished disks ($^\phi 20 \times {}^t 10$ mm)

impurities 1000 - 5000 wtppm O
500 - 650 wtppm Aℓ
300 - 500 wtppm Fe

Interaction	Temp.(°C)	Duration (h)	Observed phenomenon	Thickness (μm)
Be/$LiAlO_2$ Be/Li_2SiO_3 Be/Li_4SiO_4	550	3000	Unchanged aspect of Be surface	
Be/$LiAlO_2$ Be/Li_2SiO_3	580	500	Unchanged aspect of Be surface	
Be/$LiAlO_2$ Be/Li_2SiO_3	600	1500	Beryllium indented surface Transformed zone on Li_2SiO_3	150
Be/$LiAlO_2$ Be/Li_2SiO_3 Be/Li_4SiO_4	650	1500	Beryllium indented surface	
Be/$LiAlO_2$	700	500	Beryllium indented surface	10
Be-Ca/$LiAlO_2$ * Be-Ca/Li_2SiO_3* Be-Ca/Li_4SiO_4*	700	500	Indented surface	20

* 0.4 wt % Ca

(1/1)

【Reference】
A. Terlain et al. : "Proc. of the 15th symposium fusion technology, Netherlands, 1988", Fusion Technology, 2 (1988) 1179.

JMTR

7008

Compatibility with stainless steel and lithiated ceramics

(1) Test method : contact test
(2) Contact pressure : 1.5×10^4 Pa
(3) Atmosphere : under dynamic vacuum (0.5 to 1 Pa)
(4) Beryllium specimen : mechanical polished disks (ϕ20 x ^{t}10mm)
impurities 1000 - 5000 wtppm O
500 - 650 wtppm Aℓ
300 - 500 wtppm Fe

Interaction	Temp. (°C)	Material	Phenomenon observed	Thickness affected
Ceramic-beryllium interaction				
Be/$LiAlO_2$	600	Be	a)	–
(500h)		$LiAlO_2$	a)	–
Be/$LiAlO_2$	700	Be	White-grey surface	1 μm
(500h)		$LiAlO_2$	a)	–
Be/$LiAlO_2$	700	Be	White-grey surface	1 μm
(1500h)		$LiAlO_2$	a)	–
Be/Li_2SiO_3	600	Be	a)	–
(500h)		Li_2SiO_3	a)	–
Steel-beryllium interaction				
Be/316L	600	Be	Holes	0 - 25μm
(500h)		316L	Diffusion zone	0 - 10μm
Be/316L	700	Be	Holes	0 - 200μm
(500h)		316L	Diffusion zone	0 - 100μm
Be/316L	600	Be	Holes	0 - 100μm
(1500h)		316L	Diffusion zone	0 - 40μm
Be/HT9	600	Be	a)	–
(500h)		HT9	a)	–
Be/1.4914	700	Be	Holes	0 - 20μm
(500h)		1.4914	Diffusion zone	0 - 30μm
Be/1.4914	600	Be	a)	–
(1500h)		1.4914	a)	–

a) No phenomenon has been observed.

(1／1)

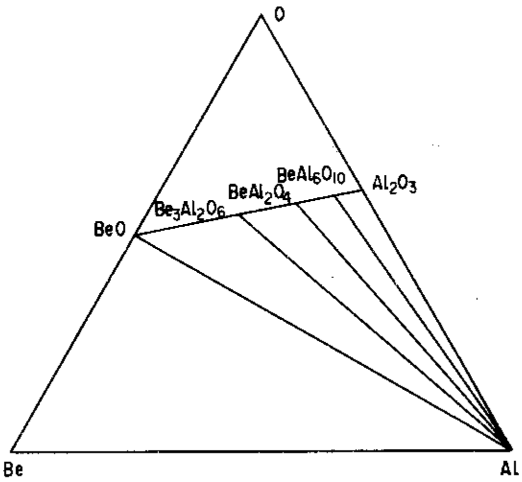
【Reference】

T. Flament et al.: "Compatibility of stainless steels and lithiated ceramics", J. Nucl. Mater., 155/157 (1988) 496.

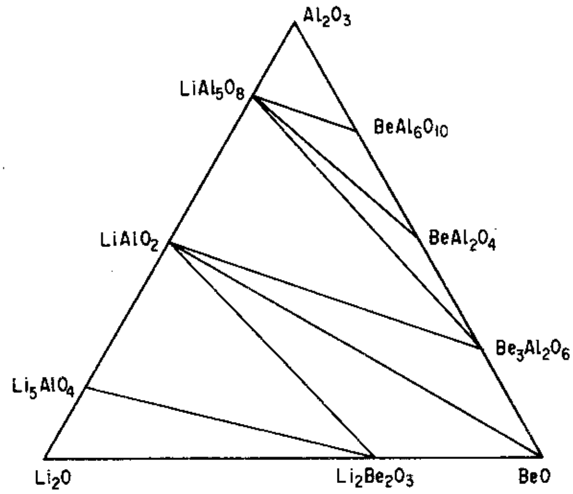
JMTR

7009

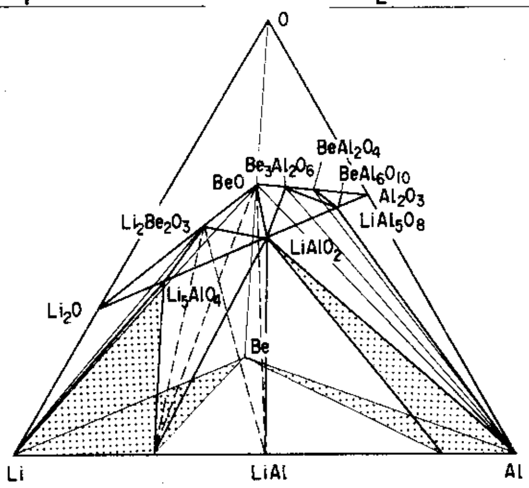
Thermochemistry in the system Li-Aℓ-Be-O



Isothermal section of the Be-Aℓ-O system up to 900K



Pseudoternary section Li_2O-BeO-$A\ell_2O_3$ up to 900K



Isothermal tetrahedron of the Li-Aℓ-Be-O system at 850K

(1／1)

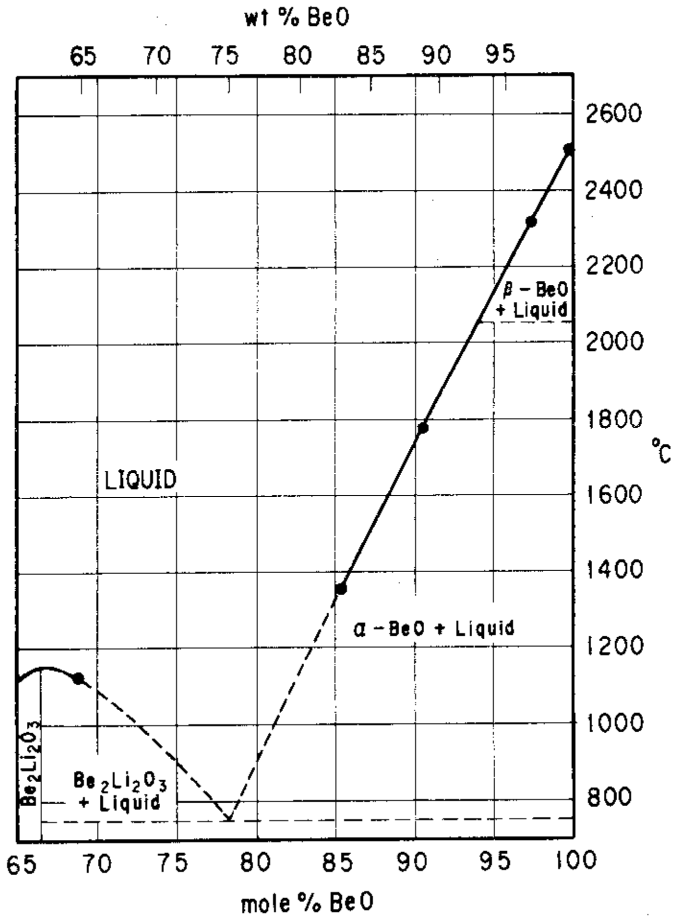
【Reference】
H. Migge : "Thermochemistry in the system Li-Aℓ-Be-O",
J. Nucl. Mater. 155-157 (1988) 455.

JMTR

7010

Tentative phase diagram of beryllia-lithia system

(1) Eutectic point : 78.5 mol % BeO
(2) Melting point of $Be_2Li_2O_3$: 1150 ± 40°C
(3) This is not equilibrium state diagram.
(4) Method : optical measurement of melting point
(5) Specimen : mixed powder of BeO and Li_2O



(1/1)

【Reference】
P. P. Turner et al. : "Tentative phase diagram of beryllia-lithia system", Inorg. Chem., 6, 4 (1967) 833.

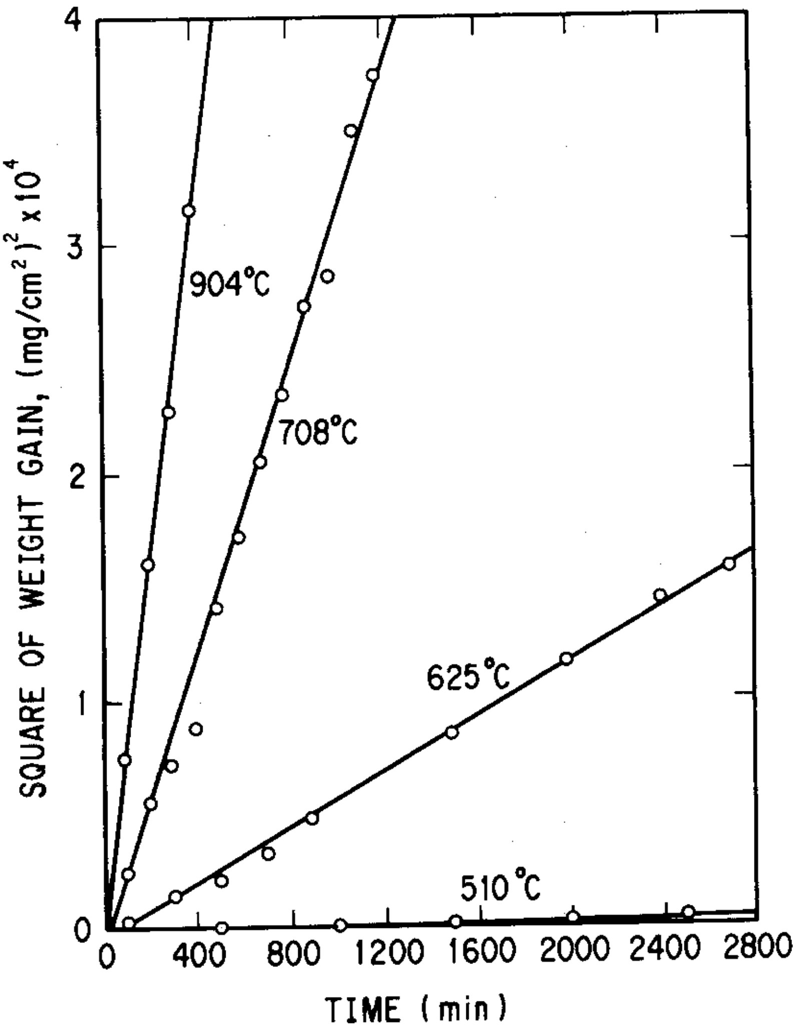
JMTR

7011

Parabolic oxidation

(1) Oxidation condition

① oxygen pressure : 0.1 atm



(1/1)

【Reference】

G. Ervin et al. : "Catastrophic oxidation of beryllium metal", J. Nucl. Mater., 12, 1 (1964) 30.

JMTR

7012

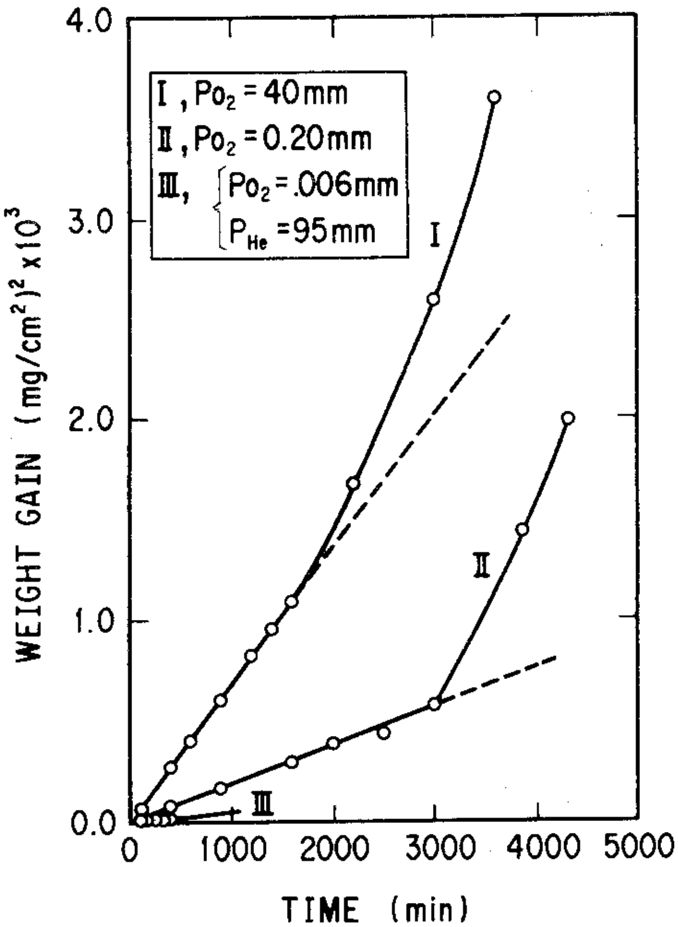
Catastrophic oxidation

(1) Specimen : hot - pressed beryllium (S-200)

(2) Oxidation condition

① annealing temperature : 750°C

② oxygen pressure : see the figure below



(1/1)

【Reference】

G. Ervin et al. : "Catastrophic oxidation of beryllium metal", J. Nucl. Mater., 12, 1 (1964) 30.

9. Interaction with Hydrogen

"Behavior of hydrogen isotopes in beryllium(8001)" shows the data on diffusion, solubility and permeation of hydrogen isotope in beryllium. "Diffusion coefficients of deuterium in beryllium(8002)" shows that the diffusion coefficient of deuterium in beryllium is formularized as follows,

extra-grade(99.8%): $D=6.7\times10^{-9}\exp(-28.4/RT)$ [m^2/s]

high-grade(99%) : $D=8.0\times10^{-9}\exp(-35.1/RT)$ [m^2/s]

"Retention of deuterium implanted in beryllium(1)-(6)(8003-8008)" shows the retention properties of deuterium implanted in beryllium under various conditions. "Thermal release of deuterium implanted in beryllium(1)(8009)" shows the results of thermal release test by Thermal Desorption Spectroscopy after implantation of deuterium(5keV) to beryllium by accelerator. Thermal release started at 200°C, and has a peak at about 400°C. "Thermal release of deuterium implanted in beryllium(2)(8010)" shows thermal release properties of deuterium from CIP-HIP beryllium implanted deuterium in 0.5, 1.5 and 3keV. "Tritium behavior in beryllium(8011)" shows the diffusion coefficient and solubility of tritium in beryllium. "Tritium release in beryllium(8012)" shows tritium release curve by heating. "Diffusion coefficient of tritium in beryllium(1)(8013)" shows that diffusion coefficient of tritium in beryllium is formularized as follows,

$\log D=-(6.53\pm0.15)-(965\pm106)T^{-1}$ [cm^2/s] (T: temperature(k)).

"Diffusion coefficient of tritium in beryllium(2)(8014)" shows that diffusion coefficient of tritium in beryllium pebble is formularized as follows,

$D=1.1\times10^{2}\exp(-2.2\times10^{5}/R/T)$ [cm^2/s] (T: temperature(k), R: 8.31J/mol/K).

"Diffusion coefficient of tritium in beryllium(3)(8015)" shows that diffusion coefficient of tritium in beryllium was formularized as follows,

$D=8.7\times10^{4}\exp(-2.9\times10^{5}/R/T)$ [cm^2/s] (T: temperature(k), R: 8.31J/mol/K).

"Diffusion coefficient of tritium in breeder and multiplier(8016)" shows diffusion coefficients of tritium in various breeders and multipliers.

"Solubility of tritium in beryllium(8017)" shows that solubility of tritium in beryllium is formularized as follows,

$$\log S=(2.12\pm0.27)-(0.095\pm0.211)T^{-1}\ [\mathrm{Std.ml/g/atm^{1/2}}].$$

"Hydrogen isotope solubility in various materials(8018)" shows the solubility of hydrogen isotope in beryllium.

JMTR

8001

Behavior of hydrogen isotopes in beryllium

Summary of published data on diffusion, solubility and permeation of hydrogen isotopes in Be

Authors	Ref. No.		Diffusion Coefficients		Solubility Coefficients		Permeation Coefficients		Temp. range [°K]
			D_0 [m²/s]	E_D [KJ/mol]	S_0 [mol/m³ · $\sqrt{Pa}$]	E_S [KJ/mol]	K_0 [mol/m·s· Pa]	E_K [KJ/mol]	
Pemsler and Rapperport	[1]	H	3×10^{-13}	0	-	-	-	-	1123−1173
Jones and Gibson	[2]	T	3×10^{-11}	18.47	1.964×10^{-3}	-1.82×10^{-3}	5.795×10^{-14}	18.47	673−1173
Al'tovskiy et al*	[3]	H	-	-	-	-	4.24×10^{-7}	86.96	773− 873
		H	-	-	-	-	3.39×10^{-11}	26.70	773− 923
Fromm and Jehn	[4]	H	-	-	2.24×10^{-3}	-1.818	-	-	523−1123
Swansiger	[5]	T	-	-	7.484×10^{-4}	112.8	-	-	713− 783
Billone**	[6]	T	1.73×10^{-9}	18.47	-	-	-	-	573−0873
			1.35×10^{-10}	0	-	-	-	-	>873

* Two different types of beryllium were studied.

** This reference describes a modified analysis to the experimental data of Jones and Gibson (Ref. 2).

[1] J. P. Pemsler and E. J. Rapperport: Trans. Metall. Soc. AIME, 230 (1964) 90.
[2] P. M. S. Jones and R. Gibson: J. Nucl. Mater., 21 (1967) 353.
[3] R. M. Al'tovskiy et al.: Russ. Metall. 3 (1981) 51.
[4] E. Fromm and H. Jehn: Bulletin of Alloy Phase Diagrams 5 (1984) 324.
[5] W. A. Swansiger: J. Vac. Sci. Technol. A4 (1986) 1216.
[6] M. C. Billone, Private communication (1988).

(1/1)

【Reference】

E. Abramov et al. : CFFTP-G-9013, "Deuterium permeation and diffusion in high purity beryllium" (1990).

JMTR

8002

Diffusion coefficients of deuterium in beryllium

(1) Diffusion coefficient in extra − grade beryllium

$$D = 6.7 \times 10^{-9} \exp\left(-\frac{28.4}{RT}\right) \ [m^2/s]$$

(T: temperature / K, R = 8.31 J/mol/K)

(2) Diffusion coefficient in high − grade beryllium

$$D = 8.0 \times 10^{-9} \exp\left(-\frac{35.1}{RT}\right) \ [m^2/s]$$

(T: temperature / K, R = 8.31 J/mol/K)

(3) Measurement method : gas − driven permeation measurement

(4) Specimens

① extra − grade beryllium
hot isostatic press, ϕ22 x 0.1 mm, 99.8 %

② high − grade beryllium
hot isostatic press, ϕ22 x 0.1, 0.2 mm, 99 %

(1/1)

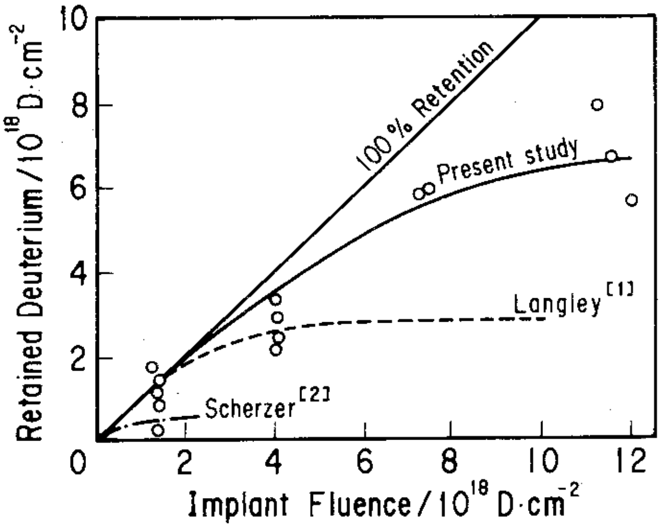
【Reference】
E. Abramov et.al.: CFFTP − G − 9013, "Deuterium permeation and diffusion in high purity beryllium" (1990).

8003

Retention of deuterium implanted in beryllium (1)

(1) Specimen
- ① material : hot pressed beryllium
- ② main impurity : 0.46 mol % BeO
- ③ surface treatment : mechanical polished prior to implanting

(2) Ion implanting condition
- ① energy : 5 keV
- ② current : 2 μA
- ③ beem diameter : 1 mm
- ④ D_2 pressure : 5×10^{-5} Torr
- ⑤ specimen temperature : 75 ℃



Retained deuterium as a function of fluence

[1] R.A.Langley : J. Nucl. Mater., 85-86 (1979) 1123.
[2] B.M.U. Scherzer et al. : J. Nucl. Mater., 85-86 (1979) 1025.

(1/1)

【Reference】
E. Ishitsuka, H. Kawamura et al. : "Surface characterization hot-pressed beryllium with X-ray photoelectron spectroscopy," Ann. Rept. Tritium Res. Center. Toyama Univ., 8 (1988) 61.

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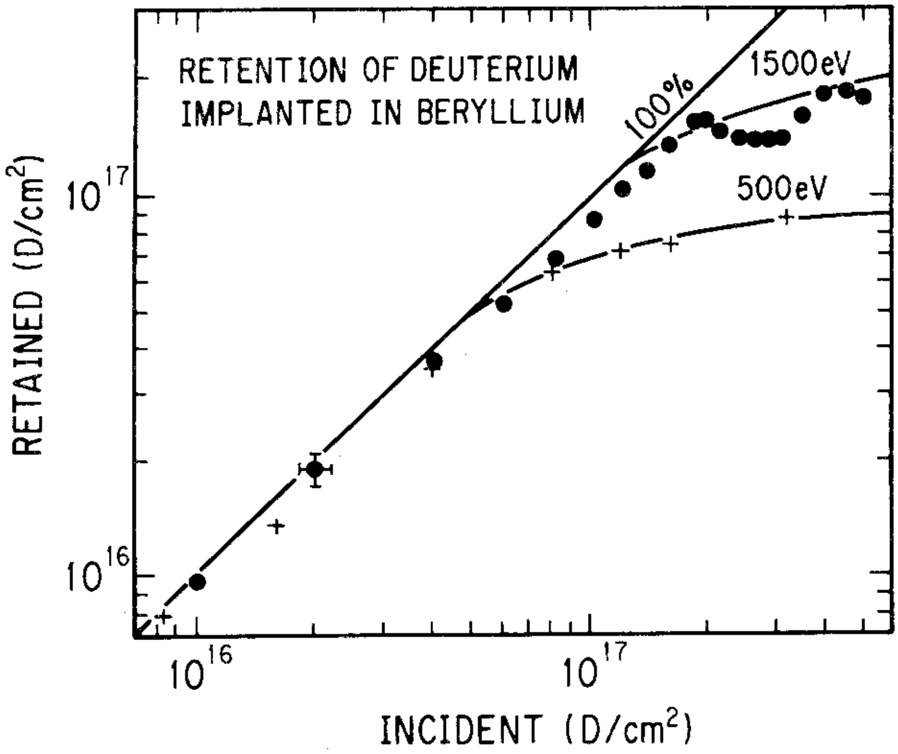
8004

Retention of deuterium implanted in beryllium (2)

(1) Specimen
① production method : CIP followed by HIP
② surface treatment : electropolished prior to implantation
③ grain size : 10μm
④ main impurity : ~0.4at% oxygen
⑤ surface oxide thickness : ~1.5nm

(2) Implanting condition
① deuterium ion energy : 500 and 1500eV

(3) Analysis
① analysis method : D(^{3}He, p)^{4}He nuclear reaction analysis



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【Reference】

W.R. Wampler : "Retention and thermal released of deuterium implanted in beryllium", J. Nucl. Mater., 122-123 (1984) 1598.

JMTR

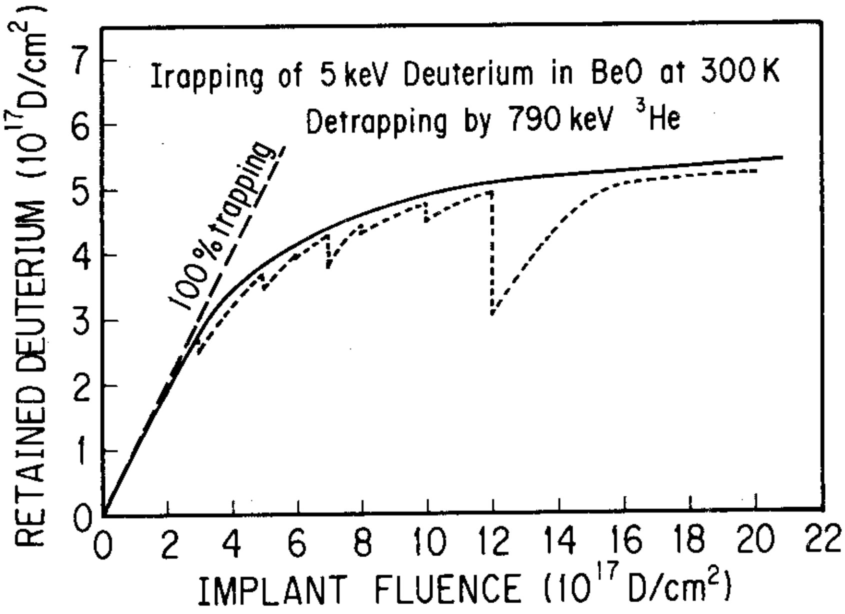
8005

Retention of deuterium implanted in beryllium (3)

(1) Specimen
① oxidized in oxygen at 750°C for 30 min
② oxide layer : 165 nm

(2) Implanting condition
① deuterium ion energy : 5 keV

(3) Analysis
① analysis method : $D(^{3}He, p)^{4}He$ nuclear reaction analysis
② ^{3}He ion energy : 790 keV



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【Reference】
B.M.U. Scherzer et al. : "Radiation induced detrapping of implanted deuterium in BeO by high energy ^{3}He and proton irradiation", J. Nucl. Mater., 85-86 (1979) 1025.

8006

Retention of deuterium implanted in beryllium (4)

(1) Specimen

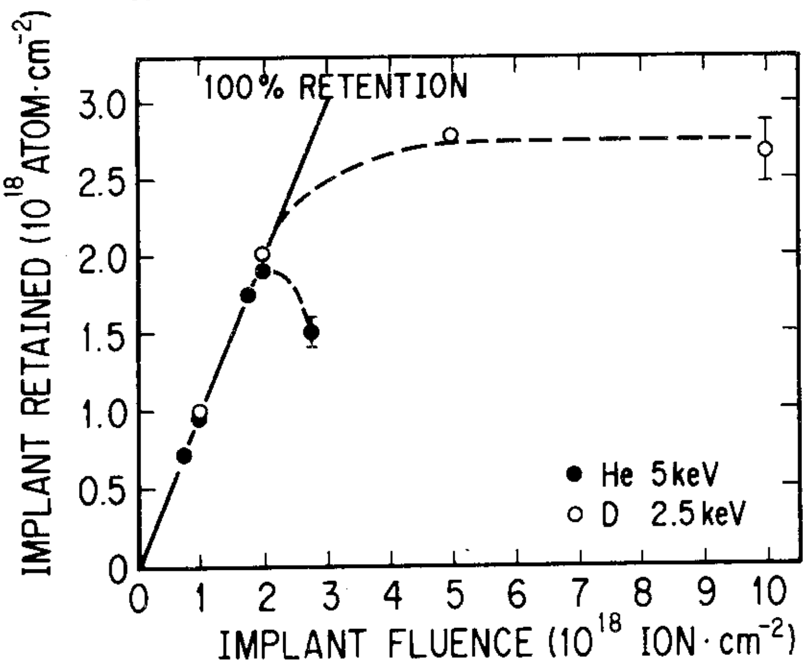
① production method : CIP followed by HIP ($\phi 10 \times {}^{t}1$mm)
② surface treatment : electropolished prior to implantation
③ grain size : 10 μm
④ surface oxide thickness : 15 nm
⑤ main impurities : O (9000wppm), Fe (165), Ni (105), Si (82), Aℓ (60), Mg (44), Cu (40)

(2) Implanting condition

① deuterium ion energy : 2.5 keV

(3) Analysis

① analysis method : elastical backscattering method
② H^+ ion energy : 2.5 MeV



(1／1)

【Reference】
R.A.Langley : "Interaction of implanted deuterium and helium with beryllium : radiation enhanced oxidation", J. Nucl. Mater., 85-86 (1979) 1123.

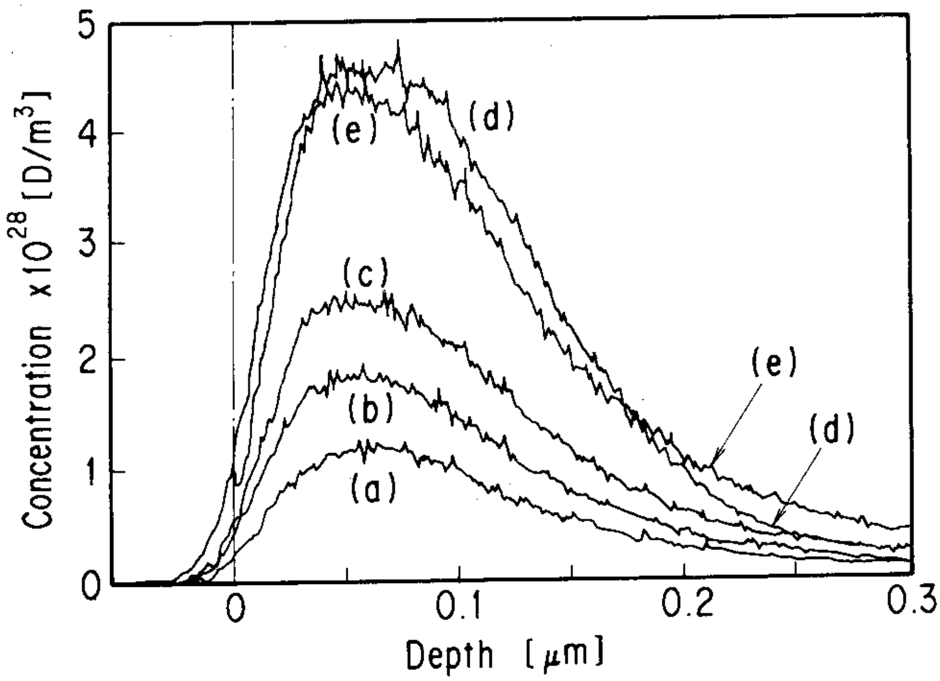
8007

Retention of deuterium implanted in beryllium (5)

(1) Specimen
① material : hot-pressed beryllium plate ($^{l}20 \times {}^{w}7 \times {}^{t}0.5$ mm)
② surface treatment : mechanical polished prior to implanting
③ main impurity : ~1.28 wt % BeO

(2) Implanting condition
① flux : $9.3 \times 10^{18} D_2^+ (5\,keV)/m^2 \cdot s$
② temperature : room temperature
③ fluence : (a) $0.5 \times 10^{22} D/m^2$ (b) $1.1 \times 10^{22} D/m^2$
(c) $1.8 \times 10^{22} D/m^2$ (d) $3.3 \times 10^{22} D/m^2$
(e) $7.3 \times 10^{22} D/m^2$

(3) Analysis
① analysis method : Elastic Recoil Detection (ERD)
② ^{4}He ion energy : 1.5 MeV



Deuterium profile in beryllium immediately after implantig

(1/2)

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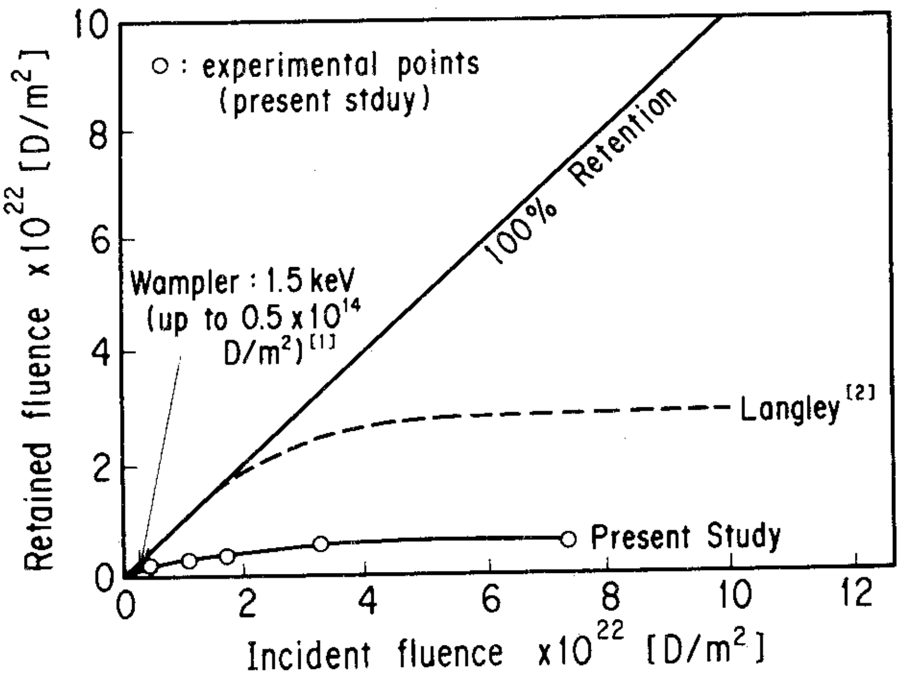


Retention of deuterium implanted in beryllium

[1] W. R. Wampler : "Retention and thermal release of deuterium implanted in beryllium", J. Nucl. Mater., 122-123 (1984) 1598.

[2] R. A. Langley : "Interaction of implanted deuterium and helium with beryllium : radiation enhanced oxidation", J. Nucl. Mater., 85-86 (1979) 1123.

(2／2)

【Reference】

H. Kawamura, E. Ishitsuka et al. : "Retention of deuterium implanted in hot-pressed beryllium", J. Nucl. Mater. 176-177 (1990) 661.

8008

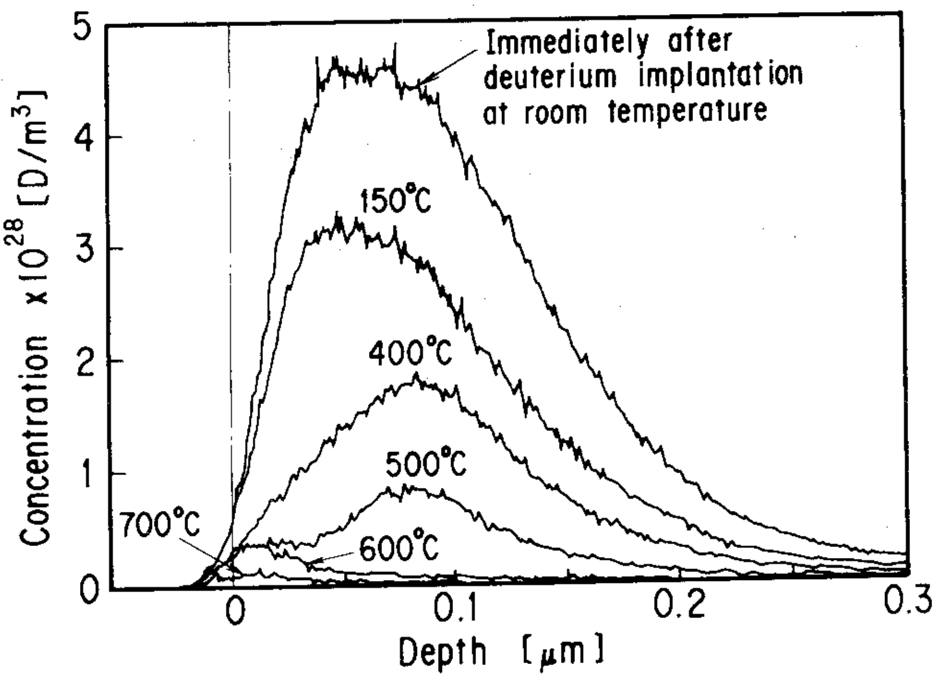
Retention of deuterium implanted in beryllium (6)

(1) Specimen
① material : hot-pressed beryllium plate ($^{\ell}20 \times {}^{w}7 \times {}^{t}0.5$ mm)
② surface treatment : mechanical polished prior to implanting
③ main impurity : ~1.28 wt % BeO

(2) Implanting condition
① flux : 9.3×10^{18} D_2^+ (5keV)/m^2/s
② temperature : room temperature
③ fluence : 2.8×10^{22} D/m^2

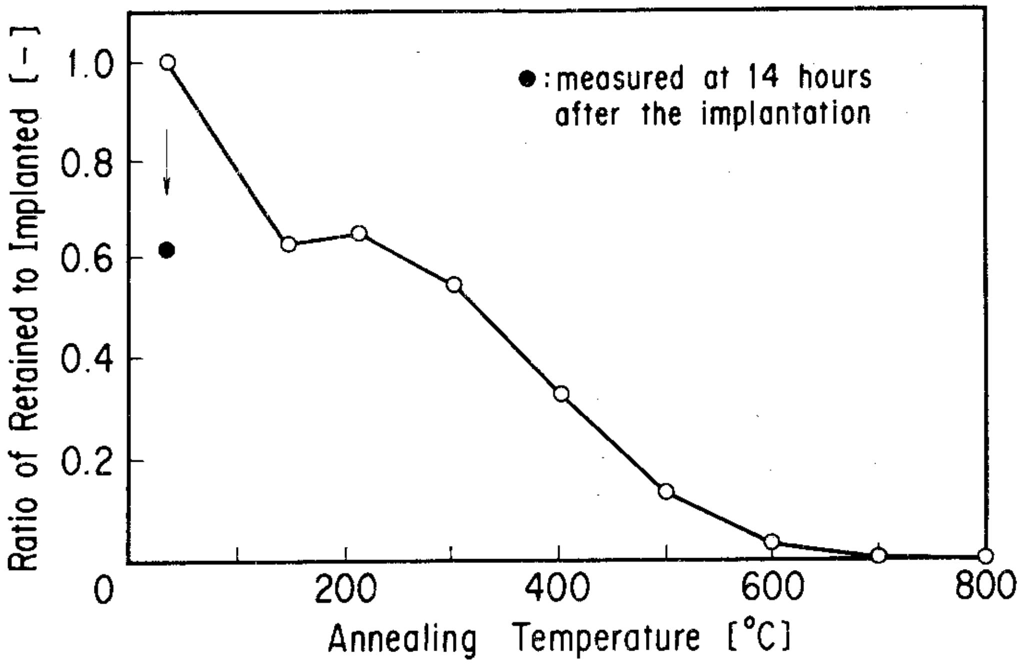
(3) Annealing condition
① at each indicated temperature for 2 min

(4) Analysis
① analysis method : Elastic Recoil Detection (ERD)
② ^{4}He ion energy : 1.5 MeV



Deuterium profile in beryllium after implanting and then annealing.

(1／2)



Deuterium retention in beryllium after implanting and then annealing

(2/2)

【Reference】

H. Kawamura, E. Ishitsuka et al. : "Retention of deuterium implanted in hot-pressed beryllium", J. Nucl. Mater., 176-177 (1990) 661.

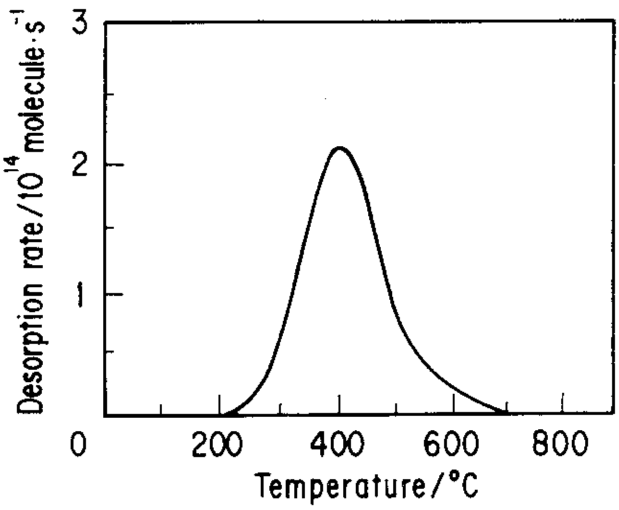
8009

Thermal release of deuterium implanted in beryllium (I)

(1) Specimen
① material : hot pressed beryllium
② main impurity : 0.46 mol % BeO
③ surface treatment : mechanical polished prior to implanting
(2) Conditions of ion implantation and TDS
① ion implantation
- energy : 5 keV
- current : 2 μA
- fluence : 7×10^{18} D·cm^{-2}
- been diameter : 1 mm
- D_2 pressure : 5×10^{-5} Torr
- specimen temperature : 75 ℃

② TDS
- heating rate : 1.6 ℃/s
- start temperature : 75 ℃
- maximum temperature : 800 ℃
- hold time : 2 min

(3) Measurement
① measurement method : Thermal Desorption Spectroscopy (TDS)



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【Reference】
E. Ishitsuka, H. Kawamura et al. : "Surface characterization of hot-pressed beryllium with X-ray photoelectron spectroscopy," Ann. Rept. Tritium Res. Center. Toyama Univ., 8 (1988) 61.

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8010

Thermal release of deuterium implanted in beryllium (2)

(1) Specimen

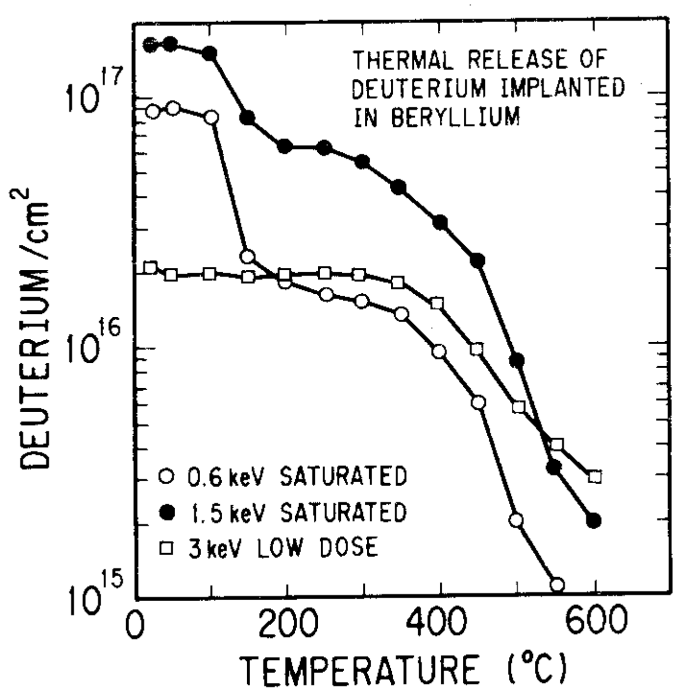
① production method : CIP followed by HIP
② main impurity : ~0.4 at % oxygen
③ surface treatment : electropolished prior to implantation
④ grain size : 10 μm
⑤ surface oxide thickness : ~1.5 nm

(2) Implanting condition

① deuterium ion energy : 0.5, 1.5 and 3 keV

(3) Analysis

① analysis method : $D(^3He, p)\,^4He$ nuclear reaction analysis



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【Reference】

W.R. Wampler : "Retention and thermal released of deuterium implanted in beryllium", J. Nucl. Mater., 122-123 (1984) 1598.

JMTR

8011

Tritium behavior in beryllium

	JONES GIBSON	WAMPLER	BALDWIN ET AL.	ABRAMOV ET AL.
Method	Stepped-anneal	Stepped-anneal	Stepped-anneal	Permeation
Temp., °C	300-900	25-600	300-611	347-502
Time Step, h	25-100	0.17	20-200	---
Diffusivity				
D_0, m^2/s	3.0×10^{-11} $(1.73 \times 10^{-9})^{a}$	---	---	6.7×10^{-9} 8.0×10^{-9}
Q, $kJ \cdot mol^{-1}$	18.5	---	---	28.4 35.1
Solubility				
So, $appm\text{-}Pa^{-0.5}$	1.9×10^{-2}	---	---	---
Q_s, $kJ \cdot mol^{-1}$	-1.82×10^{-3}	---	---	---

a : Re-analyzed by Billone.

(1／1)

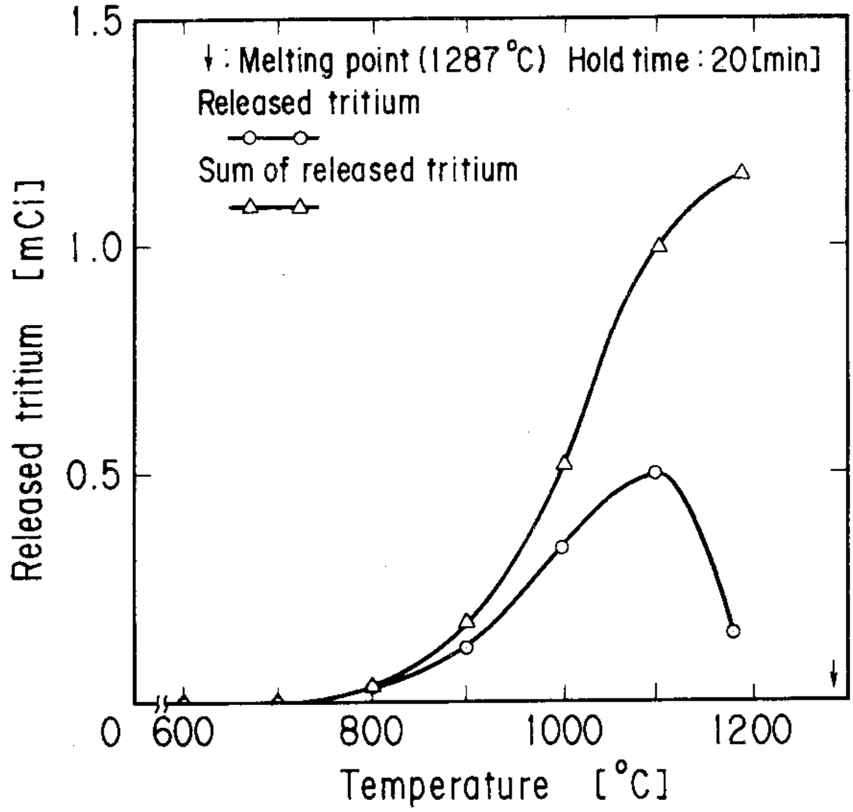
【Reference】
M.C. Billone, C.C. Lin and D.L. Baldwin : PNL-SA-18966, "Tritium and helium behavior in irradiated beryllium" (1990).

JMTR

8012

Tritium release in beryllium

(1) Specimen
① hot pressed beryllium disk (ø 10 x t 1.4 mm)
② main impurity : 1.28 wt. % BeO
(2) Irradiation conditions
① irradiation temperature : 200 °C
② first neutron fluence : 3.8×10^{20} n/cm²
③ thermal neutron fluence : 6×10^{20} n/cm²
(3) Tritium production : ~10mCi/cm²



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【Reference】
E. Ishitsuka, H. Kawamura et al. : JAERI-M 90-013, "Experiments on tritium behavior in beryllium (2) - Tritium released by recoil and diffusion -" (1990).

JMTR

8013

Diffusion coefficient of tritium in beryllium (1)

(1) Diffusion coefficient of tritium in beryllium

$$\log D = -(6.53 \pm 0.15) - (965 \pm 106)\, T^{-1} \quad [cm^2/s]$$

(T : temperature / K)

(2) Specimen

Vacuum casted beryllium, $\phi 1.003 \times {}^{t}0.031$ inch

Diffusion coefficient of tritium in beryllium

Temperature °C	Number of Samples	Mean Slope of Curves, h^{-1}	Diffusion Coefficient, $cm^2\ s^{-1}$
200	2	0.0075	3.0×10^{-9}
300	2	0.012	4.8×10^{-9}
400	4	0.034	1.4×10^{-8}
500	2	0.036	1.5×10^{-8}
800	2	0.056	2.3×10^{-8}
900	2	0.12	4.8×10^{-8}
950	4	0.17	6.9×10^{-8}

(1／1)

【Reference】

P. M. S. Jones et al. : AWRE－0－2, "Hydrogen in beryllium" (1967).

8014

Diffusion coefficient of tritium in beryllium(2)

(1) Specimen

Shape		Pebble	Disk
Producting Method		Rotary Electrode	Hot Press
Dimension		ø 1 mm	ø10 x ^{t}1.4 mm
Oxide Layer Thickness		0.48 μm	0.02 μm
Chemical Composition	Be	98.2 (wt.%)	99.3 (wt.%)
	BeO	1.51	0.8
	Al	0.078	0.03
	C	0.023	0.07
	Fe	0.11	0.06

(2) Reactor : JMTR

(3) Irradiation condition

Condition \ Specimen	Pebble	Disk
Thermal Neutron Fluence (n/cm^2)	8×10^{20}	5×10^{20}
Fast Neutron Fluence (n/cm^2)	2×10^{20}	5×10^{20}
Irradiation Temperature (°C)	200	200

(1／2)

JMTR

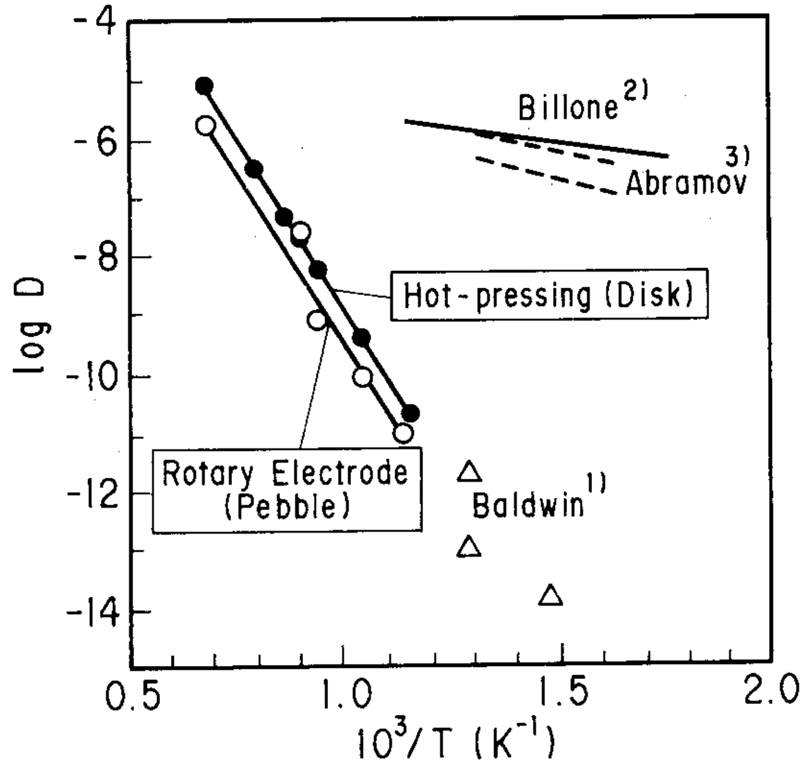
(4) Diffusion coefficient of tritium

① pebble : $D = 1.1 \times 10^{2} \exp(-2.2 \times 10^{5}/R/T)\ cm^{2}/s$

② disk : $D = 3.9 \times 10^{2} \exp(-2.2 \times 10^{5}/R/T)\ cm^{2}/s$

(R : 8.314 J/K/mol)

(T : $873 K \leqq T \leqq 1073 K$)



1) D.L.Baldwin, D.S.Gelles and O.D.Slagle, PNL-SA-16998 (1990).
2) M.C. Billone, C.C. Lin and D.L. Baldwin, PNL-SA-18966 (1990).
3) E. Abramov, M.P. Riehem, D.A. Thompson and W.W. Smeltzer, GFFTP-G-9013 (1990).

(2／2)

【Reference】
E. Ishitsuka, H. Kawamura et al. : Read at the meeting of the Atomic Energy Society of Japan in Osaka, on Mar. 28-30, 1991.

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8015

Diffusion coefficient of tritium in beryllium (3)

$D = 8.7 \times 10^{4} \exp(-2.9 \times 10^{5} / R / T)$, cm^2/s

(T : temperature / K, R = 8.31 J/mol/K)

(1) Specimen

① hot-pressed beryllium disk (φ10 x^t 1.4mm)

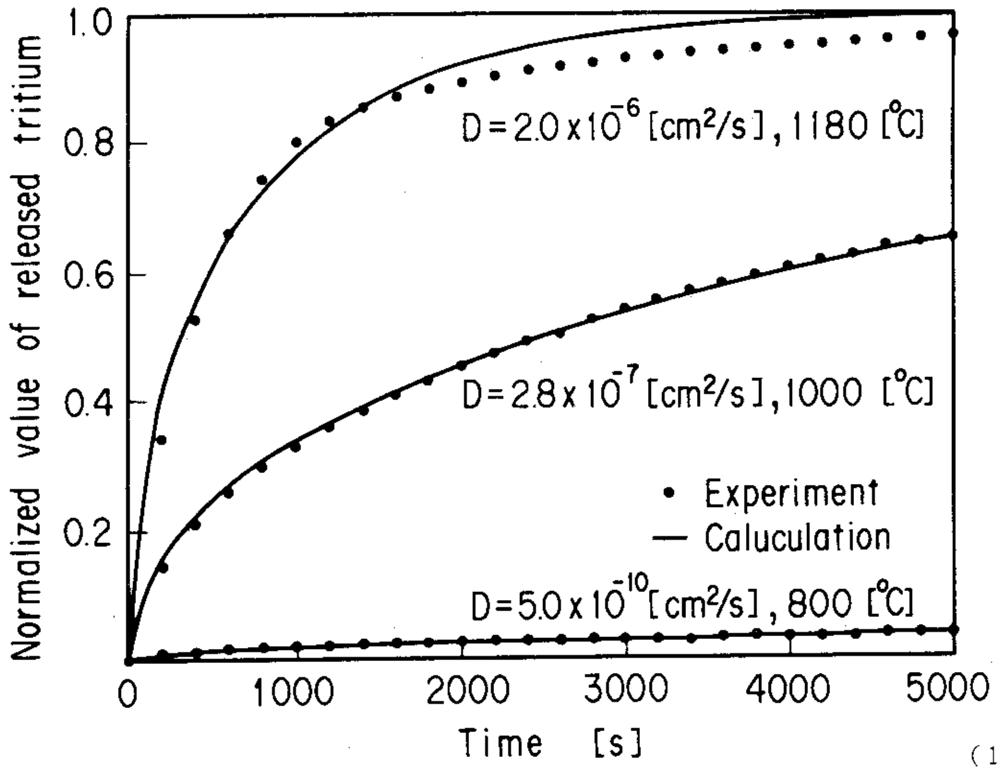
② main impurity : 1.28 wt% BeO

(2) Irradiation conditions

① irradiation temperature : 200 ℃

② first neutron fluence : 3.8×10^{20} n/cm^2

③ thermal neutron fluence : 6×10^{20} n/cm^2



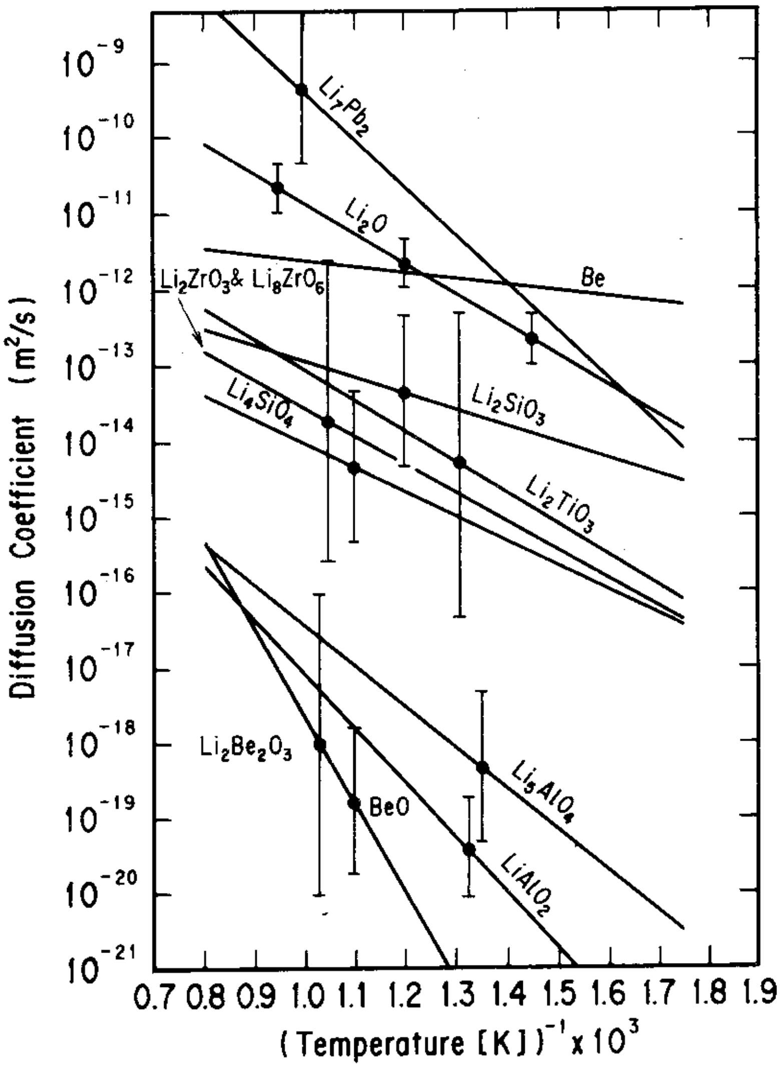
(1/1)

【Reference】

E. Ishitsuka, H. Kawamura et al. : JAERI-M 90-013, "Experiments on tritium behavior in beryllium (2) —Tritium released by recoil and diffusion—" (1990).

8016

Diffusion coefficient of tritium in breeder and multiplier



Diffusion coefficient of tritium in breeder and multiplier

(1／1)

【Reference】

E. C. Bell et al. : UCLA-ENG-86-44, "Modeling analysis and experiments for fusion nuclear technology" (1987).

JMTR

8017

Solubility of tritium in beryllium

(1) Solubility of tritium in beryllium

$$\log S = (2.12 \pm 0.27) - (0.095 \pm 0.211)T^{-1} \;[\mathrm{Std.\,ml/g/atm^{1/2}}]$$

T : temperature (K)

(2) Specimen

vacuum casted beryllium ; ϕ 1.003 x ^{t}0.031 inch

Solubility of tritium in beryllium

Run	Time, h	Dosing Conditions		Solubility	
		Tritium Pressure, cmHg	Temperature, ℃	std ml/g/atm$^{1/2}$	ppm by weight/atm$^{1/2}$
1*	15	8.95	287	5.2×10^{-3}	1.41
2	125	33.8	569	15.6×10^{-3}	4.20
4	70	48.3	747	14.7×10^{-3}	3.94
5	46	3.7	745	9.4×10^{-3}	2.53
6	24	15.9	826	7.0×10^{-3}	1.89
7	144	54.1	372	6.2×10^{-3}	1.72

* Not fully saturated

(1/1)

【Reference】

P. M. S. Jones et al. : AWRE-O-2, "Hydrogen in beryllium" (1967).

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8018

Hydrogen isotope solubility in various materials

Material	Isotope	Sfevert's Constant (K_s [appm/atm$^{0.5}$])	Temperature range (K)
Al_2O_3	D	1.1×10^5 exp(-64[kJ/mol]/RT)	800 − 1300
Li_2O	T	1.73×10^7 exp(-72[kJ/mol]/RT)	500 − 1300
Li_7Pb_2	T	0.20 exp(68[kJ/mol]/RT)	500 − 1100
$Li_{17}Pb_{83}$	T	170	500 − 1000
Be	T	6.1	700 − 1200

(1/1)

【Reference】

E.C. Bell et al. : UCLA-ENG-86-44 "Modeling, analysis and experiments for fusion nuclear technology" (1987).

10. Handling

"Safe heating limits(9001)" shows safe heating limits on beryllium and beryllium alloy. The safe heating limits on beryllium is 700°C. "Hazard potential of occupations involving Be exposure(9002)" shows the hazard potential in various occupations. "Air cleaning equipment (9003)" shows air cleaning equipments in beryllium workshop and their collection efficiency. The collection efficiency of every air cleaning equipment is above 95%. "Selection of respiratory protection equipment(9004)" shows respiratory protection equipments in each beryllium concentration in air. "Medical examination for beryllium worker(9005)" shows medical examination which beryllium worker should undergo. "Diagnosis of chronic beryllium disease(9006)" shows issues required as diagnosis of chronic beryllium disease.

JMTR

9001

Safe heating limits

Product	Safe Temperature Cutoff	Comments
Beryllium metal	700℃	Will develop 3mm Hg pressure at 800℃
Beryllium oxide (ceramic)	In hydrogen atmosphere at 1550℃, no detectable Be in environment	Care should be exercised in cleaning and maintaining furnace since water vapor will combine with beryllium molecules at high temperatures and remain in the furnace
Beryllium copper	Aging temperature of 200-350℃ (550-700°F) can result in scale containing up to 12% beryllium oxide	Scale developing in forging can cause high air concentrations; should not be blown off; requires exhaust ventilation and/or pickling

(1／1)

【Reference】

M.D. Rossman et al.: "Beryllium - biomedical and environmental aspects -", Williams & Wilkins, Baltimore (1991) 269.

JMTR

9002

Hazard potential of occupations involving Be exposure

Occupations with Significant Risk Potential

1. Production and maintenance workers in
   a. Beryllium extraction plants
   b. Basic beryllium plants producing
      Metallic beryllium
      Beryllium alloys
      Beryllium oxide powders
2. Foundries melting beryllium alloys
3. Beryllium machine shops
4. Plants in which beryllium oxide powders are processed
5. Operations involving
   a. Grinding, lapping or otherwise abrading beryllium-containing materials
   b. Welding, brazing or melting of beryllium-containing materials
   c. BeO furnace cleaning or rebuilding
   d. BeO pressing or extrusion
   e. Laser cutting, scribing or trimming
   f. Dental laboratory operations utilizing beryllium alloys
   g. Heat treating of beryllium alloys
   h. Chemical milling of beryllium

Occupations With Minimal or No Exposure Potential

1. Inspection, cleaning, assembling, transporting, or otherwise handing solid shapes of beryllium-containing materials.
2. Machining, drawing, stamping, or bending of beryllium alloys
3. Soldering of BeO parts

(1／1)

【Reference】

M. D. Rossman et al.: " Beryllium − biomedical and environmental aspects −", Williams & Wilkins, Baltimore (1991) 254.

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9003

Air cleaning equipment

Production Operations	Air Cleaning Equipment	Collection Efficiency
Beryllium Machining Beryllium alloy-melting and casting	Cyclone—baghouse—high-efficiency filter	99.00+
Beryllium powder processing	Baghouse—high-efficiency filter	99.99+
Beryllia machining	Water/oil demister—high-efficiency filter	99.99+
Beryllium hydroxide Conversion to beryllium sulfate to oxide	Packed tower scrubber and high-efficiency demister	99.00+
Conversion of beryllium ores to beryllium hydroxide Beryllium hydroxide conversion to beryllium pebbles	Venturi scrubber—packed scrubber—high-efficiency dimister	95.00+
Pickling of beryllium alloys	Packed tower scrubber and demister	95.00+

(1/1)

【Reference】
M.D. Rossman et al.: "Beryllium − biomedical and environmental aspects −", Williams & Wilkins, Baltimore (1991) 242.

JMTR

9004

Selection of respiratory protection equipment

NIOSH Assigned Protective Factor	Concentration or Condition	Minimum Respiratory Protection
10	20μg/m³ or less	Half-mask air-purifying respirator equipped with high-efficiency filters
50	100μg³ or less	Full-facepiece air-purifying respirator equipped with high-efficiency filters, or
50	100μg³ or less	Powered air-purifying respirator equipped with high-efficiency filters
1000	2000μg/m³ or less	Half-facepiece supplied air respirator operated in pressure demand mode
2000	4000μg/m³ or less	Full-facepiece supplied air respirator operated in pressure demand mode
10,000	Unknown concentration or greater than 4000 μg/m³ or firefighting	Full-facepiece supplied air respirator operated in pressure demand mode with a personal emergency reserve air tank or a pressure demand type SCBA

NIOSH : the National Institute for Occupational Safety and Health
SCBA : Self contained Breathing Apparatus

(1/1)

【Reference】
M.D. Rossman et al. : "Beryllium - biomedical and environmental aspects -", Williams & Wilkins, Baltimore (1991) 246.

9005

Medical examination for beryllium workers

Examination	History and Physical	Chest Radiograph	Spirometry (FVC and FEV1)	DL_{co}
Preplacement				
O	X	X	X	X
A	X	X	X	
B	X	X	X	
Periodic				
O	Biannual	Biannual	Annual	
A	Annual	Annual	Semiannual	
B	Annual	Annual	Quarterly	Semiannual
Termination	X	X	X	B only

FVC : Forced Vital Capacity
FEV1 : Forced Expiratory Volume in 1 second
DL_{co} : Carbon monoxide diffusion capacity

O = Exposure to respirable Be particles impossible ;
A = Exposure possible, but generally at low levels ;
B = Low-Level exposures likely, with the possibility of accidental higher excursions.

(1/1)

【Reference】

M.D. Rossman et al.: "Beryllium − biomedical and environmental aspects −", Williams & Wilkins, Baltimore (1991) 190.

JMTR

9006

Diagnosis of chronic beryllium disease

A definite diagnosis of CBD requires:
1. Positive proliferative response of bronchoalveolar cells to beryllium, and
2. Histological evidence of pulmonary granulomas

A probable diagnosis of CBD can be made :
1. Histological evidence of pulmonary granulomas and,
2. History of excessive exposure or documentation of exposure by :
   a. Positive blood proliferative response to beryllium,
   b. Elevated urine beryllium levels, or
   c. Elevated beryllium in lung or mediastinum.

CBD : Chronic Beryllium Desease

(1／1)

【Reference】
M. D. Rossman et al. : " Beryllium – biomedical and environmental aspects – ", Williams & Wilkins, Baltimore (1991) 174.

11. Conclusion

Important technical data in this report are shown as follows,

(1) Upper temperature limit on beryllium of fusion blanket material is 650°C.

(2) The amount of tritium production on beryllium irradiated up to 5×10^{22} n/cm^2 (E>1MeV) in ATR is 8.23Ci/g.

(3) Threshold energy on (n,2n) reaction in beryllium is about 1.85MeV.

(4) The amount of swelling per 10^{22} n/cm^2 on beryllium irradiated in ETR was 0.2~0.3%.

(5) Swelling of beryllium irradiated in EBR-II and ATR is formularized as follows.

$$\Delta V/V_0=(0.086\pm0.031)G\alpha^{1.035}[1+22.2G\alpha^{0.5}T^{1.5}\exp(-9322/T)](\%).$$

(6) From the results of observation on cross section of annealed beryllium up to 1180°C after irradiation up to 3.8×10^{20} n/cm^2 (E>1MeV) at 200°C in JMTR, it is clear that swelling takes place with growth of blister and pore by annealing.

(7) From the results of investigation about the effects of annealing on the changes of hardness and density, it becomes clear that hardness begins to decrease and density changes begin to increase at about 600°C.

(8) The irradiation test above 7×10^{-3} appm He and at 350~700°C is needed for properties evaluation of beryllium as fusion blanket material.

(9) From the results of investigation about tensile strength, elongation and drawing on hot pressed beryllium at various temperatures, tensile strength decreases with increasing testing temperature, and has flat region at 400°C~600°C, then decreases with increasing testing temperature again. The elongation and drawing property increase with testing temperature, and has a peak at about 400°C, then decreases above that temperature.

(10) Tensile strength at room temperature on cold press-sinter-HIP beryllium is larger than hot press beryllium and decreases with increasing testing temperature, then the elongation becomes max., value 50% at 400°C.

(11) Tensile strength and 0.2% yield strength of hot pressed beryllium decrease with increasing temperature. The elongation has a peak at about 800°C, and has a tendency to decrease with increasing

beryllium oxide content.

(12) Generally, S-S curve on beryllium does not show yield phenomenon.

(13) Elongation coefficient on beryllium is 0.87. The beryllium is brittle material.

(14) Young's modulus on beryllium is formularized with parameters of porosity and temperature,

$$E=297\exp(-3.5P)[1-1.9\times10^{-4}(T-293)]$$ (T: Temperature(K), E: Young's modulus)

(15) Strength of beryllium relates to grain size by the Hall-Petch law.

(16) Specific heat on beryllium is formularized as follows,

$$Cp=4.54+2.12\times10^{-3}T-0.82\times10^{5}T^{-2}\ (cal/g/^\circ C)$$ (T: Temperature(°C)).

(17) Only ^{9}Be is stable within beryllium isotopes(^{6}Be~^{10}Be) and its atomic weight is 9.015.

(18) Linear expansion and the coefficient of expansion are formularized as follows,

$$\Delta\ell/\ell_0=8.43\times10^{-4}(1+1.36\times10^{-3}T-3.53\times10^{-7}T^2)(T-298)\quad(298\leq T\leq1500K)$$

$$\alpha=5.01\times10^{-6}(1+3.451\times10^{-3}T-1.979\times10^{-7}T^2)\quad(298\leq T\leq1500K).$$

(T: Temperature(K), α: Coefficient of expansion)

(19) Vapor pressure of beryllium is formularized as follows,

$$\log P(atm)=6.186+1.454\times10^{-4}T-(16734\pm80)T^{-1}$$ (T: Temperature(K))

$$\log P(Torr)=6.494-11710T^{-1}$$ (1577-2058°C)

(20) Oxygen potential on formation of beryllium oxide is lower than all Li-containing ceramics except Li_5AlO_4. Therefore, beryllium reduce them.

(21) The threshold temperature on reaction between beryllium and SUS316L and between beryllium and 1.4919 stainless steel are 580°C and 650°C, respectively.

(22) In beryllium, oxidation rate considerably increase immediately after oxidation progressed in accordance with parabolic law.

(23) Diffusion coefficient of deuterium in high purity beryllium is formularized as follows,

extra grade(99.8%): $D=6.7\times10^{-9}\exp(-28.4/RT)$ [m^2/s]

high grade(99%) : $D=8.0\times10^{-9}\exp(-35.1/RT)$ [m^2/s]

(24) From the results of thermal release test by thermal desorption spectroscopy after implantation of deuterium (5keV) to beryllium by accelerator, it becomes clear that thermal release starts from 200°C and it has peak at about 400°C.

(25) Diffusion coefficient of tritium in beryllium is formularized as follows,

$$\log D=-(6.53\pm0.15)-(965\pm106)T^{-1}\ [cm^2/s]\quad (T: \text{Temperature(K)}).$$

or

$$D=8.7\times10^4\exp(-2.9\times10^5/R/T)\ [cm^2/s]\quad (T: \text{Temperature(K)},\ R: 8.31J/mol/K).$$

(26) Solubility of tritium in beryllium is formularized as follows,

$$\log S=(2.12\pm0.27)-(0.095\pm0.211)T^{-1}\ [Std.ml/g/atm^{1/2}]\quad (T: \text{Temperature(K)}).$$

(27) Concerning safety, the safe heating limits on beryllium are 700°C.

Acknowledgement

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