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ITER Solid Breeder Blanket Materials Database

by

M. C. Billone, W. Dienst, T. Flament,
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ITER SOLID BREEDER BLANKET MATERIALS DATABASE

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ITER SOLID BREEDER BLANKET MATERIALS DATABASE

M.C. Billone, W. Dienst, T. Flament, P. Lorenzetto, K. Noda, and N. Roux

ABSTRACT

The databases for solid breeder ceramics (Li_2O , Li_4SiO_4 , Li_2ZrO_3 , and LiAlO_2) and beryllium multiplier material are critically reviewed and evaluated. Emphasis is placed on physical, thermal, mechanical, chemical stability/compatibility, tritium, and radiation stability properties which are needed to assess the performance of these materials in a fusion reactor environment. Correlations are selected for design analysis and compared to the database. Areas for future research and development in blanket materials technology are highlighted and prioritized.

1. INTRODUCTION

The primary functions of a fusion reactor breeding blanket are: production and transport of tritium for fuel processing; and heat generation and removal for power-producing energy conversion. The blanket, which is bounded on the plasma side by the first wall and on the back side by the shield, can be a flowing liquid metal (e.g., Li or LiPb) in which tritium and heat are generated and transported or a ceramic breeder (e.g., Li_2O or ternary ceramics) with a neutron multiplier (e.g. Be), a liquid (e.g., H_2O) or gas (e.g., He) coolant for heat transport, a separate purge gas (e.g., He) for tritium convection, and structural material (e.g. 316 SS or HT9) to separate and contain the different blanket materials.

In assessing the performance of a blanket design, there are many factors to consider. In addition to traditional economic and safety issues, desirable features of the blanket are a tritium breeding ratio greater than 1, low-activation to minimize waste disposal concerns, reliability and ease of maintenance, and neutron shielding to reduce the burden on the shield itself. In contrast to fission, the fusion reaction is relatively difficult to initiate and sustain. The primary blanket safety issues involve the response of the system to under-cooling or loss-of-coolant events after shut-down. From this safety perspective, blankets with low after-heat from the reaction products and low inventory of retained tritium and radioactive by-products — both radiological source terms — are desirable.

To allow for an in-depth treatment of primary candidate materials for fusion reactor breeding blankets, this review focuses on the thermal, mechanical, tritium transport, chemical stability and compatibility, and radiation stability and performance properties of lithium-based ceramic breeder materials (Li_2O , Li_4SiO_4 , Li_2ZrO_3 , and LiAlO_2) and of the beryllium multiplier material. Properties of the coolant, purge gas, and structural materials are referred to only insofar as they are relevant to assess chemical compatibility, interfacial heat transport, and tritium transport. For a review of critical issues for liquid-metal breeding blankets, the reader is referred to Ref. 1.

The degree to which blanket material properties influence blanket performance depends on the specific details of the blanket design and the planned mode of operation. For example, breeder/beryllium compatibility is only an issue for those designs which mix the two materials to achieve a more homogeneous distribution of tritium and heat generation. The thermal diffusivity of the blanket

materials is an important parameter during unplanned reactor transients and for planned pulsed-mode of normal operation, but it is less important for steady-state normal operation. The same is true for transient tritium transport. In the next section, several solid-breeder conceptual designs are summarized to demonstrate the range of material combinations and geometries which have been proposed. To some extent, the type of material properties needed for design analysis and the degree to which these properties need to be known (e.g., order of magnitude, factor of 2, 10%, etc.) depend on the design itself. The process is really iterative in that designs are proposed based on a limited knowledge of materials performance. Design sensitivity studies determine which properties need to be better modeled or measured to enable the designer to predict performance with a reasonable degree of confidence. Research and development (R&D) efforts are initiated and conducted to improve on the materials database accordingly, and designs are modified based on the R&D findings.

2. EXAMPLES OF SOLID-BREEDER BLANKET DESIGNS

Table 1 summarizes the materials choices of some of the proposed solid-breeder blanket designs. Most of the studies included conceptual designs for liquid-metal coolant/breeder and water or helium coolants with more than one candidate ceramic for the solid breeder. Therefore, the examples in Table 1 are chosen to give the reader a variety of materials combinations and materials form. With the exception of STARFIRE and ITER/CDA, the examples do not necessarily reflect the selection of the best breeder design for each of the studies.

Figure 1 shows the main features of the US design proposed for the Conceptual Design Activity (CDA) phase of the International Thermonuclear Experimental Reactor (ITER) program. The first wall (FW) and blanket structural material is annealed Type 316 stainless steel and the primary coolant is water — as agreed to by the ITER team. The water coolant is in the temperature range of 60–100°C. Beryllium layers (sintered blocks with densities of 65–85%) are placed between the coolant and the Li_2O solid breeder ceramic (80% dense sintered blocks) for the purposes of neutron multiplication to enhance breeding in the ceramic and of thermal resistance to elevate the breeder temperatures for enhanced tritium release. Tritium is convected out of the breeder by He purge lines. The He contains 0.2% H_2 (protium) to enhance release and decrease tritium inventory in the ceramic. The Be, Li_2O , and H_2O are all separated from each other by steel membranes (to inhibit chemical interaction), with only the coolant walls serving a structural function. The layered configuration in Fig. 1 has the advantage of being a compact design which has been optimized with regard to tritium breeding and tritium release within the temperature constraints of the materials. However, the influence of thermally-induced and radiation-induced deformation of both the Be and the Li_2O on the interfacial heat transport is an area requiring very careful analysis. Also, the Be layer next to the first wall must have reasonably good heat transfer at the interface without overly stressing the first wall. Other issues are related to the effects of possible Be and breeder cracking on the heat transport and Be/steam and Li_2O /steam interactions in case of leaks in the walls of the water coolant channels and the steel cladding layers.

The ITER/CDA blanket design proposed by Japan is shown in Fig. 2. It uses essentially the same materials as the US design, but the material form of the breeder and multiplier is quite different. In order to minimize the impact of interfacial heat transport, of possible cracking, and of possible over-loading of the first wall due to deformation of sintered Be, the breeder and multiplier are in the form of pebble beds.

The pebble beds also may result in a simplification in fabrication as, in principle, the breeder and multiplier can be poured in after construction of the blanket frame. In earlier designs, the pebbles were mixed in the same zone, but concerns over chemical interaction between Be and Li_2O led to the separation of these two materials by 1-mm thick steel membranes. The penalty in going to a packed bed is that the effective thermal conductivity of the bed is considerably lower than that of a sintered product form. This requires many more layers to keep the temperature rise across each layer within the temperature limits of the materials and results in a lower tritium breeding ratio. Other issues with regard to the packed bed are possible densification and separation within the bed and the effects of irradiation-induced deformation on the thermal performance of the bed.

In contrast to the layered approach, the European Community (EC) design proposed for the ITER/CDA uses a concentric arrangement of materials. Figure 3 shows the EC breeder-in-tube (BIT) concept. The breeder (LiAlO_2) is in the form of sintered solid pellets. The pellets are clad in a porous steel cladding, followed by a He gas gap for temperature control and tritium removal, a second steel cladding, an annular water coolant channel, a third cladding tube, the Be multiplier, and an outer cladding. The tubes closer to the plasma are smaller in diameter because of the higher heat generation rate. Special spacers are used to maintain the gas gap width which is made to vary with the poloidal variation in the heat generation rate. Advantages of the design are the use of tubes (rather than layers) for which there is a great deal of experience from the fission reactor industry, situating the Be in a low temperature zone to minimize concerns about irradiation-induced swelling, and using a controlled gas gap for thermal resistance to bring the breeder temperature up to the desired range. Features of the design concept which could pose special problems are: fabrication and assembly of the concentric tubes which must contour poloidally over about 10 m of arc length; differential thermal expansion between the hot inner cladding (on the breeder side) and the cold second cladding (on the coolant side); hot and cold spots and resulting thermal stresses in the region of the gap spacers and/or in any regions of poloidal segmentation of the breeder tubes; and achieving a high enough local breeding ratio to give a net breeding ratio >1 for the machine.

Another example of a pebble bed design is the Li_2ZrO_3 concept proposed for the Next European Torus (NET). As indicated in Table 1, this design uses water as a coolant and stainless steel as the structural material.

The four previous conceptual designs were proposed for the ITER/CDA and NET. As these are to be experimental reactors, not necessarily optimized for energy conversion, low-pressure, low-temperature water was selected for the coolant. Demonstration-type reactor blanket concepts, such as the one shown in Fig. 4, are optimized with regard to energy conversion efficiency, tritium breeding, and lifetime. One of the EC designs considered for DEMO uses helium coolant, beryllium multiplier material, helium (plus hydrogen) purge gas and a breeder consisting of Li_4SiO_4 pebbles. The pebble form was chosen over the sintered product form to minimize concerns about thermal-stress-induced cracking. Also, as this ceramic has relatively poor conductivity in the sintered product form, there is less of a percentage decrease in effective thermal conductivity in going to the packed bed design. Some of the design issues associated with Fig. 4 are the deformation of relatively dense (90–100%) beryllium particularly at high fluence (i.e., high He content) and burnup-induced changes in the ternary ceramics which may slow down tritium release.

In summary, the conceptual designs presented in this subsection as examples all use beryllium as a multiplier and helium (plus protium) as a tritium purge gas. The functions of the beryllium range from a simple neutron multiplier to both a multiplier and a thermal resistance layer. Densities range from 65–100% and product form includes both sintered product and pebble bed. Also, the mass ratio of beryllium-to-solid-breeder ranges from 4–20 in order to achieve a breeding ratio greater than one. All four of the solid breeders reviewed in this section are considered as solid-breeder candidates, either in the sintered product form or the pebble-bed form. Basic geometries range from layers to tubes.

3. MATERIALS PROPERTIES DATABASE

There have been many reviews of the properties database for solid breeder and beryllium materials over the past 15 years. Incorporated into most of the design studies listed in Table 1 (Refs. 2– 8) is a summary and assessment of the database. In addition, Suiter (1983)⁹ gives a summary of the physical, crystalline, thermal, and chemical properties of a wide range of lithium-based ceramics. The Materials Handbook For Fusion Energy Systems (MHFFES, 1980–1986)¹⁰ contains data and correlations for physical and thermal properties of lithium ceramics and beryllium, although distribution is limited. M. A. Abdou et al.¹¹ include the mechanical properties of these materials as well. Billone and Grayhack (1988)¹² focus solely on the mechanical properties database and correlations. Many other partial and comprehensive reviews appear in technical reports and the open literature. However, the reader is cautioned about using earlier references, as the experimental database and modeling for material performance increased considerably during the 1980's. Also, it took a number of years to resolve discrepancies in the database and to filter out mistakes (e. g., 1705°C vs. the correct 1705 K for the melting temperature of Li₂O) which tended to propagate with each review as the reviewers got farther and farther removed from the original work. These issues were addressed at the ITER Specialists' Meeting on Blanket Materials Database in February 1990. Attending this meeting were representatives from the United States, Japan, and the European Community, who were either principal investigators for the experimental work, colleagues of the experimenters in their home institution, or in close collaboration with experimenters from other institutions. Following the three-day meeting, each specialist spent two months summarizing the experimental data for the material assigned, evaluating the database to determine future R&D needs, selecting models/correlations representing the peer-approved data, and distributing the final report (April 13, 1990)¹³ to the designers as part of the effort of standardizing the correlations to be used in all future ITER/CDA design work. Although the detailed report was never published formally, a summary of it is contained in Ref. 14. Much of the material which follows is based on the work in Ref. 13, with new data and/or interpretations used to update the database/correlations.

3.1 Materials Properties Correlations

Tables 2–6 summarize the correlations/models recommended, along with temperature, porosity, and stress ranges of the databases used to develop these correlations. The tables are organized by material in terms of baseline physical properties, thermal properties, mechanical properties, chemical compatibility/interaction with blanket coolant, purge gas, and structural materials, and irradiation effects. The baseline physical properties, thermal properties and mechanical properties are relatively straightforward. However, in general, the data which form

the bases for these correlations are much less extensive than the data for fission reactor materials. In some cases (e.g., Young's modulus for Li_2O), only room temperature data are available. Temperature extrapolations are based on general trends for a wide variety of ceramics. In other cases (e.g., bending strength of Be), only data for 100% dense material are available, and again extrapolations in porosity are based on trends for a variety of ceramics and metals. Data on the effects of radiation on these properties is very limited. The evaluation of the databases for these properties is contained in Section 3.2. The comparison of breeder/beryllium properties is treated in Section 3.3.

For some of the irradiation effects (e.g., tritium retention/release, helium retention/release, and helium-induced swelling), more detailed models and validation of models (than contained in the tables) are needed to predict performance. Also, the data and correlations are for sintered-product ceramics and Be. These data are used in more detailed models to predict the performance (e.g., thermal) of packed beds. Discussion of models for these more complex phenomena is contained in Section 4.

3.2 Database Evaluation

The assessment of the breeder ceramic databases is contained in Table 9a. Ceramic breeder properties were grouped under baseline physical properties, baseline mechanical properties, chemical stability/compatibility, tritium solubility/transport, and radiation effects.

With regard to baseline properties of ceramic breeders, the databases for Li_2O and LiAlO_2 were judged to be reasonably complete. The open circles for Li_4SiO_4 and Li_2ZrO_3 vapor pressure indicate that only a single set of limited data is available. This ranking suggests that more work is required in this area in order to develop a reliable database for the vapor pressure of these ceramics. The solid circles for Li_2ZrO_3 melting temperature and Li_4SiO_4 thermal conductivity reflect the fact that new data sets have become available which are significantly different from the results of previous studies. In such cases, a third data set would be useful in resolving the conflicting results. However, in the case of LiAlO_2 more than one recent data set suggest that the thermal conductivity is higher than previously measured values. Thus, it rates a closed rectangle meaning adequate database and good agreement.

The database for the mechanical properties is, in general, more limited than for the other properties. The important variables in establishing correlations are porosity and grain size, temperature, and fast-fluence/burnup. There is a reasonably complete database for the mechanical properties of unirradiated LiAlO_2 . More data are needed for the compressive and bending strength of Li_2O , the compressive strength of Li_4SiO_4 , and the compressive strength and creep properties of Li_2ZrO_3 . The mechanical properties are important in determining whether the breeder materials will crack under differential thermal and swelling strains and how much pressure they can exert on cladding materials if contact is established.

The chemical stability/compatibility properties are important in establishing temperature limits and optimum purge gas composition and impurity control. Li_2O has received the most attention in the area of vapor pressure and vapor transport. Calculations indicate that vapor transport should be considerably less for the ternaries. However, additional data are desirable to confirm these expectations for the ternary ceramics. With regard to breeder compatibility with Be, baseline data are

needed for $\text{Li}_2\text{O}/\text{Be}$, particularly as mixing of these two materials in a pebble bed has been considered in some design concepts. The database on breeder/stainless-steel (SS) is reasonably complete. A recent data set for $\text{Li}_2\text{O}/\text{SS}$ indicates that the reactions may be slower than indicated by previous studies and that the reaction rate may depend on the purity of the $\text{Li}_2\text{O}^{22a}$. This observation should be confirmed by a third study.

Tritium solubility and transport have been studied in significant detail for Li_2O , which is the only breeder material for which multiple single-crystal tritium diffusion measurements have been made. The solubility data for $\text{Li}_2\text{O}/\text{H}_2\text{O}$ are quite good and consistent, but the solubility data for the $\text{Li}_2\text{O}/\text{H}_2$ system are quite scattered and sensitive to the measurement technique, moisture impurity control, and fabricated form (powder vs. single crystal). Thus, the closed circle in the table refers specifically to the solubility of gaseous hydrogen isotopes in reduced form in Li_2O . The desorption/decomposition data for moisture release from LiOH and Li_2O have a factor of 10 scatter, with the main cause appearing to be differences in measurement technique (e.g., tritium counting vs. mass spectrometer). Adsorption, as with solubility, needs to be determined more reliably for both the $\text{Li}_2\text{O}/\text{H}_2$ and $\text{Li}_2\text{O}/\text{H}_2\text{O}$ systems. On the other hand, solubility/adsorption/desorption are reasonably well characterized for the $\text{LiAlO}_2/\text{H}_2\text{O}$ system, but not for the $\text{LiAlO}_2/\text{H}_2$ system. All of these mechanisms are poorly characterized for Li_4SiO_4 and Li_2ZrO_3 ceramics.

Radiation effects on the physical and mechanical properties, on swelling, and on tritium transport are, in general, poorly characterized in the anticipated design range of fast fluence and burnup. Most of the data come from post-irradiation studies of the FUBR-1A samples. While this was a good experiment, it should be pointed out that it was a closed-capsule experiment with questionable moisture control which may have had an influence on the results. Several low-burnup experiments (e.g., MOZART, EXOTIC) have been conducted with breeder materials irradiated under similar conditions. These experiments are good for comparing tritium transport and retention performance of the breeders and for deriving performance parameters (e.g., tritium residency time) for the particular experimental conditions. However, the integral results by themselves do not give enough information as to how to extrapolate to design tritium generation rates and purge flow compositions and rates. It is important to have each separate mechanism characterized to be able to extrapolate. One exception to these generalizations is the case of Li_2O for which the single-crystal diffusivity for tritium has been determined as a function of neutron exposure. Recently, the single crystal diffusivity of LiAlO_2 was also determined for a lightly-irradiated sample.⁹⁶ However, the rate controlling mechanism for this experiment may have been surface desorption. Thus, the uncertainty on the diffusion coefficient deduced from this experiment may be high.

Table 9b contains a parallel assessment of the database for Be. The baseline physical properties of Be are understood reasonably well. The decrease in thermal conductivity with increasing porosity is well characterized. However, there are some gaps in the database (e.g., temperature dependence for $54 < p < 100\%$ dense Be and porosity dependence for $54 \leq p \leq 70\%$ dense Be).

Beryllium mechanical properties are highly sensitive to microstructural parameters (e.g., grain size and porosity) and impurity content (e.g., BeO) which vary with fabrication technique. Some attempt has been made to re-analyze existing data to isolate properties for anticipated fabrication methods (e.g., isostatic-cold-

pressing/sintering) from the broader properties database which includes data from materials fabricated by methods which are not considered acceptable (e.g., arc-casting). More mechanical properties data are needed within the anticipated fabrication methods. As with the breeder ceramics, Be is not a structural component of the blanket. However, it is important from a heat-transfer perspective to know under what differential thermal expansion and swelling strains Be will crack and what the Be/steel mechanical interaction will be.

The compatibility of Be and stainless steel is well characterized for a nonradiation environment. The compatibility of Be and moisture is quite good below 600°C. The reaction is slowed considerably by the formation of a fine layer of BeO. More information is desirable for temperatures above 600°C where the interaction is more extensive. One recent study⁷⁴ indicates a severe reaction between porous Be and steam at temperatures as low as 600°C.

Tritium transport solubility/trapping in Be is poorly characterized and understood. Table 8 summarizes the results of some post-irradiation annealing studies designed to determine tritium retention/release vs. as-fabricated porosity, temperature, and He content. The existing database is useful in assessing tritium release during overheating events (e.g., post-shutdown decay heating with loss of coolant). However, no data are available for on-line tritium release with generation occurring at the release temperature.

Very limited data are available for the effects of radiation on the Be physical properties. One study showed that neutron damage has no effect on the Be thermal conductivity for temperatures above room temperature. However, He-induced swelling will degrade the thermal conductivity in the same manner as fabricated porosity. It appears sufficient to account for in-reactor effects on the thermal conductivity by decreasing the porosity correction factor as a function of He swelling. No degradation of the Be matrix conductivity is anticipated. He-induced swelling has been measured as a function of fast ($E > 1$ MeV) neutron fluence and in-reactor time at temperature for several low-temperature reactor (e.g., ATR and BR-2) positions and intermediate-temperature (427-487°C) reactor (EBR-II) positions. Post-irradiation anneals from 1-24 hours have also been performed on these samples at intermediate and high temperatures. However, most correlations have been expressed in terms of fast neutron fluence. For fusion reactor blankets, which have very different neutron spectra than the test reactors, it is important to rewrite the correlations in terms of He concentration. Unfortunately, this introduces a high degree of uncertainty as estimated conversion factors range from 2200-6000 appm (He)/ 10^{22} n/cm² fast fluence in the ATR and BR-2 reactors. Also, no swelling data are available for porous Be. More work needs to be done in this area to provide reliable guidance for design analysis. Finally, fracture and creep properties need to be determined as a function of He content and temperature for the anticipated range of design parameters. In particular, irradiation creep, which relieves differential swelling stresses and Be/steel contact stresses, needs to be determined.

3.3 Comparison of Properties

As discussed previously, the functions of a ceramic breeder are: 1) production of tritium from the neutron/lithium reaction and the efficient release of tritium to the purge stream; 2) production of thermal energy and the conduction of this energy to the blanket coolant; and 3) shielding of neutrons. Thus, in evaluating ceramic breeder candidates for design, lithium atom density, tritium retention/release

characteristics, and thermal transport properties are considered primary parameters. The primary function of beryllium in blankets is to multiply neutrons through the (n, 2n) reaction. However, both tritium and heat will be generated in Be. Also, in some designs, the Be is used as a thermal barrier between coolant and breeder. Thus, its heat transport properties become even more important in these circumstances.

Table 10a summarizes some of the properties of ceramic breeders. The companion table (10b) does a similar treatment for Be. ^6Li density is important to tritium breeding. The oxide is clearly superior to the ternary compounds in this category. Generally, it is considered the only ceramic candidate for achieving a TBR > 1 in the absence of a multiplier. However, many designs employ large quantities of Be and high ^6Li enrichments to boost the TBR as high as possible to allow for uncertainties and tritium losses. Under these conditions, the ^6Li density is less critical. A high melting temperature is desirable from an accident analysis perspective. In this sense, two of the ternaries (Li_2ZrO_3 and LiAlO_2) are superior. However, these materials also tend to have lower thermal conductivities and lower thermal diffusivities than Li_2O . Thus, from an overall thermal performance viewpoint during both normal operation (steady-state or pulsed), Li_2O appears to be superior to the ternaries with LiAlO_2 a close second. The thermal conductivity and thermal diffusivity of Li_2O and LiAlO_2 are clearly superior to the orthosilicate and zirconate ternaries. This is also shown graphically in Figs. 51 and 52, where the ceramics are compared to steel and Be materials. The thermal diffusivity is particularly important for the pulsed-mode of operation. For optimum tritium release, it is necessary for the breeder to heat up relatively quickly. With a very slow blanket thermal response time, the breeder may never achieve the desired temperatures within the burn duration or it may not achieve these temperatures for a long enough period of time.

Thermal expansion and in-reactor volume change, as well as possible volume changes with phase change, are important considerations in overall blanket lifetime. Generally, the smaller these quantities are, the more desirable it is from a design viewpoint. While volume change with solid-state phase change is not an issue, Table 10a shows that thermal expansion and He-induced in-reactor swelling may be issues. Two of the ternaries (zirconate and aluminate) have relatively low thermal and in-reactor volume changes. Figure 53 compares the thermal expansion of the breeder ceramics to that of Be, HT9 (ferritic-martensitic Fe-Cr alloy) and PCA (primary candidate alloy, Ti-modified Type 316 material developed to reduce void swelling). However, the expansion of Li_2O is partly compensated for by a relatively high creep rate which may mitigate breeder/metal mechanical interaction. The mechanical properties are summarized in Tables 10a and 10b, as well as in Figs. 54-56. The dashed part of the lines in the figures represents extrapolation in temperature beyond the existing database. The use of 10 microns in the comparison of mechanical strength properties is arbitrary. Better strength properties can be realized by using smaller grain sizes, as is frequently done for Li_2ZrO_3 and LiAlO_2 .

The hydrogen-isotope diffusivity in several solid-breeder materials is compared to other oxides, solid metals, and liquid metals in Fig. 58. In the case of Be, there is a high uncertainty because of the usual presence of BeO surface layers with their very low tritium diffusivity.

The final item in the comparison table for solid breeders is related to tritium residency time. This is a very convenient parameter for designers, but also a

deceiving one. The residency time is defined as the average time a triton spends in the breeder between generation and release. It is actually based on a simple diffusion/desorption model for which the residency time (τ) can be used to relate the tritium inventory (I) at steady-state to the tritium generation rate ($\dot{G}$): $I = \tau \dot{G}$. Thus, for a residency time of one day, the steady-state inventory would be equivalent to a one-day generation of tritium. Generation rates range from about 100 g/day for an experimental reactor concept like ITER to about 1 kg/day for a commercial power plant like STARFIRE. Included in Table 10a are the estimated minimum temperatures for which the residency time is one day. For higher temperatures (see Fig. 57), the residency time, and hence the tritium inventory, will be considerably smaller. As a low minimum temperature (T_{min}) is desirable from a design viewpoint, then it appears that the oxide and the zirconate are superior to the orthosilicate and the aluminate in terms of minimizing tritium inventory. While the numbers in the table may be valid in a relative sense, they are based on interpretations of tritium release data from very short-time, in-reactor, purge-flow tests under optimum microstructure and purge chemistry conditions. Deducing retained tritium from measured tritium release rates and calculated tritium generation rates involves subtracting two uncertain quantities which are close together. This subject is treated in more detail in Section 4.3.

There are several items not included in Tables 10a and 10b which deserve special consideration. Up to this point in the comparison, lithium oxide appears to be the best breeder ceramic candidate from neutronic, thermal, and tritium transport considerations. However, Li_2O is more hygroscopic than the other ceramics and requires more careful moisture control during fabrication, assembly, and operation. Figure 15 shows the critical temperatures and moisture pressures at which second-phase $LiOH$ can form. For example, at 400°C, 34 Pa of moisture is sufficient to precipitate out $LiOH$, which is a volatile, corrosive, low melting temperature (471°C) compound. Figure 59 shows more directly that lithium oxide has the highest moisture solubility, and hence tritium retention, at high temperatures for the ceramics studied. While mass transport of $LiOH$ vapor at high temperature has been studied for lithium oxide alone, based on thermodynamic calculations, it appears that it has the highest mass transport rates. Also, the chemical interaction with steel is highest for lithium oxide, although not as high as the Be/steel interaction (Fig. 60). Finally, with regard to the possibility of mixing lithium oxide with Be, it appears that this combination is more incompatible than for the ternary ceramics. Thus, lithium oxide is very attractive from neutronics, thermal transport and tritium transport viewpoints, but it requires more careful moisture control than any of the other breeders.

4. MODELS

The previous discussion has focused on the properties database and correlations for sintered-product ceramic breeders and beryllium. In some cases, the material form (e.g., packed bed) requires additional models or the phenomena (e.g., interfacial heat transfer, Be swelling/creep, tritium retention/release) are too complicated to be described adequately by a simple correlation. This was recognized early in the ITER/CDA effort, and models were proposed to facilitate design calculations in these areas. These models are summarized in the following under the headings of thermal performance, mechanical performance, tritium retention/release, and He-induced swelling models.

4.1 Thermal Performance Models

The Hall and Martin model⁸² can be used for the effective thermal conductivity of a sphere-pac or pebble bed with one particle size and packing fractions in the range of $0.524 \leq P_f \leq 0.635$:

$$k_{\text{eff}} = \frac{P_f}{0.524} \left\{ \frac{(\pi/2)(1-\lambda)}{\delta(1-\lambda)-1} - \frac{(\pi/2)(1+m)}{[\delta(1-\lambda)-1]^2} \ln \left[\frac{\delta(1+\lambda m)+m}{(1+\delta\lambda)(1+m)} \right] + (1-\pi/4)(1+\lambda) \right\} k_g \quad (1)$$

where

$$k_g = \text{He conductivity} = 3.366 \times 10^{-3} T^{0.668}, \text{ W/m-K} \quad (1a)$$

$$T = \text{temperature in K}$$

$$\delta = k_g/k_b \quad (1b)$$

$$k_b = \text{conductivity of pebble material (see Tables 2-6)}$$

$$m = 2 \text{ g/D}_p = 3.0833 \times 10^{-4} T^{1.168}/(P_g D_p) \quad (1c)$$

$$P_g = \text{He pressure in MPa}$$

$$D_p = \text{particle diameter in } \mu\text{m}$$

$$\lambda = 4.4919786 \times 10^{-11} T^{2.332} D_p \quad (1d)$$

Equation (1) was developed by Hall and Martin for an idealized cubic packing array of spheres with a packing fraction of 0.524. Larger packing fractions can be achieved, with hexagonal packing giving the theoretical limit of 0.74. In practice, the packing of spheres in tubes is limited to ~0.635 packing fraction. The ratio of the sphere diameter (D_p) to the bed thickness is an important parameter in determining what packing fraction can be achieved. The correction factor of ($P_f/0.524$) is imposed on the Hall and Martin model to allow extrapolation in the range of $0.524 \leq P_f \leq 0.635$. Also, based on sensitivity studies and comparisons to data, the radiation term (λ -term) is limited in application to $D_p \leq 1000 \mu\text{m}$ (1 mm) because it enhances k_{eff} too much for $D_p > 1000 \mu\text{m}$.

To achieve higher packing fractions than 0.635, a binary mixture of large (D_p) and small (d_p) particles may be used. Ideally, 0.87 packing fraction may be achieved. However, a more practical limit is ~0.80-0.85. Based on sensitivity studies with more complicated models than the one proposed by Hall and Martin, the effective thermal conductivity increases by a factor of ~2 in going from a single-particle packed bed of packing fraction ~0.52 to a binary packed bed of packing fraction ~0.82. Thus, for the binary case, $P_f/0.524$ is set to 2 for design analysis calculations.

The Hall and Martin model is compared to data for the effective thermal conductivity of Li_2O , Li_4SiO_4 , and Li_2ZrO_3 packed beds in Table 11. On the average, the model predictions are low by about 10%. This is well within the uncertainties in the data for the bed conductivity, as well as the baseline data for the thermal conductivity of the pebbles themselves. Thus, the model is probably adequate for design analysis of packed beds with single particle sizes of low conducting ceramics. More detailed models can be found in Ref. 84.

At the interface between the stainless steel cladding and sintered breeder ceramic or Be, the model used for the heat transfer coefficient is the same as the one developed and validated for fission reactor materials. It consists of a gas conductance term which includes a hot gas gap (G), the rms roughness height (r) and the jump distance (g); a solid-solid conductance term; and a radiation conductance term. The model and modeling parameters are described in detail in Refs. 86 and 87. They are repeated in the following:

$$h = \frac{k_g}{(r_1 + r_2) + (g_1 + g_2) + G} + \frac{2k_1 k_2}{k_1 + k_2} \frac{1}{Ar_{12}^{1/2}} \frac{P_{12}}{H_s} + \left\{ \sigma / [1/\epsilon_1 + 1/\epsilon_2 - 1] \right\} (T_1^2 + T_2^2)(T_1 + T_2), \quad (2)$$

where

$$\begin{aligned} k_g &= \text{He conductivity (Eq. 1a)} \\ r_1 &= \text{root-mean-square (rms) roughness height of the steel, m} \\ r_2 &= \text{rms roughness height of breeder or Be} \\ &= (1 + 110 \times P) \times 10^{-6}, \text{ m} \end{aligned} \quad (2a)$$

$$\begin{aligned} P &= \text{porosity volume fraction of breeder or Be} \\ g_1 + g_2 &= 4.625 \times 10^{-11} T_g^{1.168} (1/a_1 + 1/a_2)/P_g, \text{ m} \end{aligned} \quad (2b)$$

$$\begin{aligned} P_g &= \text{He pressure in MPa} \\ a_1 &= \text{accommodation coefficient for steel (0.12)} \\ a_2 &= \text{accommodation coefficient for ceramic breeder (0.2) or Be (0.145)} \\ G &= \text{hot gap, m} \\ k_1 &= \text{steel thermal conductivity in W/m-K} \\ &= 12.7[1 + 1.36587 \times 10^{-3}(T - 255.4) - 4.69725 \times 10^{-8}(T - 255.4)^2 \\ &\quad + 2.765813 \times 10^{-13}(T - 255.4)^3] \end{aligned} \quad (2c)$$

$$\begin{aligned} k_2 &= \text{thermal conductivity of 100% dense breeder or multiplier} \\ A &= 0.05 \text{ m}^{1/2} \\ \epsilon_1 &= \text{steel thermal emissivity (0.9)} \\ \epsilon_2 &= \text{emissivity of ceramic breeders (0.8) or Be (0.6)} \\ \sigma &= \text{the Stephan-Boltzmann constant } (5.67 \times 10^{-8} \text{ W/m}^2\text{-K}^4) \\ T_1 &= \text{steel surface temperature, K} \\ T_2 &= \text{breeder or Be surface temperature, K} \end{aligned}$$

$$T_g = (T_1 + T_2)/2 = \text{average gap temperature, K}$$

$$P_{12} = \text{contact pressure, MPa}$$

$$r_{12} = [(r_1^2 + r_2^2)/2]^{1/2}, \text{ m}$$

and

$$\begin{aligned} H_s &= \text{hardness of the softer material (steel)} \\ &= 2.25 \times 10^3 (1 - 7.94 \times 10^{-4} T_1), \text{ MPa} \end{aligned} \quad (2d)$$

Table 12 shows typical gap-conductance values from Eq. (2) for a Be/steel interface as a function of hot gas gap, gas pressure and temperature.

In the case of the sphere-pac or pebble bed, models and data are available^{8,4} for the wall heat-transfer coefficient for both high and low conducting spheres encased in stainless steel. The uncertainty in model parameters and raw data is quite high. In particular, the direct measurement of wall heat transfer coefficient is quite difficult. The approach taken in design analysis is to use the ratio of h/k_{eff} from the database. For example, based on Li_4SiO_4 particles of diameter 0.5 mm and packing fraction of 62%, the ratio is $2700 \pm 2300 \text{ m}^{-1}$. This would correspond to wall heat transfer coefficient of $\sim 3100 \text{ W/m}^2\text{-K}$ for an equivalent Li_2O single size bed and $\sim 5700 \text{ W/m}^2\text{-K}$ for an Li_2O binary bed in the He pressure range of 0.05-0.10 MPa. Design sensitivity studies have been performed in the lower range of 1600-3100 $\text{W/m}^2\text{-K}$ for a Li_2O sphere-pac bed to add additional conservatism to the analysis.

For a Be pebble bed, the heat transfer coefficient should be at least as high as for the Li_2O bed but no higher than for the conductance for sintered Be/steel interface at nominal contact. Thus, the values recommended are between 3100 $\text{W/m}^2\text{-K}$ and the values listed in Table 12.

4.2 Mechanical Performance Models

Tables 2 through 6 contain some of the information needed to perform a structural analysis for blanket components. However, with the exception of Be, neither He-induced swelling models nor in-reactor creep models are available for the ceramic breeders. In order to perform a mechanical analysis, a constitutive law is needed. In the following, a uniaxial constitutive law for Be is given as an example of what is needed. Sample calculations are also presented.

Let ϵ be the total strain which is composed of an elastic component (ϵ_e), a thermal expansion component (ϵ_{th}), a swelling component (ϵ_s), and a creep component (ϵ_c):

$$\epsilon = \epsilon_e + \epsilon_{th} + \epsilon_s + \epsilon_c \quad (3)$$

A more complete relationship would also include a "time-independent" plasticity term which has been excluded from the current analysis for these relatively brittle materials. The elastic term is simply the uniaxial stress (σ) divided by Young's modulus (E) from Table 6. The thermal expansion term is the mean thermal expansion coefficient (α_m) from Table 6 times $(T - T_r)$, where T_r is the

reference temperature. The swelling strain [$\epsilon_s = \Delta V / (3V_0)$ in absolute units] and the thermal creep component (ϵ_c^{th}) can be determined from the information in Table 6. An athermal in-reactor creep term has also been derived (from the one data point in Ref. 88) in terms of D (displacements per atom). Substituting all of these terms into Eq. 3 gives:

$$\epsilon = \sigma / E + \alpha_m (T - T_r) + \int_0^t \Delta V / (3V_0) dt + \int_0^t \left[\dot{\epsilon}_c^{th} + 3.2 \times 10^{-6} (1 - P^{2/3})^{-1} \dot{\sigma} \right] dt \quad (3a)$$

where t is time in seconds.

A sample problem is selected to show the type of design calculation which can be performed once the constitutive equation is known. Consider the first row (closest to the plasma) of Be blocks in Fig. 1. The blocks are 27-mm thick in the radial, poloidal, and toroidal directions and 85% dense ($P = 0.15$). The average block temperature is 358°C with extreme temperatures of 312°C and 404°C. The average helium generation rate and displacements-per-atom rate are 3.56×10^3 appm/y and 4.72 dpa/y. Assume that the blanket has been designed with enough space in the radial direction to accommodate thermal expansion. The question remains as to what swelling-induced compressive stresses may develop in the Be. An upperbound answer to this problem can be found quite simply by assuming complete constraint of the block in the radial direction. This means that the total strain (minus the thermal expansion strain) is zero. Thus, as the Be tries to swell against its fixed boundaries in the radial direction, a compressive elastic stress builds up in time. The material creeps in the poloidal and toroidal directions to accommodate the strain mismatch in the radial direction. Thus, swelling acts as a stress generator and creep acts as a stress relaxer. The solution can be found by taking the time derivative of Eq. 3a and substituting in known quantities. Let $\sigma_e = -\sigma$ be the equivalent stress. Then

$$\dot{\sigma}_e = 224.2[1 + 0.9304 t_y^{0.5} - 1.5436 \times 10^{-2}(1 + 4.73 \times 10^{-6} \sigma_e^{2.6}) \sigma_e] \quad (3b)$$

where t_y is time in years. Equation 3b can be solved numerically to give the results presented in Fig. 61. Initially, when the stress is low, the athermal creep term dominates in relaxing the stress. As the stress increases, the thermal creep term becomes comparable. In any case, the two mechanisms balance each other to give a long-time quasi-steady stress which is below the compressive failure stress of the material. While the detailed problem of partially constrained deformation including strain gradients across the material is quite complicated, the simple solution presented above is very useful for design purposes in bounding the stress.

4.3 Tritium Retention/Release Models

The tritium residency time correlations in Tables 2 through 5 are based on transient release data for the four ceramics. While these formulas are useful for comparing breeders, they may not be accurate enough for calculating tritium inventory. For most of the experiments, tritium inventory was never even measured at the end of the test to allow a direct validation of the residency time correlations. More sophisticated models are needed to predict tritium performance for both the breeder ceramics and the Be multiplier.

A detailed discussion of the status of modeling tritium behavior in breeder ceramics is contained in Ref. 89. The modeling and database for Li₂O are presented in detail in Ref. 30. The results from Ref. 30 are summarized below to give the reader some indication of the progress made in this area. The methodology used in modeling lithium oxide behavior involves determining rate constants for important mechanisms from laboratory tests on unirradiated samples and on samples which have been irradiated at low temperatures in fission-reactors then annealed in an out-of-reactor furnace at higher temperatures. The overall validation of the models, rate constants, and algorithms is done by comparing computer code predictions to the data from in-reactor purge flow tests in which on-line tritium release is measured and after which tritium inventory is measured directly.

Rate constants for tritium transport in Li₂O involve the lattice diffusivity (D), desorption rate constant (k_d), and adsorption rate constant (k_a). These are all contained in the porosity/solid boundary condition for mass flux (q) leaving the solid and entering the porosity:

$$q = -D\partial C/\partial r|_a = k_d C(a,t) - k_a P_{HT} \quad (4)$$

where

$$D = 4.03 \times 10^{-2} \exp(-95.1 \text{ kJ} \cdot \text{mol}^{-1} / RT), \text{ cm}^2 / \text{ s} \quad (4a)$$

$$k_d = 25.3 (a \cdot a_s \cdot \rho_{th} / 3) P_{H_2}^{0.5} \exp(-131 / RT), \text{ cm} / \text{ s} \quad (4b)$$

$$k_a = 9.08 (a \cdot a_s \cdot \rho_{th} / 3) \exp(-147.6 / RT), \text{ wppm} \cdot \text{ cm} / (\text{ s} \cdot \text{ Pa}) \quad (4c)$$

a = effective grain radius (assuming spherical grains) in cm

a_s = specific pore-solid surface area in cm²/g

ρ_{th} = theoretical density of Li₂O in g/cm³

C(a,t) = time-dependent surface concentration of tritium in weight parts per million (wppm)

P_{HT} = local HT partial pressure (in Pa) in the porosity

P_{H2} = local H₂ partial pressure (in Pa) in the porosity

T = local temperature in K

and

R = ideal gas constant (8.314 × 10⁻³ kJ·mol⁻¹·K⁻¹)

The adsorption rate constant was determined indirectly from solubility data under equilibrium conditions and from transient desorption data. It assumes that H/T >> 1 and P_{HT}/P_{HTO} >> 1. Both of these assumptions are reasonable for design-type purge conditions (e.g. 0.2% H₂ in 1-atm He purge). For steady-state analysis, the complete solubility expression may be used directly in calculating inventory. The resulting expression for solubility (S_t in wppm) is:

$$S_t = 0.101 \left\{ B \times 10^{-A} P_{H_2O}^{B-1} P_{HTO} + 3.55 \exp(-2000/T) P_{H_2}^{-0.5} P_{HT} \right\} \quad (5)$$

where

$$A = 11.667 - 2.502 \times 10^{-2} T + 9.62 \times 10^{-6} T^2$$

$$B = 0.427 + 1.7 \times 10^{-4} T$$

$$P_{H_2O} = \text{local } H_2O \text{ moisture pressure in Pa}$$

and

$$P_{HTO} = \text{local HTO moisture pressure in Pa}$$

While post-irradiation annealing test results have been used to determine a baseline set of material properties for Li_2O , in-reactor purge-flow test results are more appropriate for validation because tritium is simultaneously generated at temperature, transported within the solid to the porosity, and convected away by means of the purge gas. Several types of data are generally available from the in-reactor purge-flow tests. Tritium inventory, corresponding to generation rate, temperature, purge concentration of protium, and purge flow rate during the last run of the experiment, can be measured directly. These data are extremely useful in that a very small error or uncertainty is associated with such data. The major uncertainty in using such data for model validation is associated with changes in breeder microstructure (e.g. grain size, porosity, pore-solid surface area) which may have occurred during irradiation, but may not have been characterized.

The second type of information which may be derived from in-reactor purge-flow test results is inventory change associated with changes in generation rate, temperature, purge-flow protium concentration, and/or purge-flow rate. What is really measured is a time history of tritium concentration in the purge gas far downstream from the sample. This can be converted to a tritium release rate, which when compared to the generation rate, can be integrated to give a change in inventory (retained tritium) before and after the change in operating conditions. There are two major uncertainties with this approach. One uncertainty is associated with possible changes to the tritium detection system (e.g. ion chambers) calibration and baseline due to changes in operating conditions (e.g. protium concentration in the purge). The second is the uncertainty in the tritium generation rate, which forms a baseline for the calculations.

The third type of information is the time history of the tritium release rate during the transient in operating conditions. In using this information for model validation, the same uncertainties associated with deriving an inventory change are involved in deriving a release rate. In addition, there is the uncertainty of the degree to which the tritium processing equipment and the overall time response of the system influence the time history of the signal.

For Li_2O , very few post-test inventory data are available at this time. Table 13 summarizes the microstructural and operating conditions for several in-reactor purge-flow tests used for model validation. Table 14 and Fig. 62 summarize the measured data and the model predictions. The VOM-15H test results, because of the absence of protium purging and the high temperature that this test ended at during its last run, basically test the solubility model. The model prediction of 0.303 wppm is in reasonable agreement with the data of 0.7 ± 0.2 wppm considering the

uncertainties in operating conditions and temperature distribution throughout the sample. For the higher temperature EXOTIC-2 case, the predicted inventory (4.73×10^{-3} wppm) is small and the measured inventory is small (<0.1 wppm). However, because the inventory was within the noise of the measurements, no precise numerical comparison is possible. For the lower temperature EXOTIC-2 case, the predicted inventory (0.263 wppm) is significantly smaller than the measured inventory (1.5 wppm). It is not clear whether this disagreement represents a deficiency in the models and/or model parameters, or it merely reflects the influence of a significant change in sample microstructure (densification and grain growth) due to the moisture buildup in this under-purged sample. Finally, the model (0.061 - 0.331 wppm) under predicted the measured inventory (0.54 ± 0.32 wppm) for CRITIC-1. As this sample was initially quite dense (92%), experienced higher-than-planned moisture levels, and experienced significant He-induced swelling leading to local densities as low as 80%, again it is not clear whether the discrepancy is due to uncertainty in model input or inadequacy of models and model properties.

In summary, there are only 4 data points available for tritium inventory in Li_2O following in-reactor purge-flow tests. Reasonable agreement was obtained with the VOM-15H data, but the operating conditions (high-temperature and no protium added to the purge) are quite different from anticipated design operating conditions. Qualitative agreement was obtained with the 610°C EXOTIC-2 data, but this data point was within the noise of the measurement system. With regard to the 445°C EXOTIC-2 data point and the CRITIC-1 data, both of these samples experienced significant change in microstructure during irradiation leading to uncertainty in modeling input. Clearly more inventory data are needed from experiments with controlled, well-characterized operating conditions and microstructural variables. Although the BEATRIX-II inventory data are not available yet, there will be at least one data point at 620°C for the thin-ring specimen in 0.1% H_2 and at least 3 data points for the thick temperature-gradient sample in 0.1% H_2 . Pre-test model predictions have been made for all four of these BEATRIX-II data (see Table 14 for thin-ring prediction and Fig. 63 for solid pellet predictions⁹⁴).

With regard to the second type of validation data from in-reactor purge-flow tests -- implied inventory change with changes in operating conditions -- only the BEATRIX-II temperature change results were used because of the large uncertainty associated with a baseline for the protium-concentration changes (see Table 15). For four temperature decreases of $\sim 90^\circ\text{C}$ the average model prediction for inventory increase was 0.321 wppm (37 mCi) as compared to a data average of 0.56 ± 0.09 wppm (65 ± 10 mCi). For the corresponding temperature increase, the predicted tritium decrease was 0.32 wppm (37 mCi) as compared to the value from measurements of 0.71 ± 0.13 wppm (82 ± 15 mCi). Thus, on the average, the predicted inventory change results are within a factor of 2 of the inventory change implied by the BEATRIX-II data. This agreement is reasonable for samples with low (<1 wppm) inventory. The results of this comparison are shown in Fig. 64.

For the third type of validation data -- time history of tritium release rate -- the BEATRIX-II temperature change data were used. Figure 64 shows the measured decrease in release rate (i.e. decrease in ion chamber concentration) for a temperature decrease of $91 \pm 5^\circ\text{C}$ in 0.1% H_2 for the thin-ring sample at 80, 215, and 280 effective full power days (EFPD) of operation. Also shown in the figure is the increase in tritium release rate during the temperature increase of $91 \pm 5^\circ\text{C}$. The data imply only an $8 \pm 3\%$ peak decrease in release rate and a $14 \pm 7\%$ increase in release rate with the corresponding temperature changes. However, the reader should be

cautioned that tritium-processing system effects may have a slow enough time constant to distort the breeder tritium release rate profile in time.

The model predictions are compared to the transient data in Fig. 65. As the model predicts much larger decrease (81%) and increase (460%) in release rates than the data, the model predictions are shown with a very different tritium release rate scale. Also, the model predicts single peaks for both temperature increase and decrease. For the first three cases, the data exhibit double peaks -- a sharp peak associated with HT release and a broad peak associated with HTO release. For the 280 EFPD case, the broad peak appears to be suppressed. It is not clear at this time whether the evolution of the signal from a double-peak response to a single-peak response is due to changes within the breeder or changes in the overall tritium processing system.

In summary, reasonable agreement was achieved between model predictions and data for the very limited end-of-life (EOL) inventory data and for the BEATRIX-II implied inventory change data. There is some indication that the model predictions may be a factor of 2 to 5 low in inventory predictions. This is well within the uncertainties in the database used to set the initial values of model parameters. However, it is essential that this be confirmed once the EOL BEATRIX-II inventory data are available. If this trend continues throughout the validation exercise, then the model parameters will be changed to be consistent with the EOL inventory data from the in-reactor purge flow tests.

With regard to tritium behavior in beryllium, more data are needed before models can be developed and validated. Figure 46 shows the results of post-irradiation annealing experiments on unirradiated, dense Be^{77} [J&G(0%)], ion-bombarded, dense Be^{78} [W(0%)], highly irradiated, dense Be^{95} [DLB(0%)], moderately irradiated, dense $\text{Be}^{76,95}$ [DLB(0.4%)], and moderately irradiated, porous Be^{95} [DLB(19.1%)]. The numbers in parentheses are as-fabricated porosities. Table 8 also summarizes the variables and conditions for Baldwin's (DLB) experiments. From the data, it appears that there is little to no release below a certain temperature ($T_0 = 300 - 500^\circ\text{C}$) and above a certain temperature ($T_b = 600-900^\circ\text{C}$) there is a burst release. For $T_0 < T < T_b$, there is a gradual, almost linear, increase in tritium release with increasing temperature. There is strong evidence that as-fabricated porosity enhances release and decreases inventory (see Baldwin's two samples which were irradiated and then annealed under identical conditions). There is also a clear indication that He content and He-induced swelling play a major role in affecting T_b . One would also expect that time-at-temperature, grain size, and overall sample dimensions would also influence retention/release. However, the database is not complete enough to allow models and validation at the same level of sophistication as for breeder ceramics.

4.4 Helium-induced Swelling Models

In reviewing the database on Be swelling for design applications, special consideration was given to data sets for hot-pressed Be as opposed to extruded Be and to data sets for which the He content was measured directly rather than just calculated. In the past, correlations have been developed for Be swelling in fission reactors as a function of fast ($E > 1 \text{ MeV}$) neutron fluence. However, the primary driving force for the swelling is helium production. Most of the He is produced from the $(n, 2n)$ reaction which has a threshold energy of 2.7 MeV and a cross-section which peaks at $\sim 0.66\text{b}$ at 3.25 MeV. Thus, considering the vastly different fast flux

spectra for thermal and fast fission reactors and fusion blankets, it is insufficient to develop correlations vs. fast fluence. The effective cross-section is quite different for test and design applications. It is more useful to have a swelling correlation as a function of He content.

The database for swelling of hot-pressed and extruded Be is reviewed in Ref. 79. Figure 47 shows the swelling data vs. helium content for hot pressed Be for which the relationship between helium retention and fast fluence has been measured. These data sets include Be irradiated in ATR at $T \approx 75^\circ\text{C}$,⁸⁰ ATR-irradiated Be subjected to one hour post-irradiation anneals (ATR-A) at $200 \leq T \leq 500^\circ\text{C}$,⁸⁰ BR2-irradiated Be at $T \approx 45^\circ\text{C}$,⁸¹ BR2-irradiated Be subjected to 24 hour anneals at 400, 600, and 800°C (BR2-A),⁸¹ and Be irradiated in EBR-II at $427 \leq T \leq 487^\circ\text{C}$.⁸⁰ All samples were 100% dense with similar microstructures ($\sim 25 \mu\text{m}$ grain diameter) and oxygen impurity contents (1.5-2.0 wt.% BeO).

Figure 48 shows the agreement between the correlation and database. This agreement is quite good considering the scatter in the data base. Figures 49 and 50 show the deviation between correlation values and data vs. He content and temperature, respectively. The root-mean-square or one-sigma deviation between the correlation and data is 0.34% volumetric swelling.

The correlation has been validated for $T \leq 600^\circ\text{C}$ and for He contents ($\leq 26,000$ appm or 2.6 at.%) much greater than ITER/CDA end-of-life values. It is believed that extrapolation to 650°C would give reasonable results, but that for $T \geq 700^\circ\text{C}$ swelling involves more complicated phenomena. As temperature is increased, gas release would tend to decrease swelling, but the formation of large matrix bubbles would more than compensate for this by producing larger swelling before interlinkage of bubbles and significant gas release would occur. Essentially, the correlation is validated in the regime for which intergranular bubbles (lower limiting volume increase before interlinkage and venting) tend to dominate. More work needs to be done to extend the validity of the correlation to higher temperatures, as well as to higher ($p > 0$) as-fabricated porosity volume fractions.

As successful as the correlation is in matching most of the Be swelling database, it does not include fabrication variables (e.g., grain size and porosity), a coupled He release model, and grain-boundary vs. grain matrix bubble distributions, such as are found to be important in modeling swelling in fission reactor fuels. Models which have been applied to describe noble-gas-induced swelling in ceramic and metallic fission reactor fuels should be adapted to Be and the fusion blanket ceramics.

5. SUMMARY OF BLANKET MATERIALS

The database, materials design correlations, and models for the performance of breeder ceramics and beryllium have been presented. For some of the properties, the database is adequate for developing correlations to describe the performance of the material throughout the anticipated range of fabrication and operational parameters. In a number of cases, data are available for only one temperature or only one porosity value, and extrapolation is necessary. In these cases, trends in the behavior of similar materials were used to develop "zeroeth" order approximations, and the generation of additional data is suggested. In other cases, particularly with regard to tritium and helium behavior, the phenomena are too complicated to be described by a single correlation. For these phenomena, the database is reviewed

along with the status of the modeling effort. Based on this critical review, the following areas are highlighted for additional study.

5.1 Thermal Performance

The thermal properties of unirradiated ceramics and Be are well characterized in terms of temperature and porosity dependence. There is no strong evidence that the thermal properties are degraded with irradiation in the operation temperature range >600 K, beyond the increased-porosity effects of helium-induced swelling. Considerable degradation could occur at lower temperatures. Thermal conductivity data and correlations/ models are available for both sintered products and pebble beds. In the case of a high conducting material such as Be, pebble-bed data are desirable because the models presented and their validation pertain to low conducting ceramics. The solid/solid conductance term in these models may not adequately describe the behavior of a Be bed. The same is true for the model to describe interfacial heat transfer. It has been developed and validated primarily for ceramic/metal interfaces, rather than metal/metal interfaces.

For both the sintered product and the pebble-bed, uncertainties in thermal transport exist because of the feedback of deformation and possible cracking on the thermal performance.

5.2 Tritium Performance

Sophisticated models have been developed to describe tritium retention in, and release from, ceramic breeder materials. Also, there is a large database from laboratory tests and in-reactor purge-flow tests with on-line tritium monitoring. The database for Li_2O is the most extensive. However, most of the tests are relatively short-term in duration resulting in low burnup and low fast neutron exposure. There are unresolved issues, particularly with regard to the ternary ceramics, as to the burnup effects on tritium performance. These mainly concern changes in stoichiometry and chemical form with lithium burnup. The BEATRIX-II test results will extend the database for Li_2O up to about 5 at. % burnup. It is important to demonstrate good tritium performance for burnups as high as 20-30%.

While the database for tritium performance of lithium-based ceramics is quite large, there have been problems in interpreting these data and in separating out systems effects and instrumentation response from ceramic breeder performance for the on-line transient release data. The most direct way of validating the models and codes is to compare predictions to end-of-test tritium inventory data. For Li_2O , there are only four such data points available. The BEATRIX-II test results will double that number. Fewer direct inventory data are available for the ternary ceramics. Thus, there is still some question as to whether enough data are available and enough validation of models has been done to answer two important design questions with confidence. The first question concerns the minimum local temperature that the breeder can operate at without building up excessive inventory. No inventory data are available below a minimum local temperature of 425°C . The second question concerns the amount of purge protium needed to insure low tritium inventory. Typically 100:1 protium/tritium ratios are recommended from the inventory perspective. However, the higher that this ratio is, the more difficult it is to separate out the tritium from the purge for reprocessing purposes. Although the protium:tritium ratio has been varied as an experimental parameter over the range of about 0 to 1000, the results are ambiguous.

The Be multiplier material will also generate tritium. Although the generation rate in the Be is about 1/100 of that in the breeder, kilograms of tritium will be generated in the Be over the life of the fusion reactor. Thus, tritium retention during normal operation and tritium release during overheating transients are still issues for the Be. There have been no on-line experiments with Be to monitor tritium release with changing operating conditions. The limited postirradiation database available suggests that tritium is essentially "trapped" in Be below a temperature T_0 (300–500°C for dense Be depending on the He content). Between T_0 and an upper temperature T_b (500–900°C for dense Be, again depending on the He content), some of the tritium is released. At and above T_b , the tritium is released in a burst mode after several hours. However, the same tests performed on porous Be (about 80% dense) indicated low-temperature in-reactor release, a gradual release with increasing temperature, and little burst release. These results suggest that as-fabricated porosity and porosity created by He-induced swelling have a significant effect on enhancing release and reducing inventory. Other parameters which may be important are BeO content and distribution, grain size, and overall sample size. While separate-effects tests have been unsuccessful in generating rate constants (e.g., diffusivity) and solubility, enough data are available for a preliminary validation of models (e.g., those developed for gas release from fission reactor fuels) which contain mechanisms for porosity and swelling effects on gas release.

5.3 Mechanical Performance

While the materials characterized in this report are not used as structural materials, their stress/strain/deformation/fracture behavior may influence the thermal performance of the blanket and blanket lifetime. Below is a rather specific list of mechanical properties which should be determined for breeder ceramics and Be in order to allow an assessment of the impact of these materials on thermal performance and lifetime.

The fracture toughness of Li_4SiO_4 has been determined for unirradiated material over a wide range of grain sizes and porosities at room temperature. High temperature data are needed for this material. The fracture toughnesses of the other three materials are needed as a function of porosity, grain size and temperature. Bending strength is another useful parameter. This needs to be determined for Li_2O as a function of porosity, grain size and temperature. More bending-strength data are available for the ternaries. However, the database needs to be broadened. Both fracture toughness and bending strength are responses of the material to applied mechanical loads. The data can be used to try to predict the response of the material to thermal loads. However, there is a great deal of uncertainty in this calculation. Usually it gives a lower bound on the temperature gradient which will cause fracture. It would be very useful to measure the thermal shock resistance of the ceramics directly in tests with temperature gradients or changes of up to 300°C. This would cover the range of most design applications. As pulsed operation is considered for some designs, the tests should also be cyclic for pulses ranging from 200-1200 s.

The database for out-of-reactor thermal creep is reasonably well developed at high temperatures (>700°C) for all of the ceramics except Li_2ZrO_3 . However, most designs call for a significant fraction of the breeder to operate well below this temperature. Extrapolation of the creep correlations to in-reactor temperatures below 700°C is complicated by the unknown effects of radiation on the deformation rates of these materials and by the changing of thermal creep mechanisms (e.g.,

matrix creep vs. grain boundary sliding). Lower temperature data are needed under in-reactor conditions in order to predict the mechanical response of the breeder/cladding system after contact has been established. The more the porous ceramic creeps and hot-presses in response to load, the less the stress will be on the cladding.

The swelling of the breeder is important from two perspectives. Swelling is a driving force for breeder/cladding contact and stresses on the cladding. Also, differential swelling within the breeder can cause internal stresses which may crack the breeder. Results from the FUBR-1A experiment have provided the primary estimate of breeder swelling rates. For the two materials which exhibited the highest swelling rates (i.e., Li_2O and Li_4SiO_4) more data are needed in the temperature range of 400-600°C under controlled moisture conditions. In FUBR-1A the Li_2O actually experienced grain growth and sintering at 500°C after long exposure. Such behavior is often associated with the formation of LiOH(T) due to possibly high moisture levels in the closed FUBR-1A capsules.

Many experimental results are reported in the literature on the mechanical properties of unirradiated and irradiated Be. The mechanical properties, particularly the fracture and ductility properties, are highly dependent on the method of fabrication which affects the resulting oxygen impurity content and the grain size. Initial porosity and generated He also have strong influence on the mechanical properties. It is important to first summarize the Be properties for anticipated design fabrication methods and then to recommend additional tests to determine the ductility, fracture strength, and yield strength as functions of temperature, fabricated porosity, and He content. This work is in progress within the U.S. ITER R&D program.

Helium-induced swelling in beryllium is important to the mechanical performance, as well as the tritium release characteristics. Recent progress has been made in determining the He content of irradiated Be and in quantifying swelling as a function of annealing temperature in postirradiation tests. However, it is also important to conduct in-reactor tests with simultaneous heat and helium generation. Also, more data and better modeling are needed in quantifying the effects of fabrication variables (e.g., grain size and porosity), impurity concentrations (e.g., BeO), and overall dimensions on swelling.

5.4 Chemical Stability/Compatibility

The chemical stability and compatibility of the breeder ceramics are important in establishing upper temperature limits for the bulk of the breeder and for breeder interfaces with other materials. A related performance parameter is Li mass transport. Based on calculations and data, it appears that mass transport may be an issue for Li_2O and for Li_4SiO_4 . The baseline data for Li_2O comes from two data sources with consistent results. Basically, the data show that if the only source of oxygen in the system comes from Li burnup, then mass transport can be minimized by proper control of the purge flow system. However, these findings need to be substantiated on a component-scale level with prototypical temperature gradients. For Li_4SiO_4 material, baseline data on mass transport are still needed.

With regard to compatibility, the key issues appear to be $\text{Li}_2\text{O}/\text{Be}$ compatibility both in- and out-of-reactor for the anticipated temperature range of 400-700°C and Be/steam reactions for overheating events. The thermodynamic driving force for

these chemical reactions is high, but there is some question about the kinetics of the reactions. The reaction between Li_2O and stainless steel, while apparently faster than the other ceramics, is still reasonably slow at anticipated design interface temperatures. However, there are some recent results which suggest that for relatively pure Li_2O the reaction is even slower than previously thought. Additional data are desirable to resolve this point. While the interaction between the other breeders and stainless steel and Be appears to be reasonably slow at the anticipated operating temperatures, in-reactor compatibility data are desirable.

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Figure 1. Layered ceramic blanket design.

Figure 2. Ceramic blanket "layered" concept --pebble bed design--.

OUTBOARD BLANKET MIDPLANE SECTION

BLANKET MODULE - DETAIL

Figure 3. BIT blanket design.

Figure 4. Radial-toroidal cross section at the equatorial plane of the outboard blanket box and (below) radial-poloidal section of the first wall (dimensions in mm).

Figure 5. Thermal conductivity data for porous Li_2O .

Figure 6. Thermal expansion of sintered Li_2O .

Figure 7. Thermal expansion of single-crystal Li_2O .

Figure 8. Estimated compressive failure strength for 80%-dense, 10- μ m-grain-diameter Li_2O . PCA and HT9 curves are shown for reference purposes.

Figure 9. Bending failure strength of 80%-dense, 10- μ m-grain-diameter Li_2O . PCA and HT9 tensile failure strengths are shown for reference purposes.

Figure 10. Secondary thermal creep rate of 80%-dense, 10- μm -grain-diameter Li_2O at 700°C. PCA and HT9 curves are shown for reference purposes.

Figure 11. Secondary thermal creep rate of 80%-dense, 10- μm -grain-diameter Li_2O at 800°C .

Figure 12. Atomic fraction of tritium (X_T) and hydrogen (X_H) dissolved in Li_2O crystals at 876 K as a function of the equilibrium pressure of carrier-free T_2 and HT-H_2 mixed gas, respectively; (o) single crystal and (●) crystalline powder.

Figure 13. Hydrogen solubility in Li_2O at 10 Pa of H_2 or H_2O .

Figure 14. Model predictions vs. data for OH solubility in Li₂O for $P(\text{H}_2\text{O})=3$ to 107 Pa.

Figure 15. Hydroxide solubility limit and critical moisture pressure in Li_2O .

Figure 16. Swelling data for FUBR-1A Li₂O.

Figure 17. The grain size of irradiated Li_2O , Li_4Si_4 , Li_2ZrO_3 , and LiAlO_2 . The indicated grain size was determined by a linear intercept method. 105 full power days.

Figure 18. Helium retention in Li_2O .

Figure 19. Equilibrium constant for the reaction $\text{Li}_2\text{O}(\text{s}) + \text{H}_2\text{O} = 2\text{LiOH}(\text{g})$.

Figure 20. Relationship between weight loss of Li_2O and temperature.

Figure 21. Thermal conductivity of Li_2O at different irradiation temperatures.

Figure 22. Lattice diffusion coefficient for lightly-irradiated Li₂O from Tanifuji (T), Quanci (Q), and Guggi (G).

Figure 23. Lattice diffusion coefficient for Li₂O vs. fluence (from Tanifuji).

Figure 24. Residence times for Li_2O .

Figure 25. Thermal conductivity data for porous Li_4SiO_4 .

Figure 26. Swelling of breeder ceramics from FUBR-1A experiment.

Figure 27. Helium retention in Li₂O, LiAlO₂, Li₄SiO₄ and Li₂ZrO₃ after irradiation.

Figure 28. Residence times for Li_4SiO_4 .

Figure 29. Thermal conductivity data for porous (~20%) Li_2ZrO_3 .

Figure 30. Helium retention in Li_2ZrO_3 .

Figure 31. Residence times for Li_2ZrO_3 .

Figure 32. Thermal conductivity of LiAlO_2 .

Figure 33. Hydroxide solubility in LiAlO₂.

Figure 34. Adsorption isotherms for H_2O on LiAlO_2 . θ is fractional surface coverage.

Thermal conductivity of LiAlO_2 at different irradiation temperatures, 105 FPD (heat up only).

Thermal conductivity of LiAlO_2 at different irradiation temperatures, 192 FPD (heat up only).

Thermal conductivity of LiAlO_2 at different irradiation temperatures, 297 FPD (heat up only).

Figure 35. Thermal conductivity of LiAlO_2 at different irradiation temperatures, 297 FPD (heat up only).

Figure 36. Residence times for LiAlO_2 .

Figure 37. Comparison between ITER quadratic correlation for Be thermal conductivity and data.

Figure 38. Beryllium thermal conductivity data vs. temperature and density (in % TD).

Figure 39. Effective conductivity vs. porosity.

Figure 40. Calculated Young's modulus values for 80% TD Be. PCA and HT9 curves are also shown.

Figure 41a. Porosity dependence of Young's modulus for Be at room temperature.

Figure 41b. Comparison of ITER correlation to data for E/E_0 for $0.07 < P < 0.27$.

Figure 42a. Ultimate tensile strength data for CIP/S Be vs. porosity (P).

Figure 42b. Comparison of ITER correlation to data for RT tensile strength.

Figure 43. Calculated secondary thermal creep rates for 80% TD Be at 700°C. PCA and HT9 curves are also shown.

Figure 44a. ITER correlation for Be ductility with porosity > 10%.

Figure 44b. Room temperature ductility for CIP/S Be.

Figure 45. Estimated diffusion coefficients for Be.

Figure 46. Laboratory annealing data for fractional tritium retention in dense and porous Be.

Figure 47. Swelling data for 100% dense hot-pressed beryllium.

Figure 48. Comparison of correlation and swelling data for 100% dense hot-pressed beryllium.

Figure 49. Difference between swelling correlation and data as a function of He content.

Figure 50. Difference between swelling correlation and data as a function of temperature.

Figure 51. Thermal conductivity of 80%-dense solid breeder materials.

Figure 52. Thermal diffusivity of 80%-dense solid breeder materials.

Figure 53. Thermal expansion of solid breeder and blanket materials.

Figure 54. Young's modulus of 80%-dense solid breeder materials

Figure 55. Bending (b) strength of 80%-dense, 10-micron grain size breeder materials.

Figure 56a. Thermal creep strain rate of 80%-dense breeder materials (700°C).

Figure 56b. Thermal creep strain rate of 80%-dense breeder materials (900°C).

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Figure 57. Comparison of tritium residency times for solid breeders.

Figure 58. H-isotope diffusion in blanket materials.

Figure 59. Solubility of H-isotopes in Li_2O and LiAlO_2 at 10 Pa partial pressure.

Figure 60. Extrapolation of wastage correlations to an ITER lifetime of 3 MW-y/m² (3.792 full power years).

Figure 61. Swelling-induced stress in constrained Be near the first wall.

Figure 62. Steady-state predictions vs. data for tritium in Li_2O .

Figure 63. Predicted inventory profile in the BEATRIX-II Li20 temperature-gradient sample.

Figure 64. Model predictions vs. data for BEATRIX-II inventory changes for 90°C temperature changes.

Figure 65. Predictions vs. data for BEATRIX-II tritium release rate for 90°C temperature decrease/increase.

Table 1. Summary of Several Solid Breeder Conceptual Designs

Design Study	Dates	Coolant	Breeder	Multiplier	Purge	Structural Material	Reference
STARFIRE	1979-80	H ₂ O	LiAlO ₂	Zr ₅ Pb ₃	He	PCA	2
DEMO (US)	1980-82	H ₂ O	Li ₂ O	--	He	PCA	3
BCSS	1982-84	He	Li ₂ O	--	He	HT9	4
TPSS	1984-86	He	Li ₂ O	Be	He	V-alloy	5
INTOR	1978-88						
(US)	--	H ₂ O	LiAlO ₂	Be	He	316 SS	6
(EC)	--	He	Li ₄ SiO ₄	Be	He	316 SS	6
(JPN)	--	He	Li ₂ O	Be	He	316 SS	6
ITER/CDA	1988-90						
(US)	--	H ₂ O	Li ₂ O	Be	He	316 SS	7
(EC)	--	H ₂ O	LiAlO ₂	Be	He	316 SS	7
(JPN)	--	H ₂ O	Li ₂ O	Be	He	316 SS	7
NET/EPP (EC)	1990-92	H ₂ O	Li ₂ ZrO ₃	Be	He	316 SS	98
DEMO (EC/KfK)	Ongoing	He	Li ₄ SiO ₄	Be	He	steel (manet)	8
DEMO (EC/CEA,ENEA)	Ongoing	He	LiAlO ₂ (Li ₂ ZrO ₃)	Be	He	steel	99,100
ITER/EDA	Ongoing	TBD	TBD	TBD	TBD	TBD	

Table 2. Li₂O

<u>Baseline physical properties</u>		<u>Refs.</u>
Molecular weight, g/g-mol	30.0314 - 2.002 δ , δ = atom fraction ⁶ Li in Li	9
Crystalline structure	Anti-CaF ₂ (cubic)	9
Density, g/cm ³	2.0338 (1 - 0.06665 δ)	10
Li density, g/cm ³	0.815 δ for ⁶ Li, 0.950 (1 - δ) for ⁷ Li	10
Melting point, °C	1432 ± 6	9
<u>Thermal properties</u>		
Vapor pressure, Pa	$\log P_{\text{Li}} = - (18.19 \times 10^3 / T) + 12.09$	15
	$\log P_{\text{LiO}} = - (19.85 \times 10^3 / T) + 11.21$	
	$\log P_{\text{Li}_2\text{O}} = - (20.60 \times 10^3 / T) + 13.40$	
	1352 ≤ T ≤ 1663 K	
Specific heat, kJ/kg-K	$C_p = 2.5179 + 3.328 \times 10^{-4} T - 8.382 \times 10^{-4} / T^2$	10
	306 ≤ T ≤ 1073 K	
Thermal conductivity, W/m-K	$k = (1 - P)^{1.96} [39.79 (1 + 7.067 \times 10^{-3} T)^{-1}]$	16 (Fig. 5)
	0.066 ≤ P (Porosity) ≤ 0.292; 473 ≤ T ≤ 1173 K	
Thermal expansion		
Linear expansion, %	$\Delta L / L_0 = 1.87 \times 10^{-3} (1 + 4.49 \times 10^{-4} T)(T - 298)$	10
Instantaneous coef., 1/K	$\alpha = 1.605 \times 10^{-5} (1 + 1.072 \times 10^{-3} T)$	(Figs. 6, 7)
Mean coefficient, 1/K	$\alpha_m = 1.87 \times 10^{-5} (1 + 4.49 \times 10^{-4} T)$	
	298 ≤ T ≤ 1223 K	

Table 2. Li₂O (continued)

<u>Mechanical Properties</u>		<u>Refs.</u>
Young's modulus, GPa	$E = 141 \exp(-3.5P)[1 - 2.3 \times 10^{-4} (T - 293)]$ $0.07 \leq P \leq 0.20, T = 293 \text{ K}$	12
Poisson's ratio	$\nu = 0.19$ (93% dense pellet), $T = 293 \text{ K}$ $= 0.16$ (single crystal), $293 \leq T \leq 1603 \text{ K}$	12 17
Ultimate compressive strength, MPa	$\sigma_c = 800 d_g^{-0.5} \exp(-10P) \ln(2000/T)$ $d_g = \text{grain diameter in } \mu\text{m}, \text{ NO DATA}$	12 (Fig. 8)
Ultimate bending strength, MPa	$\sigma_b = 195 d_g^{-0.5} \exp(-4.3P) \ln(2000T)$ $d_g = 10 \mu\text{m}, P = 0.2, T = 293 \text{ K}$	12 (Fig. 9)
Thermal creep rate, 1/s	$\dot{\epsilon}_c = 8.8 \times 10^2 (1 - P^{2/3})^{-n} \exp(-4.04 \times 10^4/T) \sigma^n$ $n = 5.9$ for $T < 973 \text{ K}$ $n = 5.9 [1 - 1.1 \times 10^{-3} (T - 973)]$, $973 \leq T \leq 1123 \text{ K}$ $n = 4.9$ for $T > 1123 \text{ K}$ $0.07 \leq P \leq 0.21, 973 \leq T \leq 1223 \text{ K}, 4 \leq \sigma \leq 45 \text{ MPa}$	12 (Figs. 10,11)
<u>Interaction with</u>		
Hydrogen (solubility), (H) ppm (Li ₂ O)	$S_H = 7.1 \exp(-2000/T) P_{H_2}^{0.5}$ $20 \leq P_{H_2} \leq 200 \text{ Pa}, 476 \leq T \leq 963 \text{ K}$	18 (Fig. 12,13)

Table 2. Li₂O (continued)

<u>Interaction with (cont'd.)</u>		<u>Refs.</u>																
Water																		
Liquid	$\text{Li}_2\text{O} + \text{H}_2\text{O} \rightarrow 2\text{LiOH} + 125 \text{ kJ/mole LiOH}$	9																
Vapor (solubility), (OH) ppm (Li ₂ O)	$S_{\text{OH}} = 10^{-A} (9.864 \times 10^{-6} P_{\text{H}_2\text{O}})^B$ $A = 23.667 - 2.502 \times 10^{-2} T + 9.62 \times 10^{-6} T^2$ $B = 0.427 + 1.7 \times 10^{-4} T$ $2 \leq P_{\text{H}_2\text{O}} \leq 2000 \text{ Pa}, 713 \leq T \leq 1123 \text{ K}$	19 (Figs. 13,14,15)																
316 Stainless Steel (wastage), μm	$d = 1.06 \times 10^3 \exp (-5920/T) t^{0.5}$ $773 \leq T \leq 1073 \text{ K}, 100 \leq t \leq 5600 \text{ h}$	20,21,22																
Be	NO DATA																	
<u>Irradiation effects</u>																		
Physical integrity	Fair for 500, 700, 900°C (< 3 at.% ⁶ Li burnup) Fair for 550-1000°C (4 at.% ⁶ Li burnup)	23 24																
Swelling	$\Delta V/V_0, \%$ <table><tr><th>Bu, at. %</th><th>500°C</th><th>700°C</th><th>900°C</th></tr><tr><td>1</td><td>-1.0</td><td>5.0</td><td>6.0</td></tr><tr><td>2</td><td>-3.5</td><td>7.5</td><td>6.0</td></tr><tr><td>3</td><td>-2.8</td><td>7.0</td><td>6.0</td></tr></table>	Bu, at. %	500°C	700°C	900°C	1	-1.0	5.0	6.0	2	-3.5	7.5	6.0	3	-2.8	7.0	6.0	23 (Fig. 16)
Bu, at. %	500°C	700°C	900°C															
1	-1.0	5.0	6.0															
2	-3.5	7.5	6.0															
3	-2.8	7.0	6.0															
Grain growth	at 1 at.% ⁶ Li burnup and 500°C: 3.5 → 3.5 μm 700°C: 3.5 → 7.0 μm 900°C: 3.5 → 17.0 μm	25 (Fig. 17)																

Table 2. Li₂O (continued)

Helium retention	Retained/Generated, %				Refs.
	Bu. at.%	500°C	700°C	900°C	
	1	25	25	10	26
	2	14	22	5	(Fig. 18)
	3	13	23	7	
Li transport, g/h	$W = (29.9/2) F \sqrt{K \cdot P_{H_2O}} / P_{total}$				27, 28
	F = He sweep gas flow rate (mol/h)				(Figs. 19,20)
	K = (P _{LiOH}) ² /P _{H₂O} , equilibrium constant for Li ₂ O(s) + H ₂ O(g) → 2LiOH(g)				
	P _{H₂O} = water vapor pressure in atm.				
	P _{total} = total sweep gas pressure, atm.				
Thermal conductivity	Slight decrease at low temp. due to fast neutron irradiation				29 (Fig. 21)
Young's modulus	NO DATA				
Compressive strength	NO DATA				
Bending strength	NO DATA				
Tritium diffusivity, cm ² /s	$D = 4.03 \times 10^{-2} \exp[-95.1 \text{ (kJ/mol)/RT}]$				30
	573 ≤ T ≤ 1173 K				(Fig. 22)
	Single crystal diffusivity decreases with irradiation				(Fig. 23)
Tritium residency time, h	$\tau = \exp(2.273 \times 10^4/T - 34.83)$				31
	d _g ~ 16 μm, P ~ 20%, 593 ≤ T ≤ 773				(Fig. 24)
	He + 0.1% H ₂ purge				

Table 3. $\alpha\text{Li}_4\text{SiO}_4$

<u>Baseline physical properties</u>		<u>Refs.</u>
Molecular weight, g/g-mol	120.126 (1 - 0.03315 δ), δ = ^6Li fraction in Li	9
Crystalline structure	Monoclinic	9
Density, g/cm ³	$\rho = 2.3993 (1 - 0.03332 \delta)$	10
Li density, g/cm ³	0.4805 δ (^6Li), 0.5604 (1 - δ) (^7Li)	10
Melting point, °C	1255	9
<u>Thermal properties</u>		
Vapor pressure, Pa	$\log P_{\text{Li}} = 14.943 - 23602/T$	32,33
	$\log P_{\text{O}_2} = 14.767 - 24473/T$	
	$\log P_{\text{Li}_2\text{O}} = 21.651 - 36223/T$	
	$1385 \leq T \leq 1516 \text{ K}$	
	$\log P_{\text{LiOH}} = 8.686 - 11580/T$ at $P_{\text{H}_2\text{O}} = 10.1 \text{ Pa}$	
Specific heat, kJ/kg-K	$C_p = 0.890 + 1.46 \times 10^{-3} T + 4.01 \times 10^{-5} T^2$	9,10,34
	$372 \leq T \leq 873 \text{ K}$	
Thermal conductivity, W/m-K	$k = (1-P)^{5/3} (2.49) [(1+2.06 \times 10^{-3} T)^{-1} + 1.85 \times 10^{-10} T^3]$	35,36 (Fig. 25)
	$0.16 \leq P \text{ (porosity)} \leq 0.30 \quad 373 \leq T \leq 873 \text{ K}$	
Thermal expansion		
Linear expansion, %	$\Delta L/L_0 = 1.267 \times 10^{-3} (1 + 1.065 \times 10^{-3} T) (T - 298)$	37,38
Instantaneous coef., 1/K	$\alpha = 8.669 \times 10^{-6} (1 + 3.12 \times 10^{-3} T)$	
Mean coefficient, 1/K	$\alpha_m = 12.67 \times 10^{-6} (1 + 1.065 \times 10^{-3} T)$	
	$298 \leq T \leq 1273 \text{ K}$	

Table 3. $\alpha\text{Li}_4\text{SiO}_4$ (continued)

<u>Mechanical properties</u>		<u>Refs.</u>
Young's modulus, GPa	$E = 110 (1 - P)^3 [1 - 2.5 \times 10^{-4} (T - 293)]$ $0.02 \leq P \leq 0.32, T = 293 \text{ K}$	39,40
Poisson's ratio	$\nu = 0.24, P = 0.1, T = 293 \text{ K}$	40
Ultimate compressive strength, MPa	$\sigma_c = 975 d_g^{-0.44} (1 - P)^{1.5}$ $15 \leq d_g \text{ (grain diameter)} \leq 100 \text{ } \mu\text{m},$ $0.06 \leq P \leq 0.28, T = 293 \text{ K}$	40
Ultimate bending strength, MPa	$\sigma_b = 275 \exp(-4.3 P) d_g^{-0.5}$ $4 \leq d_g \leq 50 \text{ } \mu\text{m}, 0.02 \leq P \leq 0.32, T = 293 \text{ K}$	39
Thermal creep rate, s ⁻¹	$\dot{\epsilon}_c = 1.4 \times 10^{-2} \exp(29 P) \exp(-21.5 \times 10^3 / T) \sigma$ $10 \leq \sigma \leq 40 \text{ MPa}, 0.08 \leq P \leq 0.22$ $1000 \leq T \leq 1220 \text{ K}$	40
<u>Interaction with</u>		
Hydrogen (solubility), (H) ppm (Li_4SiO_4)	NO DATA	
Water		
Liquid	NO DATA	
Vapor		
Solubility, (OH) ppm (Li_4SiO_4)	NO DATA	
Adsorption, mols (OH)/m ²	NO DATA	
Steels		
Penetration depth, μm		
Dry	$d^2 = 1 \times 10^5 t \exp(-1.20 \times 10^4 / T)$	21,41
P _{H₂O} @ 10 Pa	$d^2 = 2.5 \times 10^5 t \exp(-1.20 \times 10^4 / T)$ $25 \leq t \leq 500 \text{ h} \quad 973 \leq T \leq 1273 \text{ K}$	

Table 3. $\alpha\text{Li}_4\text{SiO}_4$ (continued)

		Refs.																
Be																		
Penetration depth, μm	$d^2 = 1.1 \times 10^4 t \exp(-1.02 \times 10^4/T)$ $100 \leq t \leq 1000 \text{ h}, 923 \leq T \leq 1023 \text{ K}$	42																
Irradiation effects																		
Physical integrity	Poor at 500, 700, 900°C (<3 at.% burnup)	23,24																
Swelling	$\Delta V/V_0, \%$ <table> <tr> <th>^6Li Bu</th> <th>500°C</th> <th>700°C</th> <th>900°C</th> </tr> <tr> <td>1</td> <td>0.3</td> <td>0.3</td> <td>0.3</td> </tr> <tr> <td>2</td> <td>--</td> <td>1.2</td> <td>0.5</td> </tr> <tr> <td>3</td> <td>0.4</td> <td>2.7</td> <td>2.0</td> </tr> </table>	^6Li Bu	500°C	700°C	900°C	1	0.3	0.3	0.3	2	--	1.2	0.5	3	0.4	2.7	2.0	23 (Fig. 26)
^6Li Bu	500°C	700°C	900°C															
1	0.3	0.3	0.3															
2	--	1.2	0.5															
3	0.4	2.7	2.0															
Grain growth	At ~1 at.% ^6Li burnup, none for 500°C, 700°C, 1 $\rightarrow$ 2 μm at 900°C	25 (Fig. 17)																
Helium retention	At 1 at.% ^6Li burnup <table> <tr> <th>T, °C</th> <th>Retained/Generated, %</th> </tr> <tr> <td>500</td> <td>0.7</td> </tr> <tr> <td>700</td> <td>0.6</td> </tr> <tr> <td>900</td> <td>0.06</td> </tr> </table>	T, °C	Retained/Generated, %	500	0.7	700	0.6	900	0.06	26 (Fig. 27)								
T, °C	Retained/Generated, %																	
500	0.7																	
700	0.6																	
900	0.06																	
Tritium diffusivity, cm^2/s	No single crystal data $D = 1.37 \times 10^{-7} \exp(-63 \text{ kJ/mol}/RT)$ Based on grain size of polycrystalline samples	43																
Tritium residency time, h	$\tau = 2.24 \times 10^{-12} \exp(165 \text{ kJ} \cdot \text{mol}^{-1}/RT)$ $d_g \sim 20 \mu\text{m}, P \sim 0.08 \quad 560 \leq T \leq 770 \text{ K}$ He + 0.1% H_2 purge	44 (Fig. 28)																

Table 4. Li_2ZrO_3

<u>Baseline physical properties</u>		<u>Refs.</u>
Molecular weight, g/g-mol	153.25 (1 - $1.31 \times 10^{-2} \delta$), δ = ^6Li fraction in Li	9
Crystalline structure	Monoclinic	9
Density, g/cm ³	$\rho = 4.1573 (1 - 1.31 \times 10^{-2} \delta)$	9
Li density, g/cm ³	0.3264 δ for ^6Li , 0.3807 (1 - δ) for ^7Li	9
Melting point, °C	1695 ± 15	45,46
<u>Thermal properties</u>		
Vapor pressure, Pa	$\text{Log } P_{\text{Li}} = -18.39 \cdot 10^3/T + 10.59$ $1031 \leq T \leq 1642 \text{ K}$	47
Specific heat, kJ/kg-K	$C_p = 1.022 - 3.696 \times 10^{-5} T - 2.791 \times 10^4 T^{-2}$ $350 \leq T \leq 1012 \text{ K}$	48
Thermal conductivity, W/m-K	$K = (1 - P)^{5/3} [3.643 (1 + 1.549 \times 10^{-3} T)^{-1} + 7.579 \times 10^{-10} T^3]$ $0.187 \leq P \text{ (porosity)} \leq 0.211 \quad 373 \leq T \leq 1063 \text{ K}$	9,49 ,51(Fig. 29)
Thermal expansion		
Linear expansion, %	$\Delta L/L_0 = 9.89 \times 10^{-4} (1 + 1.13 \times 10^{-5} T)(T-298)$	34
Instantaneous coef., 1/K	$\alpha = 9.86 \times 10^{-6} (1 + 2.27 \times 10^{-5} T)$	
Mean coefficient, 1/K	$\alpha_m = 9.89 \times 10^{-6} (1 + 1.13 \times 10^{-5} T)$	

Table 4. Li₂ZrO₃ (continued)

<u>Mechanical properties</u>			<u>Refs.</u>
Young's modulus, GPa	$E = 203.35 (1 - P)(1 - 1.286 P)^2 \cdot [1 - 2.40 \times 10^{-4} (T - 293)]$ $T = 293 \text{ K}$		52
Poisson's ratio	$\nu = 0.2$		51
Ultimate compressive strength, MPa	$\sigma_c = 396 (d_g = 0.8 \mu\text{m}, 80\% \text{ TD})$		52
	$\sigma_c = 230 \pm 31 (d_g = 2 \mu\text{m}, 80\% \text{ TD})$		48
Ultimate bending strength, MPa	$\sigma_b = 65 \pm 15 (25^\circ\text{C}), 60 \pm 20 (400^\circ\text{C})$ $63 \pm 1 (600^\circ\text{C}), (d_g = 2 \mu\text{m}, 80\% \text{ TD})$		48
Thermal creep rate, s ⁻¹	$2 \times 10^{-6} (26 \text{ MPa}), 8 \times 10^{-6} (75 \text{ MPa}),$ $4 \times 10^{-5} (144 \text{ MPa}) \text{ at } 900^\circ\text{C}$ $P = 0.13$		53
<u>Interaction with</u>			
Hydrogen:	solubility adsorption	NO DATA NO DATA	
Water:			
Liquid		Hydrolyses at 25°C and 100°C	48,50,52
Vapor:	solubility adsorption	NO DATA NO DATA	
Steels		No significant interaction in conditions explored: up to 700°C in vacuum	21
Beryllium		No significant interaction up to 650°C in vacuum slight oxidation of beryllium in wet helium	54

Table 4. Li₂ZrO₃ (continued)

<u>Irradiation effects</u>		<u>Refs.</u>
Physical integrity	Very good	23
Swelling	Less than 0.7%	23 (Fig. 26)
Grain growth	No	25
Li transport	No	56
Thermal conductivity	No significant change	48
Thermal expansion	No significant change	48
Young's modulus	~30% increase	48
Compressive strength	Significant decrease, not in agreement with bending strength behavior	48
Bending strength	Scattered values available	48
Helium retained	Very low	26 (Fig. 30)
Tritium diffusivity	No single crystal data	
Tritium residency time, h	$\tau = 1.089 \times 10^{-19} \exp(230.5 \text{ kJ} \cdot \text{mol}^{-1}/RT)$ $T \geq 583 \text{ K}, 0.5 \leq d_g \leq 1 \text{ } \mu\text{m}, 20 \leq P \leq 25\%$ He + 0.1% H ₂ purge	31 (Fig. 31)

Table 5. γLiAlO_2

Baseline physical properties		Refs.
Molecular weight, g/g-mol	66.0 (1 - 0.015 δ), δ = ^6Li fraction in Li	9
Crystalline structure	Tetragonal	9
Density, g/cm ³	$\rho = 2.6171 (1 - 0.01516 \delta)$	9
Li density, g/cm ³	0.2385 δ for ^6Li ; 0.2782 (1- δ) for ^7Li	9
Melting point, °C	1750	55
Thermal properties		
Vapor pressure, Pa	Log P_{O_2} = - 20.69 $\times 10^3/T$ + 10.39 1723 $\leq T \leq 1923$ K	56
	Log $P_{\text{Li}_2\text{O}}$ = - 23.58 $\times 10^3/T$ + 10.56 1850 $\leq T \leq 1923$ K	
	Log P_{LiO} = - 22.04 $\times 10^3/T$ + 9.78 1640 $\leq T \leq 1923$ K	
	Log P_{Li} = - 20.23 $\times 10^3/T$ + 11.17 1480 $\leq T \leq 1723$ K	
Specific heat, kJ/kg-K	$C_p = 1.40 + 1.84 \times 10^{-4} T - 3.807 \times 10^{-4} T^2$ 298 $\leq T \leq 1800$ K	57
Thermal conductivity, W/m-K	$k = (1 - P)^{5/3} [100 (2.516 + 0.0267 T)^{-1} - 0.3821 + 9.21 \times 10^{-10} T^3]$ 0.10 $\leq P$ (porosity) ≤ 0.32 300 $\leq T \leq 1173$ K	44 (Fig. 32)
Thermal expansion		
Linear expansion %	$\Delta L/L_0 = 9.00 \times 10^{-4} (1 + 2.23 \times 10^{-4} T)(T - 298)$	34
Instantaneous coef. 1/K	$\alpha = 8.40 \times 10^{-6} (1 + 4.77 \times 10^{-4} T)$	
Mean coefficient, 1/K	$\alpha_m = 9.00 \times 10^{-6} (1 + 2.23 \times 10^{-4} T)$ 298 $\leq T \leq 1173$ K	

Table 5. γ -LiAlO₂ (continued)

<u>Mechanical properties</u>			<u>Refs.</u>
Young's modulus, GPa		$E = 184.5 (1 - P)(1 - P/0.7)^2 \cdot [1 - 2.2 \times 10^4 (T - 293)]$	52,58
		$0.1 \leq P \leq 0.5 \quad 293 \leq T \leq 973 \text{ K}$	
Poisson' ratio		$\nu = 0.22, T = 293 \text{ K}$	59
Ultimate compressive strength, MPa		$\sigma_c = \exp(-10 P) d_g^{-0.5} \ln(2200/T) \times 10^3$	58
		$0.25 \leq d_g \text{ (grain diameter)} \leq 13 \mu\text{m}$	
		$0.1 \leq P \leq 0.3 \quad 293 \leq T \leq 1373 \text{ K}$	
Ultimate bending strength,		$\sigma_b = 62 \exp(-4.3 P) d_g^{-0.5} \ln(2200/T)$	12
		$1 \leq d_g \leq 8 \mu\text{m} \quad 0.18 \leq P \leq 0.26$	
		$293 \leq T \leq 873$	
Thermal creep rate, s ⁻¹		$\dot{\epsilon} = 4.82 \times 10^5 (1 - P^{2/3})^{-4} \exp(-5.15 \times 10^4 / T) \sigma^4$	12
		$50 \leq \sigma \leq 167 \text{ MPa} \quad 973 \leq T \leq 1073 \text{ K}$	
		$0.25 \leq P \leq 0.28$	
<u>Interaction with</u>			
Hydrogen:	solubility	NO DATA	
	adsorption	NO DATA	
Water:	liquid	Weak and slow at 25°C, fast at 100°C $\rightarrow \text{Al}_2\text{O}_3 \times 3\text{H}_2\text{O} + \text{LiOH}$	50,52,60
	vapor:		
	solubility, ppm (LiAlO ₂)	$S_{\text{OH}} = \exp(6.664 - 5.34 \times 10^{-3} T) P_{\text{H}_2\text{O}}^{-0.274 + 10^{-3} T}$ $3 \leq P_{\text{H}_2\text{O}} \leq 50 \text{ Pa}, 673 \leq T \leq 973 \text{ K}$	61 (Fig. 33)

Table 5. $\gamma\text{-LiAlO}_2$ (continued)

		Refs.																		
adsorption, fractional	$\log \theta = A + B \log P_{\text{H}_2\text{O}}$	61 (Fig. 34)																		
surface coverage	$3 \leq P_{\text{H}_2\text{O}} \leq 30 \text{ Pa}$	34 (Table 7)																		
	<table> <tr> <th>T, K</th><th>A</th><th>B</th></tr> <tr> <td>573</td><td>-2.687 ± 0.085</td><td>1.162 ± 0.208</td></tr> <tr> <td>623</td><td>-2.063 ± 0.055</td><td>0.660 ± 0.236</td></tr> <tr> <td>673</td><td>-1.994 ± 0.141</td><td>0.517 ± 0.182</td></tr> <tr> <td>773</td><td>-1.741 ± 0.018</td><td>0.359 ± 0.024</td></tr> <tr> <td>873</td><td>-2.591 ± 0.113</td><td>0.593 ± 0.157</td></tr> </table>	T, K	A	B	573	-2.687 ± 0.085	1.162 ± 0.208	623	-2.063 ± 0.055	0.660 ± 0.236	673	-1.994 ± 0.141	0.517 ± 0.182	773	-1.741 ± 0.018	0.359 ± 0.024	873	-2.591 ± 0.113	0.593 ± 0.157	
T, K	A	B																		
573	-2.687 ± 0.085	1.162 ± 0.208																		
623	-2.063 ± 0.055	0.660 ± 0.236																		
673	-1.994 ± 0.141	0.517 ± 0.182																		
773	-1.741 ± 0.018	0.359 ± 0.024																		
873	-2.591 ± 0.113	0.593 ± 0.157																		
Steels	No significant interaction in conditions explored: 700°C, 1500 h in vacuum	21,62																		
Beryllium	No significant interaction in conditions explored: 500-700°C, 500-3000 h in vacuum Slight oxidation of beryllium in wet helium	62																		
<u>Irradiation effects</u>																				
Physical integrity	Fair up to 500°C Fair up to 700°C Poor at 600-1100°C	23 24 27																		
Swelling	Less than 0.5% Shrinkage at $T > 750^\circ\text{C}$	23 63 (Fig. 26)																		
Grain growth	None observed	25 (Fig. 17)																		
Helium retained	Very low	26, 63 (Fig. 27)																		
Li transport	None observed																			
Thermal conductivity	No change Essentially no change for all irradiation temperatures and times	63 29 (Fig. 35)																		

Table 5. γ -LiAlO₂ (continued)

		<u>Refs.</u>
Young's modulus	No significant change	63
Compressive strength	No significant change at temperature <700°C	63
Tritium diffusivity, cm ² /s	$1.06 \times 10^{-1} \exp(-126 \text{ kJ} \cdot \text{mol}^{-1}/RT)$	96
Tritium residence time, h	$\tau = 5.538 \times 10^{-7} \exp(108.54 \text{ kJ} \cdot \text{mol}^{-1}/RT)$ P ~ 25%, dg ~ 0.5 μm , 700 ≤ T ≤ 900 K Conservative estimate based on He + 0.1% H ₂ purge	31 (Fig. 36)

Table 6. Beryllium

<u>Baseline physical properties</u>			<u>Refs.</u>
Molecular weight, g/g-mol	9.01		64
Crystalline structure	HCP		64
Density, g/cm ³	1.85		64
Melting point, °C	1283		64
Heat of melting, kJ/kg	1303		64
<u>Thermal properties</u>			
Vapor pressure, Pa	$\text{Log } (P_{\text{Be}}) = 11.192 + 1.454 \times 10^{-4} T - 1.6734 \times 10^4/T$ $1173 \leq T \leq 1556 \text{ K}$		64
Specific heat, kJ/kg-K	$C_p = 2.432 + 6.378 \times 10^{-4} T - 7.11 \times 10^4 T^{-2}$ $300 \leq T < 1556 \text{ K}$		65
Thermal conductivity, W/m-K	$k = f_p [291 (1 - 1.650 \times 10^{-3} T$		66
	$+ 1.464 \times 10^{-6} T^2 - 5.125 \times 10^{-10} T^3)]$		
	$f_p = (1 - P)(1 + 3.7 P^2)^{-1}$		67
	$0 \leq P \text{ (porosity fraction)} \leq 0.8$ $300 \leq T \leq 823 \text{ K}$		(Figs. 37,38,39)

Table 6. Beryllium (continued)

		Refs. 68
Thermal expansion		
Linear expansion, %	$\Delta L/L_0 = 8.43 \times 10^{-4} (1 + 1.36 \times 10^{-3} T - 3.53 \times 10^{-7} T^2)(T - 298)$	
Instantaneous coefficient, 1/K	$\alpha = 5.01 \times 10^{-6} (1 + 3.451 \times 10^{-3} T - 1.979 \times 10^{-7} T^2)$ $298 \leq T \leq 1500 \text{ K}$	
Mean coefficient, 1/K	$\alpha_m = 8.43 \times 10^{-6} (1 + 1.36 \times 10^{-3} T - 3.53 \times 10^{-7} T^2)$ $298 \leq T \leq 1500 \text{ K}$	
Thermal accommodation coeff.	0.0925 ± 0.0525	69
Thermal emissivity	0.6 for unpolished surface	70
<u>Mechanical properties</u>		
Young's modulus, GPa	$E = 297 \exp(-3.5 P)[1 - 1.9 \times 10^{-4} (T - 293)]$ $P = 0, 293 \leq T \leq 1088 \text{ K}$	12,71 (Figs. 40,41)
Poisson's ratio	$\nu = 0.07 \pm 0.06$	12
Ultimate compressive strength, MPa	$\sigma_c = 450 d_g^{-1/2} \exp(-5 P) \ln(9200/T)$ $d_g = \text{grain diameter, } \mu\text{m}$ $0 \leq P \leq 0.2, 293 \leq T \leq 773 \text{ K}$	12,67
Bending strength, MPa	$\sigma_b = 700 d_g^{-1/2} \exp(-5 P) \ln(9200/T)$ $P = 0, T = 293 \text{ K}$	12
Ultimate tensile strength, MPa	$\sigma_t = 450 d_g^{-1/2} \exp(-5 P) \ln(9200/T)$	12,67 (Fig. 42)

Table 6. Beryllium (continued)

		Refs.
Thermal creep rate, s ⁻¹	$\dot{\epsilon}_c = 0.751 (1 - P^{2/3})^{-3.6} \exp(-2.60 \times 10^4/T) \sigma^{3.6}$ $P = 0, 673 \leq T \leq 973 \text{ K}$ $14 \leq \sigma \leq 21 \text{ MPa}$	12 (Fig. 43)
Ductility, %	$\epsilon_u = (1.0 \pm 0.5) \exp(2.71 - 7.13 \times 10^{-3} T - 673)$ $P \geq 0.1, 293 \leq T \leq 873 \text{ K}$	67,70,71 (Fig. 44)
<u>Interaction with</u>		
Hydrogen		
Solubility, appm	$S = 1.9 \times 10^{-2} (P_{H_2}/Pa)^{1/2}$	77
Adsorption	NO DATA	
Oxidation	Rapid reaction for porous Be at $T > 873 \text{ K}$	74
Water		
Liquid	Slow and self-limiting for $T < 873 \text{ K}$ because of formation of BeO protective layer	64
Vapor		
Solubility	NO DATA	
Adsorption	NO DATA	
Stainless steel (316), μm	$d = 6.58 \times 10^4 \exp(-1.29 \times 10^4/T)t$ $100 \leq t \leq 3000 \text{ h}$ $823 \leq T \leq 1173 \text{ K}$	42,62,72,73
<u>Radiation Effects</u>		
Physical properties	No change in physical properties is anticipated for irradiation above room temperature. However, the $\Delta V/V_0$ due to He-induced swelling must be added to P in the porosity correction factor for thermal conductivity.	75

Table 6. Beryllium (continued)

		<u>Refs.</u>
Mechanical properties	He embrittlement causes a decrease in ductility for 100% dense Be tested (post-irradiation) at room temperature. In the absence of data on porous Be, the lower bound on the ductility of unirradiated Be is recommended.	70
	$\epsilon_U = 0.5 \exp(2.71 - 7.13 \times 10^{-3} T - 673)$, %	67
	The room temperature compressive strength increases significantly with fast fluence up to $\sim 2 \times 10^{22}$ n/cm ² and then decreases. The flexure and tensile strengths decrease with fluence at room temperature by ~ 50 MPa/ 10^{22} n/cm ² up to 3×10^{22} n/cm ² . For irradiation of porous Be ($P \geq 0.1$) at temperature ($T > 100^\circ\text{C}$), unirradiated properties are recommended.	
Tritium Retention/Release		
Diffusivity, cm ² /s	Wide scatter	76 (Fig. 45)
Solubility, appm	$S = 1.9 \times 10^{-2} (P_{T_2}/\text{Pa})^{1/2}$	77
Trapping	Very little tritium (<2%) is released from irradiated Be for $T < 600^\circ\text{C}$. Above 600°C , tritium release may be enhanced by He swelling. For two samples with high He content ($\sim 26 \times 10^3$ appm), $\sim 95\%$ of the tritium was released after 5 hours at 611°C . As-fabricated porosity enhances tritium release at the lower temperatures.	76,77,78 (Fig. 46) (Table 8)
Swelling	$\Delta V/V_0 = 0.115 (G_\alpha/10^3)[1 + 3.0 \times 10^{-3} (G_\alpha/10^3)^{0.5} T^{1.5} \exp(-3940/T)]$ % $0 \leq G_\alpha$ (He content in appm) $\leq 26 \times 10^3$ $293 \leq T \leq 873$ K	76,79,80,81 (Figs. 47, 48, 49,50)

Table 7.
Moisture Adsorption on LiAlO₂ at Relatively High Moisture Pressures and Surface Coverages.* The Parameter θ is Fractional Surface Coverage Assuming a Maximum OH Coverage of 10^{19} OH/m².

T, K	P _{H₂O} , Pa	θ	T, K	P _{H₂O} , Pa	θ
573	12	0.26	773	41	0.16
	33	0.30		53	0.17
	93	0.30		80	0.20
	156	0.32		93	0.20
	188	0.32		149	0.24
	232	0.35		171	0.23
	317	0.37		209	0.24
	389	0.37		324	0.27
	489	0.41		391	0.28
	636	0.42		493	0.30
	700	0.41		549	0.30
	733	0.44		685	0.33
	806	0.44		858	0.32
	962	0.45		884	0.34
	973	0.39		1028	0.34
	1130	0.45		1057	0.32
673	9	0.18	873	40	0.075
	80	0.27		64	0.091
	87	0.27		83	0.11
	153	0.31		164	0.11
	220	0.32		165	0.15
	241	0.33		220	0.14
	307	0.36		311	0.16
	372	0.35		384	0.17
	373	0.35		453	0.18
	541	0.37		477	0.19
	595	0.38		636	0.20
	637	0.38		737	0.20
	760	0.37		800	0.22
	790	0.39		862	0.22
	884	0.39		1029	0.24
	920	0.39		1046	0.23
	1036	0.39		1084	0.25
	1064	0.40		1316	0.26

* M.R. Mancini et al., "Hydrogen and Water Vapor Adsorption on Lithium Aluminate," ENEA report RT/TIB/89/1 (1989).

Table 8. Summary of ITER R&D Data on Tritium and Helium Retention in Irradiated Be

Initial Density, % TD	Fluence $10^{22}\text{n (E>1 MeV)/cm}^2$	Irrad. T °C	Tritium appm	Helium appm	Anneal. T °C	Anneal t h	Retained Tritium I/I ₀ , %
100	5.0 ± 0.3	~75	2530	26100	300	20-114	99.99
					400	142-170	99.75
					500	99-669	99.4
					600	148-202	10
					700	17	--
99.6	0.26	~75	71.8	872	300	355	99.905
					400	307	99.45
					500	365	96.7
					600	381	90.3
					700	319	73.5
					750	24	71.6
					800	24	66.8
					850	24	57.6
					900	24	3.5
80.9	0.26	~75	55.3	733	300	386	96.8
					400	335	62.0
					500	318	11.0
					600	435	1.0

Table 9a. Materials Data Base Assessment for Solid Breeders

	Li ₂ O	Li ₄ SiO ₄	Li ₂ ZrO ₃	LiAlO ₂
Baseline physical properties				
Density	■	■	■	■
Melting temperature	■	▲	●	■
Vapor pressure	▲	○	○	▲
Thermal expansion	■	▲	▲	■
Thermal conductivity	▲		▲	■
Specific heat	■	■	▲	■
Baseline mechanical properties				
Elastic modulus	▲	▲	▲	■
Poisson's ratio	▲	▲	○	▲
Fracture strength				
tensile				
compressive	○	○	○	▲
bending strength	○	▲	▲	▲
Creep properties	▲	▲	○	▲
Chemical stability/compatibility				
Composition/purity	■	■	■	■
Stability	■	■	■	■
Vapor pressure/transport	■	○	○	○
Compatibility				
water	▲	▲	■	■
beryllium		■	▲	■
SS	●	■	▲	■
Tritium solubility/transport				
Tritium solubility	●			▲
Tritium diffusivity	■	○	○	●
Adsorption/desorption	●			▲
Radiation effects				
Physical properties	○	○	○	○
Swelling	○	○	○	○
Creep				
Tritium trapping/transport	●	○	○	○
Helium trapping/transport	○	○	○	○
Fracture properties	○		○	○

■ — Adequate/good agreement
 ▲ — Limited/general agreement
 ● — Limited/important discrepancies
 ○ — Single set of data
 Blank — Very limited/non-existent/high uncertainties

Table 9b. Materials Data Base Assessment for Be

Baseline physical properties

Density		■
Melting temperature		■
Vapor pressure		▲
Thermal expansion		▲
Thermal conductivity		▲
Specific heat		■
Electrical Resistivity		▲

Baseline mechanical properties

Elastic modulus		▲
Poisson's ratio		●
Fracture properties		
Tensile		●
Bending		●
Compressive		●
Creep properties		●

Chemical stability/compatibility

Composition/purity		■
Vapor pressure/transport		■
Compatibility		
Water		●
S S		■

Tritium solubility/transport

Tritium solubility		○
Tritium diffusivity		●
Adsorption/desorption properties		

Radiation effects

Physical properties		○
Swelling		●
Creep		
Tritium trapping/transport		●
Helium trapping/transport		▲
Fracture properties		●

■	— Adequate/good agreement
▲	— Limited/general agreement
●	— Limited/important discrepancies
○	— Single set of data
Blank	— Very limited/non-existent/high uncertainties

Table 10a.
Properties of Candidate Breeder Materials at 80% Density, 10 μm Grain Diameter, and 90% Li-6 Enrichment. Values in Parentheses are Estimated or Extrapolated Well Beyond the Data Base.

Property		Li_2O	Li_4SiO_4	Li_2ZrO_3	LiAlO_2
RT density, g/cm^3		1.529	1.862	3.287	2.065
Li-6 density, g/cm^3		0.587	0.346	0.235	0.172
T_{melt} , $^{\circ}\text{C}$		1432	1255	1695	1750
Thermal conductivity at 600°C , W/m-K		3.54	0.82	1.42	2.83
Thermal diffusivity at 600°C , mm^2/s		0.857	0.300	0.357	0.715
Thermal expansion at 600°C , %		1.50	1.41	0.57	0.62
Young's modulus, GPa	RT	70.0	56.3	89.8	75.3
	600°C	(60.7)	(48.2)	(77.3)	70.5
Poisson's ratio	RT	0.19	0.24	0.2	0.22
	600°C	(0.19)	(0.24)	(0.2)	(0.22)
Compressive strength, MPa	RT	(65.8)	253	145	86.2
	600°C	(28.4)	(--)	(--)	39.6
Bending strength, MPa	RT	50.1	36.8	41.1	16.7
	600°C	(21.6)	(--)	39.8	7.7
Creep rate, $\mu\text{m/m-s}$ (800°C , 20 MPa)		4.0	0.184	(<<2)	($5.9\text{E-}4$)
Swelling (vol. %) at $1.\text{E}21$ captures/ cm^3					
	500°C	-3.0	1.5	0.8	0.4
	700°C	7.3	1.4	0.5	0.6
T_{min} ($^{\circ}\text{C}$) for 1-day tritium residency time*		320	390	320	450

* Grain sizes of $16\ \mu\text{m}$ (Li_2O), $21\ \mu\text{m}$ (Li_4SiO_4), $1\ \mu\text{m}$ (Li_2ZrO_3) and $0.4\ \mu\text{m}$ (LiAlO_2).

Table 10b.
Properties of Be at 80% Density and 20 μm Grain Diameter. Values in Parentheses are Estimated or Extrapolated well Beyond the Data Base.

Property	Value	Porosity (P) Extrapolation
RT density, g/cm ³	1.85	
T melt, °C	1283	
Thermal conductivity, W/m-K		$(1-P)(1 + 3.7 P^2)^{-1}$
200°C	79.7	
400°C	64.1	
Thermal expansion, %		
200°C	0.271	
400°C	0.555	
Young's modulus, GPa		exp (-3.5 P)
RT	0.07 $\pm$ 0.06	
400°C	--	
Compressive strength, MPa		exp (-5.0 P)
RT	128	
400°C	97	
Bending strength, MPa		exp (-5.0 P)
RT	(199)	
400°C	(151)	
Tensile strength, MPa		exp (-5.0 P)
RT	128	
400°C	97	
Irradiated ductility, %		P > 0.1
RT	0.5	
400°C	7.5	
Thermal creep rate ($\mu\text{m}/\text{m}\cdot\text{s}$) at 20 MPa		$(1-P^{2/3})^{-3.6}$
400°C	2.73E-12	
600°C	1.90E-8	
Irradiation creep rate ($\mu\text{m}/\text{m}\cdot\text{s}$) at 20 MPa and 5 dpa/y	(1.01E-5)	
Swelling (vol. %) at 14000 appm He		
RT	1.32	
400°C	3.17	

Table 11.
Comparison Between Hall and Martin Model and Data for the Effective Conductivity of Single-Size
Packed Beds of Li₂O, Li₄SiO₄, and Li₂ZrO₃

Pebble Bed	Packing Fraction, %	Particle Diameter, μm	Particle Porosity, %	Gas Pressure, MPa	T, °C	k_{eff} , W/m-K		Ref.
						Data	Model	
Li ₂ O/He	55.13	5000	25	0.1014	263	1.10±0.2	0.905	83
					350	1.13±0.2	0.977	
					440	1.20±0.2	1.020	
					525	1.14±0.11	1.061	
					613	1.13±0.06	1.105	
Li ₄ SiO ₄ /He	62	500	6.7	0.1014	52	0.736	0.592	84
					132	0.825	0.656	
					150	0.795	0.671	
					192	0.826	0.704	
					219	0.853	0.726	
					307	0.877	0.796	
Li ₂ ZrO ₃ /He	60	1200 (±100)	20	0.1014	75	0.67	0.584	85
					165	0.68	0.630	
					240	0.72	0.667	
					300	0.75	0.698	
					360	0.78	0.730	
					415	0.79	0.762	
					435	0.82	0.774	
					475	0.82	0.778	
					500	0.85	0.818	

Table 12. Sample Values of Calculated Be/Steel Heat Transfer Coefficient as a Function of Be Porosity (P), He Pressure (P_g), Hot Gap Size (G) and Gap-Temperature (T)

P	P _g , MPa	T, °C	h, W/m ² ·K		
			G = 0 μm	40 μm	80 μm
0.15	0.1014	100	6892	2684	1666
		200	7425	3041	1912
		300	7788	3342	2128
		400	8033	3599	2319
		500	8193	3818	2489
	0.0507	100	5407	2424	1562
		200	5569	2676	1761
		300	5624	2869	1925
		400	5617	3017	2063
		500	5573	3132	2179
0.35	0.1014	100	3700	2009	1379
		200	4141	2296	1588
		300	4498	2544	1773
		400	4788	2760	1939
		500	5026	2951	2089
	0.0507	100	3225	1860	1307
		200	3492	2081	1482
		300	3680	2260	1630
		400	3810	2405	1757
		500	3901	2524	1866

Table 13.

Summary of Operating Conditions and Post-Irradiation Data for Tritium Inventory in Li₂O Following In-Reactor Purge Flow Experiments. Conditions are Given for the Last Run Prior to Inventory Measurements. Estimated Values are in Parentheses.

Parameter	VOM-15H ⁹⁰	EXOTIC-2 ⁹¹	MOZART ³¹	CRITIC-1 ⁹²	BEATRIX-II ⁹³
Li ₂ O mass, g	6.665	18	2.41	103	11.95
Li-6 enrichment at. %	7.42	0.6	7.42	1.79	61
Density, %	86±2	79.6	80.0	86±6	79.3
Grain size, μm	2±1	7.5±2.5	16	55±5	5.5
Specific surface area, m ² /g	(0.1)	(0.1)	0.05	(0.035±0.025)	0.06
Purge flow rate, L(STP)/min	0.1	0.1 0.015	0.041	0.1	0.1
Inlet purge pressure, Pa:					
He	(1.6E5)	1.0E5	1.6E5	1.0E5	2.5E5
H ₂	(<1)	100	160	10	250
H ₂ O	(<1)	(<1)	(<0.07)	40	(<1)
Tritium generation rate, wppm/s	1.4E-4	3.7E-5	4.1E-5	3.7E-5	3.81E-4
H/T ratio	~1.5	670 100	1860	60	170
Li ₂ O max/min temperature, °C	760/700	630/590 465/425	530 500 450 400 350 320 310	600/540	640/600 550/510
Li burnup, at. %	0.24	0.08	0.32	1.0	6.2

Table 14.
Comparison of Model Predictions and Data for Tritium Inventory in Li₂O Following In-Reactor Purge Flow Experiments. Estimated Values are in Parentheses.

Experiment	$\bar{T}$, °C	I, wppm		Predicted Dominant Mechanism	Limiting Moisture Pressure, Pa
		Data	Model		
VOM-15H	730	0.7±0.2	0.303	solubility	5870
EXOTIC-2	610	<0.1	4.72E-3	desorption	1560
	445	1.5	0.263	desorption	77
MOZART	530	(<0.05)	4.22E-2	desorption	650
	500	(0.05)	9.03E-2	desorption	400
	450	(0.05)	0.369	desorption	166
	400	(0.05)	1.87	desorption	34
	350	(>0.67)	12.2	desorption	5.3
	320	(<4.47)	43.9	desorption	1.5
	310	(>4.47)	69.2	desorption	1.0
CRITIC-1	570	0.54±0.32	0.116	desorption	760
			(0.061-0.331)		
BEATRIX-II	620	----	0.1±0.04	desorption/solubility	1790
(thin ring)	530	----	0.473	desorption	470

Table 15. Model Predictions for Inventory Change in BEATRIX-II Thin Ring Sample in Response to Temperatures and H₂ Purge Partial Pressure Changes. Purge Flow is 0.1 ℓ/min. A Tritium Generation Rate of $(50 \pm 5) \mu\text{Ci/s} = (4.31 \pm 0.43) \times 10^{-4} \text{ wppm/s}$ is Assumed for all Calculations.

Case	T, °C		P _{H₂} Pa	$\bar{P}_{\text{HT}}$ Pa	I (model)		ΔI , mCi	
	Min	Max			wppm	mCi	Model	Data
1	598	638	150	1.72	0.0595	6.9		
							+ 6.7	+28±54
	562	600	150	1.72	0.1173	13.6	+27.4	+36±27
	513	550	150	1.72	0.3531	41.0	-26.5	-24±19
	559	597	150	1.72	0.1248	14.5	-7.6	-1 ± 36
	596	636	150	1.72	0.0597	6.9	+34.1	+42 ± 10
	513	550	150	1.72	0.3531	41.0	-34.1	-55 ± 22
	596	636	150	1.72	0.0597	6.9		
2	596	636	150	1.72	0.0597	6.9		
							+9.5	+ (15±10) x 10 ³
	596	636	~0	--	0.1412	16.4	-4.0	- (3±10) x 10 ³
	596	636	15	--	0.1065	12.4	-5.5	- (5±10) x 10 ³
	596	636	150	1.72	0.0597	6.9		
3	509	545	150	1.72	0.3939	45.7		
							+33.8	+ (15±10) x 10 ³
	509	545	~0	--	0.6855	79.5	-0.8	- (4±10) x 10 ³
	509	545	15	--	0.6781	78.7	-33.0	- (5±10) x 10 ³
4 (80 EFPD)	599	639	150	1.72	0.0567	6.6		
							+40.2	+75 ± 5
	508	544	150	1.72	0.4036	46.8	-39.9	-85 ± 15
	598	638	150	1.72	0.0595	6.9		
	(215 EFPD)	594	634	150	1.72	0.0620	7.2	
							+36.3	+63 ± 13
	511	547	150	1.72	0.3753	43.5	-36.3	-88 ± 13
	594	634	150	1.72	0.0620	7.2		
	(290 EFPD)	602	642	150	1.72	0.0537	6.2	
							+38.4	+80 ± 10
	510	546	150	1.72	0.3845	44.6	-38.4	-100 ± 10
	602	642	150	1.72	0.0537	6.2		

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