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**SUMMARY OF MECHANICAL
PROPERTIES DATA AND CORRELATIONS
FOR Li_2O , Li_4SiO_4 , LiAlO_2 , and Be^***

by

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SUMMARY OF MECHANICAL PROPERTIES DATA AND CORRELATIONS FOR Li_2O , Li_4SiO_4 , LiAlO_2 , and Be

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ABSTRACT

While considerable effort has been devoted to characterizing the heat and tritium transport properties of fusion solid breeder and multiplier materials, relatively little attention has been focused on determining mechanical properties. Even though breeders and multipliers are not "structural" materials designed to be load-bearing components, their deformation behavior can affect the design life of the blanket. In particular, thermal expansion and helium-induced swelling of these materials relative to the structural blanket materials can cause breeder-structure mechanical interaction (BSMI) which needs to be assessed in any lifetime calculation. Also, micro- and macro-cracking of these materials due to differential expansion stresses can cause added resistance to heat transfer, as well as provide a source for localized BSMI.

The data base for thermal expansion, elastic constants, compressive and tensile failure strengths and secondary thermal creep of leading solid-breeder (Li_2O , Li_4SiO_4 , and LiAlO_2) and multiplier (Be) materials is reviewed. Correlations for these properties are presented as a function of temperature, porosity, grain size, and stress (for thermal creep). Because the data base is rather sparse in some areas, general properties of ceramics and metals are used to help guide the formulation of the correlations.

The primary purpose of the data base summary and correlation development is to pave the way for stress analysis sensitivity studies. These studies will help determine which properties are important enough to structural lifetime and deformation assessments to require more data.

1. INTRODUCTION

The Materials Handbook For Fusion Energy Systems (MHFFES)⁽¹⁾ contains a limited number of physical and thermal properties for lithium-based ceramics which are candidates for fusion solid breeder blankets. Several other

publications are available for physical and thermal transport properties.^(2,3) With the exception of the "FNT Progress Report: Modeling and FINESSE" published in January 1987,⁽³⁾ relatively little attention has been focused on analyzing the mechanical properties data base and developing correlations to interpolate and extrapolate from this data base.

In this current effort, the mechanical properties data base generated at Argonne National Laboratory is combined with the mechanical properties data generated at the European laboratories to summarize the data available in reports and publications through October 1987. The materials considered are those which were leading blanket candidates in the INTOR design study and are leading candidates in the current ITER design effort: Li_2O , Li_4SiO_4 , LiAlO_2 , and Be. The properties data reviewed are for elastic constants, compressive and tensile failure strength and secondary thermal creep. Although this data base is relatively sparse, preliminary correlations are developed for these properties as functions of temperature, grain size, porosity volume fraction and stress (in the case of thermal creep). The format adopted for the tables of values is the same as that used in the MHHFES with one important exception. While the MHHFES lists tables of values for thermal properties correlations as a function of temperature, in this report the tables list data and a comparison of correlation values with data. The emphasis is on communicating to the fusion community the extent and limitations of the data base and correlations, rather than on generating a set of numbers to be used blindly in design calculations.

In a number of cases, no data are available. For these cases, "best estimates" were made based on the properties of metals and other ceramics. The intent of this work is to help identify where we are in our attempt to understand and predict the mechanical behavior of non-structural blanket materials and where we should be heading. For example, two design issues of interest are: cracking of solid breeder ceramics and breeder-structure-mechanical interaction (BSMI). While solid breeders are not structural materials, micro- and macro-cracking of these materials could affect the heat transport paths and the temperature distribution. Macro-cracks could also cause sites of stress concentration on the structural material. The issue of BSMI is important in lifetime calculations, particularly if the structural lifetime is less than the goal burnup based on tritium considerations. The

correlations presented in this report are meant as a starting point for evaluating whether the candidate solid breeder materials are relatively "hard" or "soft" compared to the candidate structural materials. The results of sensitivity studies based on the correlations presented here will help determine which properties need to be measured over a wider range of temperature and microstructural variables.

2. MECHANICAL PROPERTY DATA AND CORRELATIONS

2.1 Thermal Expansion

While thermal expansion is not formally a mechanical property, it is an important parameter in the mechanical analysis of the blanket. The mean coefficient of linear thermal expansion is defined as:

$$\alpha_m = (\Delta l/l_0)/(T-T_r), \quad (1)$$

where $\Delta l/l_0$ is thermal strain, T is temperature in K, and T_r is the reference temperature (298K). The α_m correlations for Li_2O , Li_4SiO_4 and LiAlO_2 are derived from the instantaneous thermal expansion coefficients given in Ref. 1. It should be noted that crystal-lattice-expansion data⁽⁵⁾ suggest a discontinuity in α_m for Li_4SiO_4 at 825K whereas the bulk expansion data do not. The correlation chosen for Li_4SiO_4 applies to bulk expansion. For Be the data summarized by Touloukian, et al.,⁽⁶⁾ are used. The recommended correlations are:

$$\text{Li}_2\text{O}: \quad \alpha_m = 18.7 (1 + 4.49 \times 10^{-4}T), \text{ } \mu\text{m/m-K} \quad (1a)$$

$$\text{Li}_4\text{SiO}_4: \quad \alpha_m = 16.7 (1 + 4.96 \times 10^{-4}T), \text{ } \mu\text{m/m-K} \quad (1b)$$

$$\text{LiAlO}_2: \quad \alpha_m = 8.98 (1 + 2.76 \times 10^{-4}T), \text{ } \mu\text{m/m-K} \quad (1c)$$

$$\text{Be}: \quad \alpha_m = 8.43 (1 + 1.36 \times 10^{-3}T - 3.53 \times 10^{-7}T^2), \text{ } \mu\text{m/m-K} \quad (1d)$$

It is generally accepted that thermal expansion coefficients are independent of microstructural parameters, such as grain size and porosity, and independent of irradiation. However, burnups high enough to cause

significant chemical compositional changes could affect the overall thermal expansion behavior of the ceramics. The correlations for α_m and the resulting thermal strains are plotted in Fig. 1. The dashed lines indicate extrapolations of the correlations outside the data base. The thermal expansion behavior of two fusion structural materials (austenitic PCA and ferritic HT9) are also plotted in Fig. 1 for reference purposes. The thermal expansions of Li_2O and Li_4SiO_4 are high relative to the structural materials, while that of LiAlO_2 is relatively low. For breeder-in-plate and breeder-in-tube designs, this difference in breeder-structure thermal expansion should be accommodated by gaps to avoid BSMI during start-up and subsequent cycling.

2.2 Elastic Constants

2.2.1 Young's Modulus

Young's modulus (E) is a function of temperature (T) and porosity volume fraction (P). The general form of equation assumed for this property is taken to be:

$$E = E_0 \exp(-b P) [1 - a(T-293)], \quad (2)$$

where a and b are constants and E_0 is the room temperature value. In the absence of porosity-dependent data, a value of $b = 3.5$ is assumed based on the behavior of other ceramics⁽⁷⁾ [e.g., UO_2 ($b = 1.8$), BeO ($b = 3.4$), Al_2O_3 ($b = 4.0$), and MgO ($b = 4.7$)]. In the absence of temperature-dependent data, a is assumed to scale as the melting temperature to give ~40% reduction in E from room temperature to melting. This is based on results for a variety of metals⁽⁸⁾ and oxide ceramics.⁽⁹⁾

Li_2O

The room temperature value of Young's modulus for 93% TD Li_2O has been measured sonically to be 110 GPa.⁽⁷⁾ The equation recommended for extrapolation to other temperatures and porosities is:

Fig. 1 Calculated thermal expansion strains and coefficients for solid breeder ceramics and Be multiplier. PCA and HT9 curves are also shown.

$$E = 141 \exp(-3.5 P)[1 - 2.3 \times 10^{-4}(T - 293)], \text{ GPa} \quad (2a)$$

No data were available for the Young's modulus of Li₄SiO₄. It was assumed that the behavior of this material is between that of Li₂O⁽⁷⁾ and Li₂SiO₃:⁽¹⁰⁾

$$E = 114 \exp(-3.5 P)[1 - 2.5 \times 10^{-4}(T - 293)], \text{ GPa.} \quad (2b)$$

Since this correlation was developed, some data have been generated on the Young's modulus of this material.⁽¹⁴⁾ Table 2 shows that the correlation is a reasonable fit to this limited data.

Rasneur⁽¹¹⁾ has measured sonically the Young's modulus of 50 - 90% TD LiAlO₂ at room temperature and 700°C. His empirical correlation has a slightly different functional dependency on porosity than the one assumed here. Using Eq. 2 to fit his data at P = 0.254 gives:

$$E = 185 \exp(-5.0 P)[1 - 1.1 \times 10^{-4}(T - 293)], \text{ GPa.} \quad (2c)$$

Darwin and Buddery⁽¹²⁾ summarize the data for Young's modulus for Be for a wide variety of polycrystalline samples. The room temperature data are relatively insensitive to fabrication method and BeO content in the range of 0-3 wt.%. At higher temperature, these variables become important. The E values of 297 GPa at room temperature and 255 GPa at 760°C were used to obtain the following fit:

$$E = 297 \exp(-3.5P)[1 - 1.9 \times 10^{-4}(T - 293)], \text{ GPa} \quad (2d)$$

Summary

Tables 1-4 summarize the data and correlation values (in parentheses). Figure 2 contains a sample plot of E versus T for 80% dense ceramics and Be. The Young's modulus curves for two fusion structural materials (PCA and HT9) are also shown as references. The porous ceramics are relatively "soft" with respect to Young's modulus compared to the structural materials. To the first order, Young's modulus should be independent of grain size and irradiation. Burnups high enough to cause a significant compositional change may affect the elastic behavior of the ceramic materials.

2.2.2 Poisson's Ratio

Poisson's ratio (ν) generally is within the range of 0.10 - 0.35 for ceramics. It has a slight temperature dependence, either increasing with temperature (e.g., metals) or decreasing with temperature (e.g., ceramics). It may also be dependent on porosity. Because of the scarcity of data, the first order approximation of temperature and porosity independence is assumed in this section.

Li₂O

The sonically measured value for 93% TD Li₂O at room temperature is 0.19.⁽⁷⁾

$$\nu = 0.19$$

Li₄SiO₄

No data are available. Assume

$$\nu = 0.19$$

LiAlO₂

The limited data from Ref. 10 indicate that

$$\nu = 0.19$$

Table 1

Young's Modulus Data for Li_2O . Correlation
values are in parentheses.

Material: Li_2O			Property: Young's Modulus (E)		
<u>T, K</u>	<u>P</u>	<u>E, GPa</u>	<u>T, K</u>	<u>P</u>	<u>E, GPa</u>
293	0.07	110 (110)			
	0.20	73 $\pm$ 4 (70)			

$$E = 141 \exp(-3.5 P) [1 - 2.3 \times 10^{-4} (T - 293)], \text{ GPa. Data from Ref. 7 and 10.}$$

Table 2

Young's Modulus Data for Li_4SiO_4 . Correlation values are in parentheses.

Material: Li_4SiO_4			Property: Young's Modulus (E)		
<u>T, K</u>	<u>P</u>	<u>E, GPa</u>	<u>T, K</u>	<u>P</u>	<u>E, GPa</u>
293	0.02	82.8 (106)			
	0.04	94.9* (99.1)			
	0.07	103.2** (89.2)			
	0.23	57.1* (51.0)			
	0.32	38.2** (37.2)			

$E = 114 \exp(-3.5 P)[1 - 2.5 \times 10^{-4}(T - 293)]$, GPa. Data are from Ref. 14.

*Samples from the same batch of material.

**Samples from the same batch of material.

Table 3

Young's Modulus Data for LiAlO_2 . Correlation values are in parentheses.

Material: LiAlO_2			Property: Young's Modulus (E)		
<u>T, K</u>	<u>P</u>	<u>E, GPa</u>	<u>T, K</u>	<u>P</u>	<u>E, GPa</u>
293	0.10	122 (112)			
	0.20	75 (68)			
	0.254	52 ^a (52)			
	0.30	42 (41)			
	0.40	20 (25)			
	0.50	8 (15)			
973	0.254	48 ^a (48)			

$E = 185 \exp(-5.0 P)[1 - 1.1 \times 10^{-4}(T - 293)]$, GPa. Values listed without parentheses are from Rasneur's⁽¹¹⁾ correlation with the exception of those marked with superscript "a" which are from data.

Table 4

Young's Modulus Data for Be. Correlation
values are in parentheses.

Material: Be			Property: Young's Modulus (E)		
<u>T, K</u>	<u>P</u>	<u>E, GPa</u>	<u>T, K</u>	<u>P</u>	<u>E, GPa</u>
293	~ 0	297 ^a (297)			
698	~ 0	296 (274)			
813	~ 0	264-285 (268)			
923	~ 0	207-255 (261)			
1003	~ 0	169-255 (257)			
1033	~ 0	255 ^a (255)			
1088	~ 0	90-160 (252)			

$E = 297 \exp(-3.5 P)[1 - 1.9 \times 10^{-4}(T - 293)]$, GPa. Data from Ref. 12.

Superscript "a" data are more reliable data, based on sonic measuring techniques.

Fig. 2 Calculated Young's Modulus values for 80% TD solid breeder and multiplier materials. PCA and HT9 curves are also shown.

Be

Ref. 12 reports values in the range of 0.01 - 0.13 at room temperature. Assume

$$\nu = 0.07$$

Summary

Tables 5-8 summarize the data and correlation values (in parentheses).

2.3 Compressive Failure Strength

The compressive failure strength (S_{fc}) depends on grain diameter (d_g), porosity volume fraction (P), and temperature (T). Based on the correlation recommended by Rasneur,⁽¹¹⁾ the following equation form is used:

$$S_{fc} = (A_c / \sqrt{d_g}) \exp(-B_c P) \ln(Q_c / T), \quad (3)$$

where S_{fc} is in MPa, d_g is in μm , and T is in K.

Li₂O

No data are available. The LiAlO₂ correlation of Rasneur⁽¹¹⁾ is used with the parameter A_c scaled by the ratio of the Young's moduli and the parameter Q_c scaled by the absolute melting temperatures of the two materials to give:

$$S_{fc} = (800 / \sqrt{d_g}) \exp(-10 P) \ln(2000/T), \text{ MPa.} \quad (3a)$$

Li₄SiO₄

No data are available. The correlation is developed by assuming Li₄SiO₄ is between the measured compressive failure strength for Li₂SiO₃⁽¹⁰⁾ and the estimated correlation for Li₂O:

Table 5

Poisson's Ratio Data for Li_2O . Correlation
values are in parentheses.

Material: Li_2O			Property: Poisson's Ratio (ν)		
<u>T, K</u>	<u>P</u>	<u>ν</u>	<u>T, K</u>	<u>P</u>	<u>ν</u>
293	0.07	0.19 (0.19)			

$\nu = 0.19$. Datum is from Ref. 7.

Table 6

Poisson's Ratio Data for Li_4SiO_4 . Correlation values are in parentheses.

Material: Li_4SiO_4			Property: Poisson's Ratio (ν)		
<u>T,K</u>	<u>P</u>	<u>ν</u>	<u>T,K</u>	<u>P</u>	<u>ν</u>

$\nu = 0.19$. No data are available.

Table 7

Poisson's Ratio Data for LiAlO_2 . Correlation values are in parentheses.

Material: LiAlO_2			Property: Poisson's Ratio (ν)		
<u>T, K</u>	<u>P</u>	<u>ν</u>	<u>T, K</u>	<u>P</u>	<u>ν</u>
293	0.21	0.20 (0.19)			
	0.26	0.18 (0.19)			

$\nu = 0.19$. Data are from Ref. 10.

Table 8

Poisson's Ratio Data for Be. Correlation
values are in parentheses.

Material: Be			Property: Poisson's Ratio		
<u>T,K</u>	<u>P</u>	<u>ν</u>	<u>T,K</u>	<u>P</u>	<u>ν</u>
293	~ 0	0.01 - 0.13 (0.07)			

$\nu = 0.07$. Data are from Ref. 12.

$$S_{fc} = (940/\sqrt{d_g}) \exp(-7.5 P) \ln(1850/T), \text{ MPa. (3b)}$$

LiAlO₂

Rasneur⁽¹¹⁾ gives the following correlation as a fit to his compressive failure strength data

$$S_{fc} = (1000/\sqrt{d_g}) \exp(-10 P) \ln(2200/T), \text{ MPa. (3c)}$$

The specific data base for this correlation is not given. However, independent data are available from the EXOTIC Project.⁽¹³⁾ These data are compared to Rasneur's correlation in Table 11.

Be

The compressive strength of Be depends greatly on the method of fabrication. Presumably, the important variables are the BeO content and the preferred orientation of this anisotropic material. Room temperature values vary from ~70 MPa to ~350 MPa, depending on the fabrication method. The following correlation is based on uniaxial tensile data for vacuum hot-pressed Q.V.M. Be:⁽¹²⁾

$$S_{fc} = (450/\sqrt{d_g}) \exp(-5 P) \ln(9200/T), \text{ MPa. (3d)}$$

Summary

The compressive failure strength may vary as a function of irradiation and burnup. No data are available at this time to allow an estimate of this variation. Tables 9-12 list the data and the predicted values (in parentheses) from the recommended correlations. Figure 3 is a sample plot of S_{fc} for 80% TD materials with a grain diameter of 10 μ m for all materials except LiAlO₂ (assumed grain diameter of 0.5 μ m for tritium recovery). The ultimate tensile strength of two structural materials (PCA and HT9) are also plotted in Fig. 3 as references. The compressive strength of these structural materials should be at least as large as the ultimate tensile strength.

Table 9

Compressive Failure Strength Data for Li_2O .
Correlation values are in parentheses.

Material: Li_2O				Property: Compressive Failure Strength (S_{fc})			
<u>T, K</u>	<u>d_g, μm</u>	<u>P</u>	<u>S_{fc}, MPa</u>	<u>T, K</u>	<u>d_g, μm</u>	<u>P</u>	<u>S_{fc}, MPa</u>

$$S_{fc} = (800/\sqrt{d_g}) \exp(-10 P) \ln(2000/T), \text{ MPa. No data available.}$$

Table 10

Compressive Failure Strength Data for Li_4SiO_4 .
Correlation values are in parentheses.

Material: Li_4SiO_4				Property: Compressive Failure Strength (S_{fc})			
<u>T, K</u>	<u>d_g, μm</u>	<u>P</u>	<u>S_{fc}, MPa</u>	<u>T, K</u>	<u>d_g, μm</u>	<u>P</u>	<u>S_{fc}, MPa</u>

$$S_{fc} = (940/\sqrt{d_g}) \exp(-7.5 P) \ln(1850/T), \text{ MPa. No data are available.}$$

Table 11

Compressive Failure Strength Data for LiAlO_2 .
Correlation values are in parentheses.

Material: LiAlO_2				Property: Compressive Failure			
Strength (S_{fc})							
T, K	$d_g, \mu m$	P	S_{fc}, MPa	T, K	$d_g, \mu m$	P	S_{fc}, MPa
293	~ 8	0.21	120 (87)				
	~ 1	0.26	220 (150)				

$S_{fc} = (1000/\sqrt{d_g}) \exp(-10 P) \ln(2200/T)$, MPa. Data shown are from Ref. 16.
Rasneur's (11) data are not shown.

Table 12

Compressive Failure Strength Data for Be.
Correlation values are in parentheses.

Material: Be (vacuum hot pressed)				Property: Compressive Failure Strength (S_{fc})			
T, K	$d_g, \mu m$	P	S_{fc}, MPa	T, K	$d_g, \mu m$	P	S_{fc}, MPa
293	17	~ 0	345 (375)	573	17	~ 0	286 (303)
	31	~ 0	286 (278)		51	~ 0	160 (175)
	51	~ 0	225 (217)	673	17	~ 0	265 (285)
	61	~ 0	205 (198)		31	~ 0	211 (211)
473	17	~ 0	305 (324)		51	~ 0	165 (165)
	31	~ 0	242 (240)	773	61	~ 0	145 (151)
	51	~ 0	175 (187)		17	~ 0	233 (270)
	61	~ 0	153 (171)		31	~ 0	195 (200)
					51	~ 0	169 (156)

$S_{fc} = (450/\sqrt{d_g}) \exp(-5 P) \ln(9200/T)$, MPa. Data are for uniaxial
tensile tests from Ref. 12.

Fig. 3 Calculated compressive failure strength for 80% TD breeder and multiplier materials with 10 μm grains (except LiAlO_2). PCA and HT9 curves are also shown.

2.4 Tensile Failure Strength

The correlation form for compressive failure strength is assumed for failure strength (S_{ft}) in tension. For the ceramics, which are generally weaker in tension than in compression, data from bend tests are used. For metallic Be, which behaves essentially the same in tension and compression, uniaxial tensile data are used. The equation form is taken to be:

$$S_{ft} = (A_t / \sqrt{d_g}) \exp(-B_t P) \ln(Q_t/T). \quad (4)$$

Li₂O

The only datum reported⁽¹⁰⁾ for Li₂O is for T = 293K and P = 0.2. The bending stress at failure is given as 50 ± 9 MPa. Unfortunately, no grain size is given. Assuming the sample contained 10 μm grains, the porosity dependence is the same as for Li₄SiO₄, and the temperature dependence is the same as that assumed for the compressive failure strength, gives:

$$S_{ft} = (195 / \sqrt{d_g}) \exp(-4.3 P) \ln(2000/T), \text{ MPa}. \quad (4a)$$

Li₄SiO₄

Bar et al.⁽¹⁴⁾ have measured the room-temperature bending stress at failure for 68-98% TD and 4-50 μm grain-size Li₄SiO₄ samples. The correlation which fits their data with an average deviation of only 10% is:

$$S_{ft} = (150 / \sqrt{d_g}) \exp(-4.3 P) \ln(1850/T), \text{ MPa}. \quad (4b)$$

LiAlO₂

Data are available in Ref. 11 based on bend tests. The correlation developed based on the data is:

$$S_{ft} = (62 / \sqrt{d_g}) \exp(-4.3 P) \ln(2200/T), \text{ MPa}. \quad (4c)$$

Be

The uniaxial tensile data for Be are summarized in Ref. 12. A correlation which matches the data for vacuum hot pressed Q.V.M. Be is:

$$S_{ft} = (450/\sqrt{d_g}) \exp(-5 P) \ln(9200/T), \text{ MPa.} \quad (4d)$$

Summary

The tensile failure strength may vary as a function of irradiation and burnup. No data are available at this time to allow an estimate of this variation. Tables 13-16 list the data and the predicted values (in parentheses) from the recommended correlations. Figure 4 is a sample plot of S_{ft} for 80% TD materials with a grain diameter of $10\mu\text{m}$ for all materials except LiAlO_2 (assumed grain diameter of $0.5\mu\text{m}$ for tritium recovery). Also shown in Fig. 4 are the ultimate tensile strengths for two fusion structural materials (PCA and HT9).

2.5 Creep Properties

The limited creep rate data for lithium ceramics indicate that the creep rate ($\dot{\epsilon}_c$) is dependent upon temperature (T), porosity volume fraction (P), and stress (σ). The functional form assumed for all correlations is:

$$\dot{\epsilon}_c = A(1 - P^{2/3})^{-n} \exp(-Q/RT)\sigma^n, \quad (5)$$

where A, Q, and $n = n(T)$ are material constants and R is the ideal gas constant.

Li_2O

$$\dot{\epsilon}_c = 8.8 \times 10^2 (1 - P^{2/3})^{-n} \exp(-4.04 \times 10^4/T)\sigma^n, \text{ 1/s} \quad (5a)$$

where $n = 5.9$ for $T < 973 \text{ K}$
 $n = 5.9 [1 - 1.1 \times 10^{-3} (T - 973)]$ for $973 \leq T \leq 1123 \text{ K}$
 $n = 4.9$ for $T > 1123 \text{ K}$

Table 13

Tensile (Bending) Failure Strength Data for Li_2O .
Correlation values are in parentheses.

Material: Li_2O				Property: Tensile (Bending) Failure Strength (S_{ft})			
<u>T, K</u>	<u>$d_g, \mu\text{m}$</u>	<u>P</u>	<u>S_{ft}, MPa</u>	<u>T, K</u>	<u>$d_g, \mu\text{m}$</u>	<u>P</u>	<u>S_{ft}, MPa</u>
293	10 (assumed)	0.20	50 ± 9 (50)				

$S_{ft} = (195/\sqrt{d_g}) \exp(-4.3 P) \ln(2000/T)$, MPa. Single data point is from Ref. 10. No grain size is specified.

Table 14

Tensile (Bending) Failure Strength Data for Li_4SiO_4 .
Correlation values are in parentheses.

Material: Li_4SiO_4				Property: Tensile (Bending) Failure Strength (S_{ft})			
<u>T, K</u>	<u>$d_g, \mu\text{m}$</u>	<u>P</u>	<u>S_{ft}, MPa</u>	<u>T, K</u>	<u>$d_g, \mu\text{m}$</u>	<u>P</u>	<u>S_{ft}, MPa</u>
293	4	0.32	35.0 (34.9)				
	5	0.23	41.5 (46.0)				
	10	0.07	58.0 (64.7)				
	25	0.02	43.5 (50.7)				
	50	0.04	33.0 (32.9)				

$S_{ft} = (150/\sqrt{d_g}) \exp(-4.3 P) \ln(1830/T), \text{MPa}$. Data are from bending tests as reported in Ref. 14.

Table 15

Tensile (Bending) Failure Strength Data for LiAlO_2 .
Correlation values are in parentheses.

Material: LiAlO_2				Property: Tensile (Bending) Failure Strength (S_{ft})			
<u>T, K</u>	<u>$d_g, \mu\text{m}$</u>	<u>P</u>	<u>S_{ft}, MPa</u>	<u>T, K</u>	<u>$d_g, \mu\text{m}$</u>	<u>P</u>	<u>S_{ft}, MPa</u>
293	~ 1	0.26	40 ± 7 (41)	873	~ 1	0.26	65 ± 16 (19)
	~ 8	0.21	18 ± 9 (18)		~ 8	0.21	5.2 ± 1.3 (8.2)
	~ 8	0.18	21 ± 4 (20)		~ 8	0.18	11 ± 8 (9.3)
673	~ 1	0.26	48 ± 25 (24)				
	~ 8	0.21	39 ± 4 (11)				
	~ 8	0.18	32 ± 12 (12)				

$$S_{ft} = (62/\sqrt{d_g}) \exp(-4.3 P) \ln(2200/T). \quad \text{Data are for bend tests from Ref. 13.}$$

Table 16

Tensile Failure Strength Data for Be.
Correlation values are in parentheses.

Material: Be (vacuum hot pressed)				Property: Tensile Failure Strength (S_{ft})			
T, K	$d_g, \mu m$	P	S_{fo}, MPa	T, K	$d_g, \mu m$	P	S_{fo}, MPa
293	17	~ 0	345 (375)	573	17	~ 0	286 (303)
	31	~ 0	286 (278)		51	~ 0	160 (175)
	51	~ 0	225 (217)	673	17	~ 0	265 (285)
	61	~ 0	205 (198)		31	~ 0	211 (211)
473	17	~ 0	305 (324)		51	~ 0	165 (165)
	31	~ 0	242 (240)		61	~ 0	145 (151)
	51	~ 0	175 (187)	773	17	~ 0	233 (270)
	61	~ 0	153 (171)		31	~ 0	195 (200)
					51	~ 0	169 (156)

$S_{ft} = (450/\sqrt{d_g}) \exp(-5 P) \ln(9200/T)$, MPa. Data are for uniaxial
tensile tests from Ref. 12.

Fig. 4 Calculated tensile failure strength for 80% TD breeder and multiplier materials with 10 μm grains (except LiAlO₂). PCA and HT9 curves are also shown.

Comparison of correlation predictions to data^(7,16) are shown in Table 17. The correlation matches the data within a factor of 2 for

$$\sigma > 4 \text{ MPa}, 0.07 \leq P \leq 0.27, \text{ and } 973 \leq T \leq 1223 \text{ K.}$$

$$\dot{\epsilon}_c = (1 - P^{2/3})^{-n} \exp(192.3 - 2.62 \times 10^5/T) (0.5\sigma)^n, 1/s$$

where $n = 8.20$ for $T < 1073$
 $n = 6.56 [1 - 5 \times 10^{-3} (T - 1123)]$ for $1073 \leq T \leq 1293$
 $n = 1$ for $T > 1293$

Comparisons of correlation predictions to data⁽¹⁴⁾ are shown in Table 18. In general, for $850 \leq T \leq 950^\circ\text{C}$, the correlation matches the data within a factor of 2 for $15 \leq \sigma \leq 115 \text{ MPa}$. However, with such a high effective activation energy, the correlation may not extrapolate very well below 800°C . Also, Li_4SiO_4 undergoes a phase change at 655°C . In general, the thermal creep rate changes abruptly at phase change temperatures.

$$\dot{\epsilon}_c = 4.82 \times 10^5 (1 - P^{2/3})^{-4} \exp(-5.15 \times 10^4/T) \sigma^4, 1/s$$

The data base is extremely limited: only 3 data points at 700°C ⁽¹¹⁾ and one at 800°C .⁽¹⁷⁾ Table 19 shows the comparison of the correlation and the data. Agreement is within a factor of 2.

The thermal creep rate of Be depends strongly on the method of fabrication and the BeO content. For hot-pressed Be, the recommended secondary creep rate correlation is:

$$\dot{\epsilon}_c = 0.751 (1 - P^{2/3})^{-3.6} \exp(-2.60 \times 10^4/T) \sigma^{3.6}, 1/s$$

Table 17

Secondary Thermal Creep Rate Data for Li_2O .
Correlation values are in parentheses.

Material: Li_2O				Property: Secondary Thermal Creep Rate ($\dot{\epsilon}_c$)			
<u>T, K</u>	<u>P</u>	<u>σ, MPa</u>	<u>$\dot{\epsilon}_c$, $\mu\text{m/m-s}$</u>	<u>T, K</u>	<u>P</u>	<u>σ, MPa</u>	<u>$\dot{\epsilon}_c$, $\mu\text{m/m-s}$</u>
973	0.21	26.6	2.0 (2.7)	1122	0.11	19.6	2.0 (1.7)
		36.8	20.0 (18.5)			32.6	16.3 (21.4)
		44.8	80.0 (59.1)	1173	0.11	13.3	2.0 (1.1)
1073	0.07	29.8	10.0 (5.7)			21.9	10.0 (12.9)
	0.10	24.3	2.0 (2.6)			24.3	13.8 (21.4)
		36.2	20.0 (21.3)	1223	0.11	3.6	2.0 (0.0)
	0.15	20.9	2.0 (1.9)			14.2	12.0 (6.3)
		28.8	10.0 (10.3)			17.3	23.9 (16.6)
	0.27	14.7	2.0 (0.9)			20.8	47.9 (40.9)
		22.9	20.0 (9.2)				

$$\dot{\epsilon}_c = 8.8 \times 10^2 (1 - P^{2/3})^{-n} \exp(-4.04 \times 10^4/T) \sigma^n, \text{ 1/s}$$

$n = 5.9$ for $T < 973$ K

$n = 5.9 [1 - 1.1 \times 10^{-3}(T-973)]$ for $973 \leq T \leq 1123$ K

$n = 4.9$ for $T > 1123$ K

Data are from Refs. 7, 16.

Table 18

Secondary Thermal Creep Rate Data for Li_4SiO_4 .
Correlation values are in parentheses.

Material: Li_4SiO_4 (90% TD)			Property: Secondary Thermal Creep Rate ($\dot{\epsilon}_c$)		
T, K	σ, MPa	$\dot{\epsilon}_c, \mu\text{m/m-s}$	T, K	σ, MPa	$\dot{\epsilon}_c, \mu\text{m/m-s}$
1123	127	5.0 (5.1)	1223	30.0	5.0 (5.0)
	184	20.0 (59.0)		66.2	50.0 (64.2)
	183	50.0 (56.3)		83.0	100 (135)
	230	200 (252)		97.6	200 (230)
1173	96.4	20.0 (20.4)		118	500 (428)
	126	50.0 (76.3)	1248	19.6	20.0 (85.1)
	156	100 (218)		31.6	50.0 (186)
	184	500 (492)		39.2	200 (265)
				51.0	500 (408)

$$\dot{\epsilon}_c = (1 - p^{2/3})^{-n} \exp(192.3 - 2.62 \times 10^5/T) (0.5\sigma)^n, 1/s$$

$n = 8.20$ for $T < 1073 \text{ K}$

$n = 6.56 [1 - 5 \times 10^{-3} (T - 1123)]$ for $1073 \leq T \leq 1293 \text{ K}$

$n = 1.00$ for $T > 1293 \text{ K}$

Data are from Ref. 14.

Table 19

Secondary Thermal Creep Rate Data for LiAlO_2 .
Correlation values are in parentheses.

Material: LiAlO_2				Property: Secondary Thermal Creep Rate ($\dot{\epsilon}_c$)			
<u>T, K</u>	<u>P</u>	<u>σ, MPa</u>	<u>$\dot{\epsilon}_c$, $\mu\text{m/m-s}$</u>	<u>T, K</u>	<u>P</u>	<u>σ, MPa</u>	<u>$\dot{\epsilon}_c$, $\mu\text{m/m-s}$</u>
973 ^a	0.25	50	3.97×10^{-4} (2.35×10^{-4})				
		80	1.26×10^{-3} (1.54×10^{-3})				
		100	3.75×10^{-3} (3.75×10^{-3})				
1073	0.28	167	5.0 (5.0)				

$$\dot{\epsilon}_c = 4.82 \times 10^5 (1 - P^{2/3})^{-4} \exp(-5.15 \times 10^4 / T) \sigma^4, 1/s$$

Data are from Refs. 11, 17.

^aBased on creep rates at 100 h for compressive, constant-load, creep tests.

The data base^(12,18) is for conditions of $400 \leq T_c \leq 700^\circ\text{C}$ and $14 < \sigma < 21$ MPa. The comparison of the correlation and the data is shown in Table 20. Essentially, the correlation agrees with the data of Bennett and Summer⁽¹⁸⁾ for hot-pressed Be with 30 μm grains. The agreement with the data of O'Rourke⁽¹²⁾ for hot-pressed (QVM) Be and 1% BeO and 35 μm grains is poor. The agreement with O'Rourke's 3% BeO samples is better.

Summary

At temperatures below about 1/3 of the melting points of the materials, the creep rate may be enhanced due to irradiation. No estimate of this enhancement is made at this time. Also, for finer grain size materials at low stress and high temperature, the creep rate may be enhanced by grain boundary effects. Finally, primary thermal creep may cause an enhancement in creep rate of an order of magnitude early in life. Figure 5 summarizes the correlations for creep rate versus stress at a temperature of 700°C and a density of 80% of theoretical. While there is a limited data base for Li_2O , LiAlO_2 , and Be at this temperature, there are no data for Li_4SiO_4 in this range. Figure 6 is a similar plot for 800°C which is closer to the data base for Li_4SiO_4 .

3. CONCLUSIONS

Mechanical properties data for candidate solid-breeder ceramics and Be multiplier material are summarized in Section 2. Preliminary correlations are developed based on these data. The purpose of these correlations is to facilitate sensitivity studies based on stress analysis to determine which properties are important in blanket design and which properties need to be measured over a wider range of temperatures, porosities, and grain sizes. For example, given α_m , E , ν , and S_{ft} for a ceramic, one could apply various temperature gradients typically encountered in experiments and conceptual design studies. By comparing the maximum calculated thermal stress to the estimated failure stress in tension, one can assess the conditions under which thermal stress cracking would occur. If there is some flexibility in reducing the porosity and grain size, it may be possible to fabricate a more crack-resistant ceramic. The approach can be validated by comparing calculated results to experimental results (e.g., FUBR-1A).

Table 20

Secondary Thermal Creep Rate Data for Be.
Correlation values are in parentheses.

Material: Be (Hot Pressed)			Property: Secondary Thermal Creep Rate ($\dot{\epsilon}_c$)		
<u>T, K</u>	<u>σ, MPa</u>	<u>$\dot{\epsilon}_c$, $\mu\text{m/m-s}$</u>	<u>T, K</u>	<u>σ, MPa</u>	<u>$\dot{\epsilon}_c$, $\mu\text{m/m-s}$</u>
700	117	0.28 (1.5×10^{-3})			
723	34.5	1.1×10^{-5} (6.2×10^{-5})	873	13.8	7.1×10^{-4} (1.1×10^{-3})
773	21.7	2.8×10^{-5} (1.2×10^{-4})		15.1	1.9×10^{-3} (1.5×10^{-3})
	51.0	2.8×10^{-4} (2.6×10^{-3})		15.7	2.8×10^{-3} (1.8×10^{-3})
	75.9	2.8×10^{-3} (1.1×10^{-2})		17.0	6.0×10^{-3} (2.3×10^{-3})
	69.0	5.6×10^{-5} (7.7×10^{-3})		48.3	8.3×10^{-4} (1.0×10^{-1})
811	41.4	0.28 (5.9×10^{-3})	922	23.4	0.28 (7.4×10^{-3})
823	34.5	3.3×10^{-5} (4.9×10^{-3})	1005	7.5	0.28 (6.2×10^{-3})

$$\dot{\epsilon}_c = 0.751 (1 - P^{2/3})^{-3.6} \exp(-2.60 \times 10^4/T) \sigma^{3.6}, 1/s$$

Data are from Refs. 12, 18.

Fig. 5 Calculated secondary thermal creep rates for 80% TD breeder and multiplier materials at 700°C. PCA and HT9 curves are also shown.

Fig. 6 Calculated secondary thermal creep rates for 80% TD breeder and multiplier materials at 800°C.

Similarly, one could explore the issue of breeder-structure mechanical interaction (BSMI) due to differential thermal expansion and swelling for both tube and plate geometries. The materials combination with the highest driving forces for BSMI due to differential expansion is Li_2O and HT9. However, if Li_2O is relatively "soft" because of creep and hot pressing as compared to HT9, then the interface stress will tend to relax over time. While hot pressing rates are not explicitly included in Section 2, models are available for relating hot pressing rates to thermal creep rates.

With the exception of the secondary thermal creep rate, most of the material properties covered in Section 2 have mild dependencies on temperature. Extrapolations of data to higher temperature should have less than a 50% uncertainty for these cases. However, with the high sensitivity of creep rate to both temperature and stress, there could be orders of magnitude uncertainty in extrapolating creep rate data from high temperature and stress to low temperature and stress. Most of the creep data are near or above the maximum ceramic temperatures considered in blanket designs. Also, primary thermal creep and irradiation-enhanced creep could result in an order of magnitude higher creep rate early in life even for the temperature tested.

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