COMPARITIVE ANALYSIS OF THE PERFORMANCE OF SOLID BREEDERS

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Published in the Proceedings of the 12th Symposium on Fusion Engineering, held October 12-16, 1988, in Monterey, California.

IEEE Catalog No. 87CH2507-2

FUSION
ENGINEERING

Proceedings

Volume 1

12th Symposium on Fusion Engineering
October 12–16, 1987 Monterey, California

Sponsors

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Abstract: Seventeen solid breeder/multiplier material combinations were compared in a blanket design context on the basis of selected performance parameters. The performance parameters fall in five general categories: neutronics, thermomechanics, tritium, activation and economics. The results show that Li_2O is the only ceramic which has a chance of satisfying the tritium self-sufficiency criterion without a multiplier. Among ternary ceramics, the silicates appear the most attractive for the cases with a multiplier, based on the performance parameters selected for this study. In terms of configuration, the homogeneous mixture of multiplier and solid breeder is attractive from many aspects and should be experimentally investigated. Be is superior to BeO as a multiplier and BeO is also unattractive based on its high tritium diffusive inventory. Sphere pac is preferred to sintered block as solid breeder material form.

Objectives and Calculation Framework

Solid breeder blanket research is in a material development and selection phase which requires the consideration of a large number of potential solid breeder materials, properties, behaviors, and test conditions. A consistent comparison of the effect of solid breeder material choice on blanket attractiveness has been performed to focus the test matrix by reducing the number of solid breeder materials and configurations which need to be tested. The comparison also identifies material tests required to reduce important performance uncertainties.

Table 1 lists the seventeen solid breeder/multiplier material combinations considered in the context of a representative blanket design and compared on the basis of selected performance parameters.[1] Except for Li_2O and Li_7Pb_2, those solid breeders are ternary ceramics. Beryllium is used as the neutron multiplier in combination with those solid breeders which may require better neutronics performance. Two configurations have been considered for incorporating the beryllium neutron multiplier in the blanket. In the first configuration, the multiplier is placed in a separate region in front of the breeder region. In the second configuration, the solid breeder and multiplier are mixed homogeneously. Analysis for the second configuration was limited to Li_2O and $LiAlO_2$. Since Be will chemically reduce the solid breeder materials (although the rate might be acceptably slow once an initial BeO layer forms), BeO is also included as an alternative for the homogeneous mixture cases.

Table 1 Solid Breeder Materials Considered

Without a Multiplier	Homogeneous Solid Breeder/Multiplier Mixture	With a Separate Be Multiplier Region
1. Li_2O	6. $LiAlO_2$/Be	10. Li_2O
2. Li_2ZrO_3	7. $LiAlO_2$/BeO	11. $LiAlO_2$
3. Li_8ZrO_6	8. Li_2O/Be	12. Li_5AlO_4
4. $Li_2Be_2O_3$	9. Li_2O/BeO	13. Li_2SiO_3
5. Li_7Pb_2		14. Li_4SiO_4
		15. Li_2ZrO_3
		16. Li_8ZrO_6
		17. Li_2TiO_3

The reference blanket consists of 1125 modules with a 5 MW/m^2 neutron load at the first wall. A typical module is shown in Fig. 1. The solid breeder or homogeneous solid breeder/multiplier mixture is placed in plates with a thin ferritic steel (HT9) cladding on each side. The clad plates are wire-wrapped to provide a gap between adjacent plates for the main helium coolant flow which enters through the first wall and exits between the solid breeder plates. For the cases with a separate multiplier region, an array of multiplier rods is placed in front of the breeder plates. The thickness of the breeder plates is determined so that the maximum breeder temperature does not exceed the design limit. The ^6Li-enrichment, the multiplier region radial thickness (for the cases with a separate multiplier region), and the ratio of solid breeder to multiplier volume fraction (for the homogeneous mixture cases), are chosen based on optimizing the tritium breeding ratio. The full reference module parameters are shown in Ref. [1].

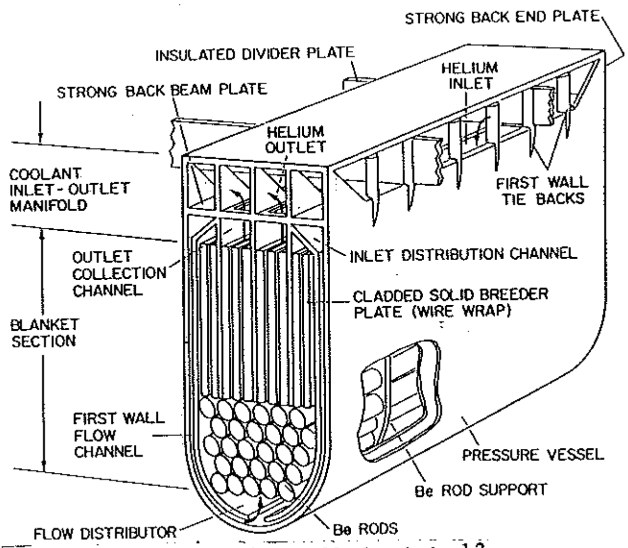

Figure 1. Reference blanket design[1,2]

Table 2 Performance Parameters

Neutronics:
Tritium Breeding Ratio
Power Multiplication (power generated in first wall and blanket, divided by the 14-MeV-neutron power)
Maximum Li Burnup at 15 MW • yr/m^2 [3 Full Power Years (FPY)]
Thermo-Mechanics:
Clad Stress and Deflection
Thermal Stress in Breeder
Tritium:
Tritium Inventory
Tritium Permeation
Activation:
Waste Disposal Rating (relative to Class C limits at 3 FPY)
Biological Hazard Potential (relative to maximum permissible concentration at 3 FPY)
Recycling Hazard
Afterheat
Economics:
Material Cost (including Be)
Net Thermal Efficiency (including pressure drop in blanket)
Power Leakage from Blanket to Shield

Blanket performance parameters were selected as a basis for the solid breeder comparison. They fall in the five general categories of neutronics, thermomechanics, tritium, activation, and economics, and are listed in Table 2. The calculations performed for the different parameters are described in detail in Ref. [1]. The results for each of these categories are summarized in Table 2 and discussed below.

Tritium Breeding Ratio

The TBR results are summarized in Table 3, which shows the optimum effective TBR (assumed to be 15% lower than 1-D TBR values)[1] for each case. To satisfy the tritium self-sufficiency criterion within the given uncertainties, the effective TBR can be ranked in different categories. Table 4 shows the risk associated with each TBR

Table 3. Blanket Performance Summary

Solid Breeder	Effective TBR[a]	Power Mult.	$\dot{q}$ [b] (W/cm3)	Peak Li Burnup (at.%)	Gross η_{th} (%)	Power Leakage (MW)	Blanket SB & M Cost ($M)	Breeder Total T Inventory (g)	Breeder Permeation Rate (g T/d)	Pumping Power Ratio (%)	Dose Rate at 1 m[c] (REM/hr-g)	Afterheat Time to Reach T_{max} (hr)
Cases Without a Multiplier												
Li_2O	1.08 (nat)	1.22	41.8	2.9	39.4	5.6	28	5.6	1.4	5.4	0.0029	183
Li_2ZrO_3	0.93 (29)	1.02	35.5	6.1	37.8	4.1	90	85.8	1.8	6.0	24.1	0.048
Li_8ZrO_6	0.98 (nat)	1.12	41.4	3.7	38.6	4.2	54	85.2	2.0	5.3	24.1	0.047
$Li_2Be_2O_3$	1.09 (nat)	1.31	47.6	5.4	39.7	3.4	135	552,000	2.4	4.1	0.031	56
Li_7Pb_2	1.22 (29)	1.18	33.7	5.0	39.1	14.9	110	1,590	2.9	5.6	2.64	0.024
Cases With a Homogeneous SB/M Mixture												
$LiAlO_2$/Be	1.51 (36)	1.51	43.9	46.8	41.4	7.1	104	230	2.2	3.1	1.86	5.4
$LiAlO_2$/BeO	1.09 (40)	1.36	43.5	35.3	40.3	6.1	96	76.5	1.3	3.6	1.27	20
Li_2O/Be	1.57 (nat)	1.52	45.9	19.5	41.2	4.7	73	8.1	2.3	3.1	0.0033	420
Li_2O/BeO	1.14 (14)	1.36	43.7	14.3	40.3	3.8	81	9.5	1.6	3.7	0.027	940
Cases With a Separate Be Multiplier Region												
Li_2O	1.24 (20)	1.42	81.6	15.8	40.7	1.2	68	43.9	1.2	3.5	0.0029	130
$LiAlO_2$	1.09 (62)	1.39	64.9	37.8	40.4	2.5	75	36.4	1.1	3.6	7.1	2.6
Li_5AlO_4	1.17 (30)	1.40	72.6	23.2	40.6	2.5	68	23	1.9	3.3	7.1	0.51
Li_2SiO_3	1.10 (50)	1.37	68.5	31.2	40.4	2.6	78	9.6	1.7	3.4	0.14	21
Li_4SiO_4	1.14 (33)	1.38	70.0	24.9	40.5	2.5	71	9.2	1.5	3.5	0.14	2.5
Li_2ZrO_3	1.17 (58)	1.27	67.1	31.8	39.7	2.4	97	47	1.3	3.9	24.1	0.041
Li_8ZrO_6	1.22 (26)	1.34	74.6	21.2	40.3	2.1	91	45.4	1.6	3.5	24.1	0.036
Li_2TiO_3	1.12 (51)	1.39	65.5	32.9	40.6	3.2	77	4.1	1.1	3.6	5.6	5

[a] % ^{6}Li enrichment corresponding to optimum TBR is shown in parentheses; (nat) is for natural lithium (7.25% ^{6}Li).

[b] At 0.5 cm from tip of breeder plate.

[c] After 3-year irradiation and 10-hour cooling.

For the separate multilplier cases, the dose rate for Be is 0.0034 REM/hr-g and is due entirely to impurities.

For the homogeneous SB/M mixture cases, the dose rates for the multiplier (0.0034 REM/hr-g for Be and ≅ 0.03 REM/hr-g for BeO) have been included in these figures.

Table 4 Classification of the Different Solid Breeder Cases Based on the Effective Tritium Breeding Ratio

Effective TBR Range	Risk Category	Cases
< 1.05	Unacceptable	Li_2ZrO_3, Li_8ZrO_6, all ternary ceramics without a multiplier element
1.05-1.10	High risk	Li_2O, $Li_2Be_2O_3$, $LiAlO_2$+Be, $LiAlO_2$/BeO
1.10-1.20	Medium risk	Li_7Pb_2, Li_2SiO_3+Be, Li_2TiO_3+Be, Li_4SiO_4+Be, Li_5AlO_4+Be, Li_2ZrO_3+Be, Li_2O/BeO
> 1.20	Low risk	Li_8ZrO_6+Be, Li_2O+Be, all solid breeder/Be homogeneous mixtures

category and classifies the different solid breeder cases based on their effective TBR. Note that since the homogeneous $LiAlO_2$/Be case is in the low risk category, it is anticipated that all homogeneous mixtures of ternary ceramics (which usually have higher Li atom densities than $LiAlO_2$) with beryllium would be in the same category.

Tritium Breeding Ratio

The general conclusions that can be made from the TBR results are that: 1) all solid breeders require a separate neutron multiplier except for Li_7Pb_2 and possibly Li_2O and $Li_2Be_2O_3$; 2) the homogeneous SB/Be cases show exceptional neutronics performance; 3) Be exhibits a much superior performance than BeO as a neutron multiplier; and 4) Li_2O is the most attractive solid breeder candidate, showing the highest TBR for the unmultiplied, separate multiplier and homogeneous SB/M cases.

Power Multiplication

The power multiplication, M, corresponding to each optimum TBR case, is shown in Table 3. The M results rend to vary in accordance with the TBR results and thus reinforce the TBR-based conclusions. A notable exception is the case of Li_7Pb_2, which, although showing a high effective TBR of 1.22, exhibits a rather low M of 1.18. This is due to the higher (n,2n) threshold energy in Pb compared to Be.

Note that the TBR and M results are rather insensitive to small changes in the volume fractions. For example, changing the breeder volume fraction from 0.70 to 0.75 in the case of Li_4SiO_4+Be does not change the power multiplication (1.37) and only decreases the 1-D TBR from 1.35 to 1.34. This indicates that the relative solid breeder behavior is fairly independent of the specific design configuration. It is also expected that the relative solid breeder neutronics performance is not significantly affected by the choice of design and coolant.

Peak Heating

Table 3 shows that the separate-multiplier cases have higher peak heating values ($\dot{q}$) than the other cases. For example, Li_2O with a separate multiplier has a 81.6 W/cm^3 peak heating value, while Li_2O/Be in the homogeneous mixture case and unmultiplied Li_2O only show 45.9 and 41.9 W/cm^3 values, respectively. These peak heating rates constrain the size of the breeder plates, and hence the breeder volume fraction. However, as noted earlier, the TBR and M results are not strongly affected by small changes in the breeder volume fraction. Consequently, the heating rates are not expected to strongly affect the solid breeder comparison.

Peak Lithium Burnup

The peak lithium burnup due to tritium-producing reactions (which constitute 99% or more of lithium burnup), was calculated at 0.5 cm from the tip of the solid breeder plate and is shown in Table 3 for each case. The peak burnup is high for the three cases involving $LiAlO_2$ with a multiplier, with the homogeneous $LiAlO_2$/Be case exhibiting the highest burnup (46.8 at .%). This is due to the high volume fraction of Be needed at the front of the SB/M region, which means that the amount of Li is small and the burnup fraction is high.

The cases without a multiplier have lower values of burnup, with Li_2O showing the lowest value (2.9 at .%). Although concern exists about the possibility of high burnups affecting the material chemical composition and compatibility at the tip of the breeder section, it si not clear yet how important this is as a criterion for comparing solid breeder materials. In general, it seems reasonable to assume that lower values of peak burnup are more attractive than higher values.

Thermomechanics

As part of the thermo-mechanics calculations, the stresses in the clad and the clad deflection caused by the breeder total volumetric expansion (thermal expansion+swelling), and the breeder thermal stresses were estimated. It was found that the stresses in the clad were well within the clad maximum allowable stress limit. However, for the use of Li_2O in particular, the clad deflection tended to be large (1.5 mm) relative to the 1 mm thickness of the gap (coolant channel) between adjacent solid breeder plates. Note that if a means for expansion is provided, such as a bellow-type arrangement at the plate ends or extra porosity, then the importance of the volumetric expansion for differentiating between the different solid breeder materials will be diminished.

Tritium Inventory

The tritium inventory in the solid breeder and multiplier was calculated as the sum of diffusion, solubility and surface adsorption components. Details about the property data (which have uncertainties ranging from a factor of 2 to a factor of 100) and about the calculations can be found in Ref. [1]. In general, swamping the purge flow with hydrogen will drastically reduce the adsorped and dissolved tritium.[3] Here, it is assumed that the tritium solubility and surface adsorption inventories are reduced to 1% of the possible inventory due to the inclusion of hydrogen in the purge flow at a ratio of 100:1 relative to the tritium.

The three components of the tritium inventory are strongly dependent on temperature. Consequently, the tritium diffusive, solubility and surface adsorption inventories were determined based on numerically integrating the inventories over the 2-D temperature and tritium generation rate profiles in the plate. The total inventory for each material is shown in Table 3 (based on average property values).

The tritium inventory results should be interpreted carefully because of the huge ranges of uncertainty, which clearly points to the need for obtaining more precise experimental property data. $Li_2Be_2O_3$, with an average diffusive inventory of 550 kg per blanket, is evidently unattractive, assuming the BeO-like tritium diffusion used in the absence of any data is correct. Li_7Pb_2 also has a high inventory (due to tritium solubility) and so does $LiAlO_2$/Be (due to diffusion). Apart from these, it is hard to differentiate between the other cases within the uncertainty range. Except for the $LiAlO_2$ cases, where the diffusive inventory is significant, and for the Li_7Pb_2 and Li_2O cases, where the solubility inventory is dominant, the total inventory for all the other cases consists mainly of the surface adsorption component. By further increasing the isotope swamping of the purge flow, these surface adsorption inventories could be further reduced beyond the 0.01 factor already used. This indicates the need for further experimental data related to the adsorption mechanism and to the effect of isotope swamping. The effect of large protium additions on tritium permeation and tritium recovery must also be considered in a blanket design context.

There are many uncertainties in the properties and design that can affect the tritium inventory indirectly. Analyses were performed to determine the effect on the tritium inventory of: 1) using a temperature dependent instead of constant thermal conductivity; 2) including the size variation of the breeder grains; and 3) insertion a helium-filled gap near the tip of the plate, assuming a sintered block form. It was found that the tritium inventory was increased in the three cases (by up to about 25%, 12% and 50%, respectively), but the magnitude of the increase is small compared to the uncertainties in the solid breeder tritium-related property data.

The diffusive inventory in the multiplier was also estimated. For Be, the inventory is very low both for the separate region case and for the homogeneous case (about 10^{-8} g per blanket). For BeO, however, the inventory is high (about 8 kg per blanket) and does not reach equilibrium during the blanket life.

Tritium Permeation

The permeability estimated for HT9 clad material and an oxide barrier factor of 100 is uncertain by about an order of magnitude, primarily because of the uncertainty in the surface conditions and associated barrier factor. From Table 3, the resulting permeation rates from the solid breeder into the helium coolant are about 1-3 g/d for a 1.6 GWe reactor, similar to the 2 g/d estimated for the BCSS $LiAlO_2$/He/Be blanket.[1] Thus, the effect of solid breeder choice is roughly a factor of three (due to differences in the breeder temperature limits and thermal conductivity) which, given the uncertainties in the permeation coefficient and barrier factor (a factor of ten), is probably not significant. Tritium is also produced in the multiplier at about 1% of its production rate in the solid breeder, or 7.5 g T/d in a 54 Gwth reactor. For mixed breeder/multiplier materials, the additional tritium would not affect the tritium permeation If the multiplier is separate and unclad, however, this tritium will eventually permeate into the coolant and would dominate over any tritium permeating through the breeder cladding, regardless of the solid breeder material. Such a permeation rate into the coolant may be unacceptably large, and require cladding on the multiplier.

Activation

The activation of different solid breeder materials (including presumed impurities) was calculated for two different spectra, one with a beryllium multiplier and one without. Also calculated for the former case was the activation of the beryllium multiplier. The fluxes used in the calculation correspond to the front of the breeder region (near the first wall). It was found that the results were approximately similar for both spectra.

The results include the dose rate (which gives an indication of the recycling hazard) and the Biological Hazard Potential (as a measure of accidental release hazard) after 3-year irradiation and 10-hour cooling and the Class C waste disposal limit after 3-year irradiation and 10-year cooling (as an indication of waste disposal hazard). The dose rate is chosen to represent activation because it is least dependent on impurities, and impurities can, in principle, be removed (at a cost). The dose rates for the different solid breeder cases are shown in Table 3. The zirconates and Li_7Pb_2 are the least attractive based on this criterion, the aluminates are marginal, while the oxide, beryllate and silicates (to a lesser extent) are attractive.

Afterheat

Decay heat values, one hour after shutdown, were calculated by assuming that the only contributions were from products of the primary elements. Contributions from products of impurity elements were ignored. They were then used to calculate the time to reach the maximum temperature after shutdown under adiabatic conditions.

The results, shown in Table 3, indicate that Li_2O and $Li_2Be_2O_3$ are very attractive (with times of 7.6 and 2.3 days, respectively) and, to a lesser extent, so are the silicates (with time of the order of 1 day). Li_2TiO_3, $LiAlO_2$, and possibly Li_5AlO_4 are adequate (with time of 5, 2.5 and 0.5 hours, respectively). However, the two zirconates and Li_7Pb_2 show times of about 1.5-3 minutes to reach maximum temperature. If a loss of coolant accident occurs, this leaves very little time for corrective action before the solid breeder is irreversibly damaged.

Material Costs

Material unit costs were estimated to compare the fabrication costs for blankets containing the various breeder and multiplier materials. The highest unit costs are for beryllium and ^{6}Li-enrichment at \$400/kg Be and \$1500/kg ^{6}Li. Table 3 lists the cost per blanket (1125 modules) for each case.

For the four homogeneous (20/80) breeder/multiplier mixture cases, the homogeneous mixture is assumed to be contained in the first 20 cm of breeder region, with only in a second 37 cm breeder region. This reduces the amount of expensive beryllium while the decrease in TBR is acceptable (the effective tritium breeding ratio is reduced from 1.59 to 1.49 for the Li_2O/Be case and from 1.53 to 1.35 for $LiAl_2$/Be).

The highest costs are for $Li_2Be_2O_3$ and Li_7Pb_2, with most of the other cases showing multiplier and breeder material costs between about \$67.5 million to \$107 million for the blanket module. The cost for the unmultiplied Li_2O case, however, is appreciably lower than those of all the other cases (\$28 million for the blanket), making unmultiplied Li_2O quite attractive on this basis. Note, however, that the solid breeder and multiplier costs are typically only about < 5% of the total commercial reactor cost.

Thermal Efficiency and Pumping Power

The cycle thermal efficiency and pressure drop results are also summarized in Table 3. The total pressure drop has been converted to a pumping power ratio (PPR), which is equivalent to the pumping power required divided by the electric power generated by the heat transported out of the blanket by the helium. The gross thermal efficiency can be seen to vary from 37.8% for the unmultiplied Li_2ZrO_3 case to 41.3% for the $LiAlO_2$ homogeneous mixture case. Apart for the unmultiplied Li_2ZrO_3 case, all the cases have thermal efficiencies within 3 percentage points. The main coolant PPR tends to vary inversely to the thermal efficiency, and shows a maximum of 6% for the unmultiplied Li_2ZrO_3 case and a minimum of 3.1% for the $LiAlO_2$ homogeneous case. However, the variation is mostly due to the number of plates in the design; fewer plates mean fewer channels and larger pumping power for a given mass flow rate. The mass flow rate here is fixed by the first wall design. For blankets where the coolant does not initially flow through the first wall, the PPR could be changed. And, since the neutronics are rather insensitive to small changes in the breeder volume fraction, it is conceivable that a fixed number of plates of the same size can be used for all the cases, which will then have essentially the same pumpng power requirements.

Power Leakage

From the neutron flux spectrum and the neutron energy at the back of the 30 cm reflector, the power leakage was calculated. This criterion can be important for space-limited reactors since higher power leakage implies the need for additional shielding, leading to larger reactor size and cost. A factor of 2 to 3 increase in power leakage typically requires about an additional 5 cm shield thickness. However, the importance of the power leakage can be minimized in a tokamak-type reactor by limiting this additional shield increase to the outboard region where space is less restricted. On the inboard region, where space is critical, the blanket thickness can be reduced by a few centimeters without a serious reduction in the tritium breeding ratio. From the results shown in Table 3, Li_7Pb_2, with the highest leakage power (about 14.9 MW for the whole blanket), is certainly less attractive than the other solid breeders. The values for the other cases all fall within the range 1.2 to 7.1 MW for the whole blanket, with Li_2O showing the lowest value.

Conclusions and R & D Priorities

The performance parameters considered are not of equal importance. TBR is the most important parameter since trititium self-sufficiency is a requirement. Safety concerns dictate that the tritium inventory is also of high importance. However, the magnitude of the uncertainties in the tritium-related property data tends to make a comparison between the different cases difficult. Other important parameters include activation, afterheat, power multiplication and ma-terial cost. The dose rate after 3-year irradiation and 10-hour cooling, which gives an indication of the recycling hazard, is the activation parameter considered here. The time to reach the maximum allowable temperature after shutdown with no coolant flow (calculated from the decay heat) is also an important parameter. It indicates how much time is available to restart the cooling system in case of accidental shutdown, without damaging and having to replace the solid breeder and/or multiplier. Power multiplication and material cost are included here as the key power and economic parameters. Note that the relative (and even absolute in some cases) values of these parameters for the different solid breeder materials tend to be independent of the geometric details of the design. An important performance parameter not considered here is the compatibility of the breeder with the structure.

These six major parameters of importance can be classified in pairs based on the indications that they give about tritium (TBR and tritium inventory), economics (power multiplication and material cost), and safety (dose rate and afterheat time to reach the maximum allowable breeder temperature). Graphical representations of the comparison of the various cases based on these three pairs of major parameters are illustrated in the point graphs shown in Figures 2 (effective TBR and reciprocal of the tritium inventory), 3 (reciprocal of material cost and power multiplication), and 4 (afterheat time to attain the maximum allowable material temperature and reciprocal of dose rate). The choice of variables is such that the more attractive cases will appear in the top right hand corner of each figure.

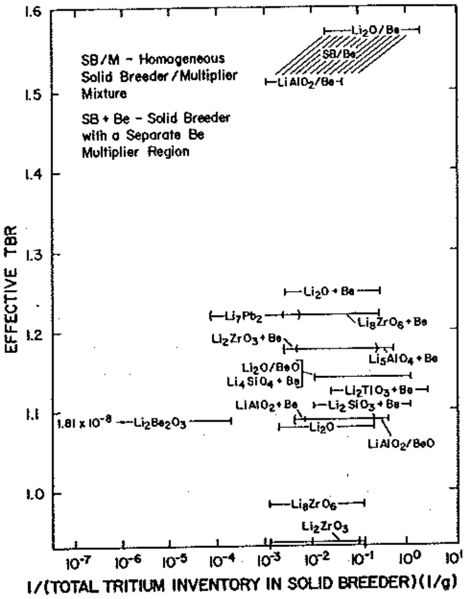

Figure 2. Point graph of the effective tritium breeding ratio and of the reciprocal of the total tritium inventory for the different cases

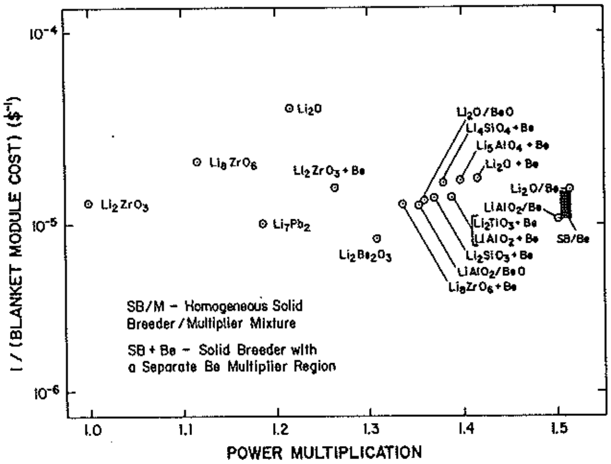

Figure 3. Point graph of the reciprocal of material cost and of power multiplication for the different cases

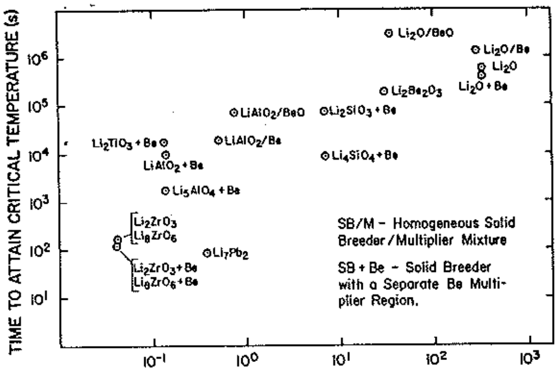

Figure 4. Point graph of the afterheat time to reach the maximum allowable temperature and of the reciprocal of the dose rate after 3-year irradiation and 10-hour cooling for the different cases

Based on the study and, in particular, on the results illustrated in Figures 2 to 4, the following general conclusions can be made:

(1) A neutron multiplier is needed for all solid breeders, except possibly for Li_2O, which has a marginal chance of satisfying the tritium self-sufficiency criterion without a multiplier. (Note that Li_7Pb_2 and $Li_2Be_2O_3$ are considered as multiplied here because of their neutron multiplier components, lead and beryllium, respectively).

(2) Based on optimized neutronics performance, a homogeneous mixture of beryllium and solid breeder is superior to separate beryllium and solid breeder regions.

(3) Beryllium is superior to BeO in terms of improvement of tritium breeding and energy production. BeO is also unattractive based on its high tritium diffusive inventory.

(4) Even if Li_2O requires the use of a multiplier, the Li_2O and beryllium combination remains more attractive than all ternary ceramic and beryllium combinations in terms of achievable tritium breeding ratio and power multiplication.

(5) Among the ternary ceramics, the Li_4SiO_4 and Li_2SiO_3 (to a lesser extent) appear to be the most attractive. They result in the least activation and their tritium breeding ratio and energy multiplication are virtually as good or better than other ternary ceramics.

(6) $Li_2Be_2O_3$ does not appear attractive because of its relatively high tritium diffusive inventory (assuming BeO-like tritium diffusion) and its marginal tritium breeding ratio. While Li_7Pb_2 shows reasonable tritium inventory, it results in lower energy multiplication and higher tritium inventory, which, combined with its limited operating temperature range, does not make it particularly attractive.

With regard to the near term experimental program for solid breeders, it is recommended that the following be emphasized:

(1) Materials: Li_2O without a neutron multiplier, and Li_2O, $LiSiO_4$, and Li_2SiO_3 with beryllium. $LiAlO_2$ should also be considered because of its attractiveness in the material stability and compatibility areas, which have not been considered in this study.

(2) Configurations: Sphere-pac is the preferred solid breeder material form. The homogeneous solid breeder/multiplier mixture is attractive from many aspects, and problems related to such a configuration, e.g., chemical instability and tritium release, should be experimentally investigated. In addition, neutronics integral experiments should include homogeneous configurations. These tests should be done in addition to the tests on the more conventional configurations with separate breeder and multiplier regions.

(3) Properties: The uncertainties in tritium-related properties are particularly large and important for designs as well as breeder comparisons.

(4) Test Conditions: A better understanding of lithium burnup is needed to clarify its importance and to accurately define the maximum allowable burnup limits. Tests should also include temperature gradients to determine the importance of cracking and/or breeder mass transfer.

References

1. M.A. Abdou, M.S. Tillack, A.R. Raffray, A.H. Hadid, et. al., "Modeling, Analysis and Experiments for Fusion Nuclear Technology (FNT Progress Report: Modeling & FINESSE)," PPG-1021, UCLA-ENG-86-44, FNT-17, University of California, Los Angeles, January 1987.

2. "Blanket Comparison and Selection Study - Final Report," ANL/FPP-84-1, Argonne National Laboratory, 1984.

3. M.C. Billone, "The Influence of Surface Desorption on Tritium Recovery and Inventory in Fusion Solid Breeders," J.Nucl. Mat., vols. 141-143, pp. 316-320, 1986.