PROCEEDINGS
2ND IEA INTERNATIONAL WORKSHOP
ON BERYLLIUM TECHNOLOGY FOR FUSION

September 6-8, 1995
Jackson Lake Lodge, Wyoming

Glen R. Longhurst

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Lockheed Martin Idaho Technologies
P.O. Box 1625
Idaho Falls, ID 83415
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
RECOMMENDED DESIGN CORRELATIONS FOR S-65 BERYLLIUM

M. C. Billone
Fusion Power Program
Energy Technology Division (Bldg. 212)
Argonne National Laboratory, Argonne, IL 60439
Telephone: (708)252-7146
Fax: (708)252-4798
E-Mail: mike_billone@qmgate.anl.gov

ABSTRACT

The properties of tritium and helium behavior in irradiated beryllium are reviewed, along with the thermal-mechanical properties needed for ITER design analysis. Correlations are developed to describe the performance of beryllium in a fusion reactor environment. While this paper focuses on the use of beryllium as a plasma-facing component (PFC) material, the correlations presented here can also be used to describe the performance of beryllium as a neutron multiplier for a tritium breeding blanket.

The performance properties for beryllium are subdivided into two categories: properties which do not change with irradiation damage to the bulk of the material; and properties which are degraded by neutron irradiation. The irradiation-independent properties described within are: thermal conductivity, specific heat capacity, thermal expansion, and elastic constants. Irradiation-dependent properties include: yield strength, ultimate tensile strength, plastic tangent modulus, uniform and total tensile elongation, thermal and irradiation-induced creep strength, He-induced swelling and tritium retention/release.

The approach taken in developing properties correlations is to describe the behavior of dense, pressed S-65 beryllium -- the material chosen for ITER PFC application -- as a function of temperature. As there are essentially no data on the performance of porous and/or irradiated S-65 beryllium, the degradation of properties with as-fabricated porosity and irradiation are determined from the broad data base on S-200F, as well as other types and grades, and applied to S-65 beryllium by scaling factors. The resulting correlations can be used for Be produced by vacuum hot pressing (VHP) and cold-pressing(CP)/sintering(S)/hot-isostatic-pressing(HIP). The performance of plasma-sprayed beryllium is discussed but not quantified.

1. Introduction

Beryllium is being considered as a plasma-facing component (PFC) material for ITER. The specific type of beryllium chosen for the PFC application is S-65 beryllium, which is characterized by < 1 wt.% BeO content, < 1800 wppm (Al+Mg+Si) content, and ≤ 20 μm.

grain size. The product is made by Brush Wellman by both vacuum hot-pressing (VHP) and cold-pressing (CP)/sintering (S)/hot-isostatic-pressing (HIP). The designation "B" or "C" which follows the label S-65 refers to Brush Wellman internal quality control specifications and has no significance with regard to properties of the final product. The product form for the PFC application will probably be VHP or CP/S/HIP tiles which are about 5-mm thick. Plasma-sprayed Be is also being considered for fabrication. In either case, it is planned to use plasma-spray techniques to repair sputtered Be layers in situ. Thus, the properties of both pressed and plasma-sprayed Be are of interest.

There are essentially no data available on porous and/or irradiated S-65 Be in either the pressed or plasma-sprayed product form. The material has been irradiated in European test programs, but the samples have not yet been analyzed. However, there is a large fission reactor data base for dense and porous S-200F Be, which allows a higher maximum BeO content (1.5 wt.%). In practice there is some overlap between S-200F and S-65 Be in that the actual BeO content of a particular lot of S-200F may be as low as 0.9 wt.% BeO. Because of this similarity and because of the absence of irradiation data for S-65 Be, the irradiation behavior of S-200F, as well as other grades of Be, is used to predict the behavior of S-65 Be.

Based on the anticipated ITER operating conditions for a lifetime fluence of 1 MW*a/m², the operating ranges for the PFC Be are: 100 ≤ T ≤ 600°C, ≤ 3000 appm He, ≤ 60 appm tritium, and ≤ 7 dpa. The He, tritium and neutron damage levels all scale with first-wall fluence if higher design lifetimes (e.g., 3 MW-a/m²) are desired. Because the He/dpa ratio for Be is so much higher than for other first-wall metals, the He content and distribution in Be tends to determine swelling and mechanical performance. Thus, swelling and mechanical performance parameters are correlated to He content in this work, as opposed to the traditional approach of correlating to neutron damage in dpa for steels, copper alloys, and vanadium alloys.

The correlations presented here for thermal-mechanical performance parameters apply to pressed (both VHP and CP/S/HIP) Be. The properties are correlated to as-fabricated (p) and He-generated (ΔV/V₀) porosity fraction, temperature (T in K) and He content (CHe in appm). It is very difficult to characterized plasma-sprayed Be because of the wide ranges of porosity content and distribution, grain and particle sizes, shapes and distributions, and post-spray heat treatments. The designer should be aware of the fact that the plasma-sprayed layer of Be which replaces the sputtered layer will have significantly different properties than the original layer. Also, any heat treatment used in the tile-repair may affect the properties of the base metal if the temperature is high enough (e.g., > 600°C).

The thermal properties presented in this work are thermal conductivity (k in W/m*K), specific heat capacity (Cp in kJ/kg*K), and thermal expansion (ΔL/L₀ in %). These properties are relatively independent of the particular grade of Be. Also, with the exception of possible He-induced swelling effects on conductivity, they are considered to be independent of irradiation. Mechanical properties considered are Young's modulus (E in GPa), Poisson's ratio (ν), yield strength (S₀ in MPa), plastic tangent modulus (Eₚ in Gpa),
ultimate tensile strength ($S_{ut}$ in Mpa), uniform elongation (UE in %), total elongation (TE in %), thermal creep ($e_c^{th}$), irradiation creep ($e_c^{ir}$) and He-induced swelling ($\Delta V/V_0$ in %). Tritium retention performance is also summarized. The elastic constants ($E$ and $\mu$) are considered to be independent of irradiation, while the remaining parameters are assumed to vary according to the accumulated He concentration. There are three survey-type references used for developing the recommended correlations: Billone, et al., Billone, Dalle Donne and Macaulay-Newcombe, and Barabash. Primary sources are referred to in the cases of newer data or to resolve conflicting viewpoints in the three survey references.

2. Irradiation-Independent Properties

The following properties are considered to be independent of irradiation as far as neutron damage to the material bulk is concerned. For those properties which depend on porosity ($p$), either as-fabricated or He-induced, a porosity dependent term is included in the correlation.

2.1 Thermal Properties

The thermal conductivity, specific heat capacity and thermal expansion recommended by Billone, et al. for Be are:

$$k = 291 f_p (1 - 1.650 \times 10^{-3} T + 1.464 \times 10^{-6} T^2 - 5.125 \times 10^{-10} T^3)$$  \hspace{1cm} (1)

where

$$f_p = (1 - p)(1 + 3.7p^2)^{-1}$$  \hspace{1cm} (1a)

$$C_p = 2.432 (1 + 2.643 \times 10^{-4} T - 2.924 \times 10^{-4} T^{-2})$$  \hspace{1cm} (2)

and

$$\frac{\Delta L}{L_o} = 8.43 \times 10^{-4} (1 + 1.36 \times 10^{-3} T - 3.53 \times 10^{-7} T^2) (T - 298)$$  \hspace{1cm} (3)

The thermal conductivity correlation is based on data up to 700°C. The data are relatively insensitive to the specific type or grade of Be. Although the S-65 data were not used to develop the correlation, the correlation matches the data to within 0.6% on the average between room temperature and 700°C. Extrapolation beyond the data base should give reasonable results. Use of the correlation for ITER design analysis involves interpolation within the data set. The heat capacity correlation is based on data up to the melting temperature of Be and applies to all types and grades of Be. It matches the specific data set for S-65 Be to within 2% which is also well within experimental error. Similarly, the thermal expansion correlation is based on data up to the melting temperature of Be. It matches the specific data set for S-65 Be to within 0.7%.
2.2 Elastic Constants

There are two basic experimental techniques for determining Young's modulus and Poisson's ratio: dynamic techniques involving either sonic or vibration methods or static techniques based on tensile stress-strain data. The dynamic techniques give a more accurate measurement of the elastic constants, which should be dependent on the strength of interatomic bonds and relatively insensitive to impurities and fabrication techniques. Also, based on dynamic determinations of Young's moduli for a large number of metals, the decrease with temperature is generally \(< 25\%\) from room temperature up to the melting temperature. Static (really slow strain rate) tensile-tests suffer from a precision/calibration problem at the very low elastic strains. Also, as temperature increases, the apparent Young's modulus determined from tensile tests decreases quite rapidly with temperature, possibly due to other deformation mechanisms (e.g., creep). The tensile-test results can be as much as an order of magnitude low as compared to the true Young's modulus. This perhaps explains the wide variation in reported Young's modulus values with BeO content, microstructure and strain rate. Figure 1 shows the dynamic and static data\(^6\) for very dense Be.

The recommended correlations for Young's modulus (E in GPa) and Poisson's ratio (\(\nu\)) are:

\[
E = 300 \exp(-4.574p)[1 - 2.016 \times 10^{-4}(T-293)]
\]

\[
\nu = 0.08 \pm 0.02
\]

The porosity dependence is based on the large number of data points for VHP and CP/S/HIP S-200 Be with as-fabricated porosities in the range of 0 to 0.3 (30\%) at 20° C and 370° C. It can also be used to describe the effects of He-induced swelling on the Young's modulus.

3. Irradiation-Dependent Properties

3.1 Tensile Yield Strength

Tensile yield strength (i.e., stress at 0.2\% plastic strain) data have been reviewed for unirradiated, dense, powder-metallurgy-produced S-65 Be\(^5,6\), S-200E Be\(^5,6\), S-200F Be\(^7\) and various grades of Be containing \(< 2\text{ wt.\% BeO}\)^\(^8,9\). Figure 2 shows the comparison between the recommended correlation for S-65 Be, the data for S-65 Be and the data for all grades of S-200 Be. The correlation which was obtained by fitting the S-65 data is:

\[
S_{yo} = 272f_p[1 - 7.675 \times 10^{-4}(T-293) - 3.393 \times 10^{-7}(T-293)^2]
\]

where \(f_p = \exp(-3.23p)\) based on HP and CP/S/HIP data for S-200F Be\(^2,3\).
Figure 1. Comparison of the recommended correlation and the dynamic data (all grades) and static data (S-65) for the Young’s modulus of dense beryllium.

In terms of irradiation effects on yield stress, most stress/strain tests on irradiated material have been conducted in compression because of the low tensile ductility of irradiated Be. The increase in compressive yield stress with He content is characterized for these tests and used to scale the tensile yield behavior. For S-200 Be irradiated in EBR-II at about 470°C and postirradiation tested at 450°C, the compressive yield strength increased from about 180 MPa to 294 MPa.10 The irradiated samples contained about 1600 appm He. Assuming a square-root dependence of yield strength on He content to get the saturation of hardness with irradiation which has been observed gives:

\[
\frac{S_{yc}}{S_{yc0}} = 1 + 1.6 \times 10^{-2} (C_{He})^{0.5}
\]  

(6a)

In the absence of well-characterized tensile data on Be irradiated and tested at the same
Figure 2. Recommended correlation and data for the tensile yield strength of unirradiated, dense, pressed S-65 and S-200 grades of Be.

temperature, it is assumed that Eq. 6a holds for tension as well as compression and that the irradiation effect is temperature independent up to the ITER-relevant temperature limit of 600°C. The recommended correlation for the irradiation effects on tensile yield strength is

\[ S_{yt} = \left[ 1 + 1.6 \times 10^{-2} (C_{Be})^{0.5} \right] S_{y0} \]  \hspace{1cm} (6b)

It should be mentioned that annealing of the irradiated samples in Ref 10 at 900°C and then testing at 500°C reduced the compressive yield strength down to levels of 100 - 200 Mpa. Thus, the irradiation effects on yield strength are somewhat reversible.

Also, irradiation and testing at lower temperatures (20 - 100°C) will most likely generate
higher yield strength values than would be calculated by Eq. 6b. Based on the work of Beeston et al.,11 the compressive yield strength of 97%-dense CIP/S/HIP Be was 216 MPa before irradiation and 930 MPa after irradiation at 75°C to 872 appm He. This gives an irradiated-to-unirradiated ratio of 4.3, while Eq. 6a gives a ratio of only 1.5. However, Eq. 6b is still recommended for ITER design analysis because the tests were conducted at a temperature characteristic of the average-to-maximum range for ITER PFC Be and the He content corresponds to about 0.5 MW·a/m².

3.2 Ultimate Tensile Strength

The treatment of the ultimate tensile strength (S_u) parallels that of the tensile yield strength. The references are also the same. The recommended correlation for unirradiated S-65 Be is

\[ S_{uo} = 438f_p [1 - 8.9 \times 10^{-5}(T - 293) - 3.83 \times 10^{-6}(T - 293)^2 + 3.7 \times 10^{-6}(T - 293)^3] \]  

(7)

where \( f_p = \exp(-4.733p) \) based on room-temperature data for VHP and CIP/S S-200F Be. Figure 3 shows the comparison of Eq. 7 and the S-65 data, as well as various lots of S-200 Be. Notice that S-65 Be tends to have higher ultimate tensile strength values for T ≤ 400°C, but the strength of S-65 Be is comparable to the S-200 grades at > 400°C.

For the EBR-II-irradiated S-200F Be, the ultimate compressive strength increased from about 250 MPa for unirradiated material at 450°C to an average of 940 MPa for material irradiated at about 470°C to an average of 1600 appm and tested at 450°C. The irradiation effects on ultimate compressive, as well as tensile, strength are assumed to be

\[ S_{uc} = \left[ 1 + 9.0 \times 10^{-3} (C_{He})^{0.5} \right] S_{uco} \]  

(7a)

and

\[ S_{uc} = \left[ 1 + 9.0 \times 10^{-3} (C_{He})^{0.5} \right] S_{uco} \]  

(7b)

Annealing at 900°C for 1 hour reduced the \( S_{uc} \) values for the irradiated samples to those of the unirradiated samples.

Low temperature ATR irradiation of S-200F Be to 872 appm He increased the room-temperature \( S_{uc} \) values from 310 MPa to 982 MPa. This factor of 3.2 increase is higher than the value of 1.3 predicted by Eq. 7a, again indicating a temperature effect on the irradiation hardening. Until this temperature effect is characterized over a wider range of temperatures, Eq. 7b is recommended for ITER design analysis because the data set on which the equation is based is closer to the anticipated operating conditions for PFC Be.

While engineering values of yield strength for Be are within the scatter of the data for both tension and compression, the engineering ultimate strength is often lower in tension than in compression. The specimen in the tensile test undergoes thinning and necking prior to cracking, while the compressive specimen undergoes "barreling" prior to cracking. If the
Figure 3. Recommended correlation and data for the ultimate tensile strength of unirradiated, dense S-65 beryllium. The data for various grades of S-200 Be are also shown.

Tension and compression data are converted to true stress-strain values, then the plastic behavior of Be is essentially the same in tension and compression. The apparent difference in behavior based on graphs of engineering stress-strain is primarily a geometric, and not a material, effect. This is important in defining a plastic tangent modulus for bi-linear modeling, which is done in the next section.

3.3 Plastic Tangent Modulus

A bi-linear representation of the engineering stress-strain behavior is recommended for ITER design analysis. In the elastic regime, the uniaxial stress (s)-strain (e) behavior is given by: $e = s/E$. In the bi-linear representation, this equation is used for $s < S_y$. For
The constitutive equation for the bi-linear model is:

\[ e = \frac{s}{E} + \frac{(s - S_p)}{E_p} \]

where \( E_p \) is the plastic tangent modulus. With \( E \) given by Eq. 4 and \( S_p \) given by Eqs. 6 and 6b, it remains to specify \( E_p \).

Beeston\textsuperscript{12} has published some engineering tensile stress-strain curves for unirradiated, dense VHP S-200 Be. Approximate values of the tangent modulus in the plastic strain range of 0.2 to 0.7% are 7 GPa at 20°C, 4.4 GPa at 427°C, 2.9 GPa at 538°C and about 0 at 826°C. An approximate linear fit to these data is:

\[ E_{po} = 7.0[1 - 1.0 \times 10^{-3}(T - 293)] \]  

For similar material irradiated in EBR-II at about 470°C to about 1600 appm He, the post-irradiation tangent modulus between 0.2% and 0.4% compressive strain was 26 GPa for a test temperature of 450°C and 15 GPa for a test temperature of 550°C. Thus, a crude approximation for the tangent modulus as a function of temperature and He content is:

\[ E_p = 7.0[1 + 0.41(C_{He})^{0.5}][1 - 1.0 \times 10^{-3}(T - 293)] \]  

3.4 Tensile Ductility

It is very difficult to find uniform elongation data for beryllium. Generally, total elongation is quoted in the literature. Sometimes, total elongation, uniform elongation and uniform ductility are used as interchangeable terms, and it is not clear what data are being presented. It is assumed in this review, that, unless otherwise specified, all data refer to total elongation. The tensile ductility (\( \varepsilon_{uo} \)) of unirradiated S-65 Be\textsuperscript{5,6} can be correlated to temperature and as-fabricated porosity according to:

\[ \varepsilon_{uo} = (4.2 \pm 1.2\%) \exp(-8.0p)[1 - 2.0384 \times 10^{-2}(T - 293) + 2.7244 \times 10^{-4}(T - 293)^2 - 3.836 \times 10^{-7}(T - 293)^3] \]  

where the porosity dependence is based on data for S-200 Be.\textsuperscript{3}

Although no data are available for irradiated S-65 Be, the tensile ductility of S-200 Be drops to about 0.2% after modest irradiation in a fission reactor, while the compressive ductility decreases to about 0.6%. Beeston, et al.\textsuperscript{10} report an average compressive uniform elongation of 0.4% for S-200 Be irradiated in EBR-II at about 470°C to about 1600 appm He and post-irradiation tested at 450°C and 550°C. The unirradiated compressive ductility for these samples was about 30%. This value decreased to 14% for samples with irradiation/test temperatures of 470/450 °C. Annealing at 900°C for one hour restored the ductility back to the unirradiated value. Thus, a crude scaling of ductility with He content can be expressed by:

\[ \varepsilon_u = \varepsilon_{uo}[1 + 2.86 \times 10^{-2}(C_{He})^{0.5}]^{-1} \]  

(10a)
3.5 Thermal and Irradiation Creep

The thermal \( e^{\text{th}}_c \) in absolute units and irradiation \( e^i_c \) in absolute units) of Be have been expressed as functions of porosity \( p \) in absolute units, temperature \( T \) in K, effective stress \( s \) in MPa, time \( t \) in s) and neutron damage \( D \) in dpa as:

\[
e^{\text{th}}_c = 0.751 (1 - p^{2/3})^{-3.6} \exp(-2.60 \times 10^4 / T) s^{3.6} t
\]

and

\[
e^i_c = 3.2 \times 10^{-6} (1 - p^{2/3})^{-1} s D
\]

The thermal creep of Be tends to decrease with increasing grain size and BeO content and increase with increasing impurity levels of Al, Mg, and Si. At about 980°C, increasing the \((\text{Al} + \text{Mg} + \text{Si})\) content from 100 wppm to 1000 wppm resulted in an increase of a factor of 9 in the stress required to produce a creep rate of \(10^{-4} \text{ s}^{-1}\). Above 1000 wppm (which includes S-65 Be), the creep rate is relatively insensitive to the levels of these impurities. At higher temperatures, the creep rate of Be varies inversely with grain size. However, in the temperature range of 650-760°C, this trend was reversed in high purity Be. For medium purity Be (1 wt.% BeO and 760 wppm Al+Mg+Si), the creep rate was insensitive to grain size in the relevant range of 10 to 50 μm. As these specifications are close to those of S-65 Be, it is recommended that a grain size dependence not be included in Eq. 11.

Crook and Webster\(^1\) report a steady-state thermal creep rate of \(10^{-8} \text{ s}^{-1}\) at 649°C and 10 MPa. Under these conditions, Eq. 11 predicts a creep rate of \(1.7 \times 10^{-9} \text{ s}^{-1}\). Thus, the measure thermal creep rate is a factor of 7 times higher than what is predicted by Eq. 11. While this may seem large to the designer, it should be emphasized that scatter in thermal creep data is generally quite large and that predictions within an order of magnitude are considered adequate. Thus, in the absence of specific thermal creep data for S-65 Be, Eq. 11 is recommended for ITER design analysis.

The irradiation creep correlation represented by Eq. 12 is based on only one data point at 43°C under low dpa and He generation conditions. Thus, the data base is inadequate for validation of the correlation.

3.6 Helium-induced Swelling

The effects of as-fabricated porosity on swelling and irradiation temperature on swelling are not well characterized. Most data are based irradiation at temperatures < 100°C followed by postirradiation anneals from 1 to 24 hours. Also, it has only been within the past five years that the He content in the irradiated samples has been characterized well enough to allow the volumetric swelling (in %) to be correlated to annealing temperature and helium content. Billone et al.\(^2,3\) have proposed a correlation to match the ATR irradiation and post-irradiation annealing data of S-200F Be:
The data base includes He contents up to 26,000 appm and annealing temperatures up to 500°C for one hour. However, with the exception of a few immersion density measurements, most of the data are actually length change measurements. The axial strains are multiplied by three to obtain an estimate of volumetric strain. Also, He content was measured for only a few high burn-up samples.

Sannen et al.\textsuperscript{14,15} have performed extensive studies of the helium content and swelling of BR2-irradiated Be. Samples were irradiated at 60°C up to He contents of 20,000 appm He. One and 24 hour anneals were performed at temperatures in the range of 200 - 800°C. Also, data consisted of both length and diameter change measurements which give a more accurate reading of volumetric swelling than simple length measurements. They used the following correlation to represent their data:

\[
\Delta \frac{V}{V_0} = 1.19 \times 10^{-4} C_{He}[1 + 9.49 \times 10^{-5} C_{He}^{0.5} T^{1.5} \exp(-3940/T)]
\]  

(13)

The correlations tend to underpredict the data for measured swelling in the range of 0.2 - 0.9%, with the Billone correlation (Eq. 13) giving slightly better agreement with the data than either of the Sannen correlations. However, the validity of the comparison of correlations to data depends on the relevance of the He measurements in the EBR-II samples after post-irradiation fracturing to the He contained in the specimens during irradiation. Clearly, what is needed for validation of correlations for ITER application is another set of data for Be irradiated at temperatures from 400 - 600°C with well-characterized He contents in the range of 3000 - 9000 appm.

In choosing a design correlation for ITER for calculation of Be swelling during normal operation, as well as over-heating events, it is useful to compare Eqs. 13 and 14 to determine which correlation is an upper bound. The comparison between the Billone correlation (Eq. 13) and the Sannen correlation (Eq. 14) based on the 24-hour anneals is shown in Fig. 5 for 3000 appm He (1 MW•a/m²) and 9000 appm He (3 MW•a/m²). The agreement between the correlations is quite good for temperatures < 450°C. In the range of 450 - 600°C and for higher temperatures, Eq. 13 is an upper bound to Eq. 14. Thus, the
Figure 4. Comparison of the EBR-II swelling data and the swelling correlations of Billone et al.\textsuperscript{23} (based on 1-hour anneals) and of Sannen\textsuperscript{15} (based on 1- and 24-hour anneals). The EBR-II data are for temperatures of 427 - 487°C and He contents of 1000 - 2000 appm.

Billone correlation is recommended for ITER design analysis. There is very good confidence in using this correlation to predict the swelling of Be under normal operating conditions for $T \leq 400°C$ and for overheating events of $< 24$-hour duration up to $800°C$. However, it remains to demonstrate that the correlation is either a best fit or an upper bound for normal operating temperatures of $400 - 600°C$ up to He contents of 9000 appm. Such a validation requires the generation of new data.

In using Eq. 13 to estimate the degradation of properties with swelling porosity, it is important to convert the results of Eq. 13 from percent values to fractional values for use in Eqs. 1a, 4, 6, 7, and 10 - 12. Also, the designer should be aware of the fact that the
swelling of Be with as-fabricated porosity has not yet been characterized due to a lack of data in this area.

4. Tritium Retention

There are no data on tritium retention/release from S-65 Be. Also, there are no relevant data for on-line tritium release. Most of the available data are for pressed S-20OF Be and cast Be based on post-irradiation annealing studies. Table I summarizes the tritium retention/release data gathered so far. The most recent data set is from the SIBELIUS experiment. It appears that as-fabricated porosity, as well as He-induced
swelling, enhances tritium release. No simple design correlation has been found to match these data sets. However, KfK has developed the ANFIBE code to predict tritium, as well as He, behavior in Be.\textsuperscript{5} In the absence of a design correlation, the designer may use the data directly from Table 1 to estimate tritium inventory in Be.

**Table 1.** Summary of tritium and helium retention in beryllium irradiated at low temperature (except for SIBELIUS) and post-irradiation annealed at high temperature. Fast ($E > 1$ MeV) fluence is in units of $10^{22}$ n/cm$^2$.

<table>
<thead>
<tr>
<th>Initial Density %TD</th>
<th>Fab. Form</th>
<th>Fluence/ Irr. T, °C</th>
<th>Tritium/He appm</th>
<th>Anneal T °C</th>
<th>Anneal t Hours</th>
<th>Retained Tritium %</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>HIP</td>
<td>5.0 ± 0.3/75</td>
<td>2530/26100</td>
<td>300</td>
<td>20-114</td>
<td>99.99</td>
<td>2</td>
</tr>
<tr>
<td>99.6</td>
<td>CIP/S</td>
<td>0.26/75</td>
<td>71.8/872</td>
<td>300</td>
<td>355</td>
<td>99.905</td>
<td>1</td>
</tr>
<tr>
<td>98</td>
<td>Arc-Cast</td>
<td>0.061/550</td>
<td>3.8/140</td>
<td>550</td>
<td>Irrad.</td>
<td>???</td>
<td>17</td>
</tr>
<tr>
<td>80.9</td>
<td>CIP/S</td>
<td>0.26/75</td>
<td>55.3/733</td>
<td>300</td>
<td>386</td>
<td>96.8</td>
<td>2</td>
</tr>
</tbody>
</table>

5. Discussion

As stated in the introduction, the correlations presented in this work apply to vacuum hot-pressed and/or cold-pressed/sintered/hot-isostatic-pressed Be. In cases for which baseline data for 100% dense, unirradiated, pressed S-65 Be are available, correlations are developed for the performance of this material as a function of temperature. Porosity-dependent and He-dependent terms are developed based on data for pressed S-200 Be, with an emphasis on S-200F material. These terms are then applied to the S-65 Be correlations.
It is difficult to characterize the performance of plasma-sprayed Be. Without post-spray heat treatment, the thermal conductivity of plasma-sprayed Be tends to be significantly lower, particularly in the spray direction, from what is obtained from Eqs. 1, la. Optimization of particle size, shape and purity, along with spraying techniques, have led to densities as high as 95% and thermal conductivities as high as 70% of what is predicted by Eqs. 1, la. The mechanical properties of plasma-sprayed Be are quite poor in terms of ductility and strength. Post-spray heat treatments, which may not be practical for ITER applications, have resulted in strengths and ductilities even higher than for pressed Be.

Given that plasma-spraying is an evolving art and given the near-impossibility of characterizing plasma-sprayed Be as a class of materials independent of specific data for a specific technique, it is recommended that the designer use the properties of pressed Be for the design analysis. If problems arise in the performance of pressed Be, then the designer should be aware that these problems will only get worse for plasma-sprayed Be. Exceptions to this are in the areas of Be/copper/steel mechanical interaction where the plasma-sprayed Be may be too weak to exert much force on the other layers, and tritium retention and He-induced swelling for which the plasma-sprayed Be may release more tritium and He than a corresponding pressed Be.

References


