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Beryllium and Lithium Resource Requirements for Solid Blanket Designs for Fusion Reactors

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Beryllium and Lithium Resource Requirements

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Abstract

The lithium and beryllium requirements are analyzed for an economy of 10^6 MW(e) CTR capacity using solid blanket fusion reactors. The total lithium inventory in fusion reactors is only ∿0.2% of projected U.S. resources. The lithium inventory in the fusion reactors is almost entirely Li^6, which must be extracted from natural lithium. ∿5% of natural lithium can be extracted as Li^6. Thus the total feed of natural lithium required is ∿20 times that actually used in fusion reactors, or ∿4% of U.S. resources. Almost all of this feed is returned to the U.S. resource base after Li^6 is extracted, however. The beryllium requirements are on the order of 10% of projected U.S. resources. Further, the present cost of lithium and the cost of beryllium extraction could both be increased tenfold with only minor effects on CTR capital cost. Such an increase should substantially multiply the economically recoverable resources of lithium and beryllium. It is concluded that there are no lithium or beryllium resource limitations preventing large-scale implementation of solid blanket fusion reactors.

Introduction

The solid blanket concept uses a high melting point solid compound of lithium to breed tritium instead of using liquid lithium metal or salts, as in the UWMAK-1 or Princeton reference designs. The companion element(s) [i.e., Al in LiAl, AlO_2 in $LiAlO_2$, etc.], compete with lithium for neutrons. At high neutron ene-gies, the cross sections of the competing elements are comparable to that of lithium. As a result, the number of Li^7 reaction/DT fusion is considerably less in solid lithium compounds than in liquid lithium metal. It does not appear possible to achieve a breeding ratio of 1.0 with a solid or liquid lithium compound, without adding a neutron multiplier. The maximum breeding ratio is probably on the order of 0.9. The breeding ratio can be readily increased to 1.0 or greater by including neutron multipliers in the blanket.

Beryllium is a good neutron multiplier and also does not activiate, and has been used in the BNL solid blanket designs.

Since almost all of the tritium generating reactions are by neutron absorption in Li^6, which exhibits a much higher neutron reaction cross section than Li^7, the inventory of lithium in a solid blanket is much less than that in a liquid lithium metal blanket that depends in large part on Li^7 reactions to generate tritium.

Lithium Resource Requirements

The enriched lithium (90% Li^6) inventory in the BNL aluminium reference design(1) is 2.2 kg/m^2, which at the first wall load of 1.77 MW(th)/m^2 and thermal efficiency of 40%, is 3.9 kg/MW(e) [0.0039 metric ton/MW(e)]. Assuming that the true breeding ratio is 1.0 instead of the calculated 1.2 [the margin is taken so as to include possible errors in cross section data, three-dimensional geometry effects, etc.], and that the blanket modules are in the reactor for 3 years with an 80% plant factor, ∿19% of the lithium inventory is burned out by the time the module is replaced.

Considerably higher first wall fluxes are possible with the aluminium blanket. The thermal conductivity of aluminium is high, which avoids the thermal stress limitations of stainless steel and the refractory metals, and cooling of the first wall is easy, even up to quite high first wall fluxes. Table 1 lists the lithium inventory as a function of first wall load and thermal conversion efficiency, assuming the same lithium loadings/m^2 as in the BNL reference design. An efficiency of 40%, CTR energy to electricity, seems achievable with an optimized aluminium blanket design and a conventional power cycle. A high efficiency cycle using hydride compressors[(2)] operated by low-grade auxiliary solar or geothermal energy could convert ~80% of the CTR energy to electricity. Use of this power cycle would effectively cut the lithium resource requirements by a factor of two.

The blanket would have to be completely changed at approximately 2 year intervals with a first wall load of 3 MW(th)/m^2 and yearly intervals at a first wall load of 6 MW(th)/m^2.

Since Li^6 is extracted from natural lithium, more lithium resources are required than just the enriched lithium in the CTR. The separated Li^7 can be used instead of natural lithium for most other purposes, so the CTR only locks up the Li^6 component. Table 1 lists the lithium resource requirements for a CTR economy of 10^6 MW(e) using solid blanket reactors. Of the 7.5% Li^6 content in natural lithium, 5% is assumed to be extracted for use in CTR's and 2.5% is lost along with the separated Li^7.

The lithium inventory in fusion reactors for 10^6 MW(e) is very small, on the order of 0.2% of the projected U.S. resources of 500,000 metric tons of lithium[(3)]. The natural lithium feed required to supply the enriched lithium for the 10^6 MW(e) capacity is on the order of 4% of projected U.S. resources. Almost all of this natural lithium is returned to the U.S. resource base after the Li^6 is extracted, however. Liquid lithium metal blankets of the UWMAK-1 type require about 1 metric ton/MW(e) and would require about 2 times the projected U.S. resources for a 10^6 MW(e) economy.

Very high lithium costs can be tolerated with solid blanket reactors. For example, if natural lithium is assumed to cost $1,000/kg (more than an order of magnitude greater than the present price of $20/kg), the cost of the natural lithium needed to supply the enriched lithium for the CTR is at most about $40/kw(e), and should be considerably less (Table 1). [The value of the separated Li^7 is assumed zero]. A cost of $1,000/kg for natural lithium should result in a much larger U.S. resource base, and one could exploit deposits that were not economical to mine for other purposes. A natural lithium cost of $1,000/kg would probably be prohibitive for UWMAK-1 type reactors.

It thus appears that solid blanket reactors require much less lithium resources than liquid blanket reactors, and can afford to pay much higher prices for the needed lithium. There appears to be no lithium resource problem for solid blanket reactors, even at CTR capacities considerably greater than 10^6 MW(e).

Beryllium Resource Requirements

As with lithium, the beryllium inventory/MW(e) will also depend on the first wall load and power conversion efficiency. Table 2 shows the beryllium resource requirements for solid blanket reactors, assuming the Be inventory/m^2 of the BNL reference design[1]. This inventory may be greater than necessary, since the calculated breeding ratio, 1.2, is greater than the ratio actually needed, i.e., slightly above 1.0. As cross section data and calculational techniques are refined, it may be possible to reduce the Be inventory.

The Be inventory required for a 10^6 MW(e) CTR economy is on the order of 10% of the total U.S. resources (250,000 short tons of Be metal, discovered plus projected)[4] and on the order of 5% of total world resources (discovered plus projected). Since the current yearly consumption is a very small fraction (~1%) of the total discovered U.S. resources, there is no incentive to find new deposits.

Most of the U.S. production comes from low grade bertrandite deposits at Topaz mountain in Utah. This deposit was identified only recently, but is now the most important commercial beryllium ore deposit in the world.[5]

The cost of extraction of beryllium from this ore is ~\$33/kg of contained Be.[6] This is equivalent to about \$1/kw(e) for the solid blanket CTR (Table 2). If extraction cost were an order of magnitude greater, the cost of Be for the solid blanket CTR would still be minor. A tenfold increase in extraction cost would undoubtedly considerably increase the Be resource base. For example, there is about 30,000 tons of Be contained in the spodumene bearing pegmatites of North and South Carolina that are being mined for lithium.[4] This Be is not extracted now since cheaper deposits are available, but would be used if higher Be extraction costs were allowable, e.g., a factor of ten higher.[6]

The beryllium inventory values given in Table 2 are the total inventory in the reactor for a 10^6 MW(e) economy. It is important to note, however, that it will probably take several decades to reach this degree of CTR capacity after its introduction. Demand for Be for CTRs will increase during this interval, and it is helpful to gain some appreciation of the projected yearly and cumulative demands for Be for CTRs as a function of time. Projections are summarized in Table 3 for two scenarios developed for future helium demands for CTRs[7,8] as part of a recent study on helium reserves and projected demands

(ERDA-13). These two scenarios are termed MS (Massive Shift) and BC (Base Case) and reflect different degrees of growth of U.S. electrical generation capacity. The MS scenario corresponds to an accelerated electrification of the U.S. energy economy. For the two scenarios, the total U.S. electrical capacity is as follows[7]:

Year	MS Capacity GW(e)	BC Capacity GW(e)
2000	1560	1390
2010	2040	1600
2020	2520	1800
2030	3000	2000

The rate of increase of the electrical capacity, together with a CTR market penetration estimate, then defines the CTR capacity as a function of time for the interval 2000-2030. The CTR capacity is given in Table 3 at intervals of two years. The market penetration curve[7] for new additions rises approximately linearly after CTR commercial introduction, saturating at 82% in 2020 and is constant thereafter.

The yearly and accumulative Be demands are summarized in Table 3. A first wall load of 6 MW(th/m^2 and 40% cycle efficiency are assumed. The yearly processing fractional loss is taken as 0.004 (blankets are assumed to be processed yearly), and the Be burnup is taken from the BNL reference design.[1] The yearly demand is taken as (7)

$$U_i = XI_i + (a + b) X \left[T_{j-1} + \frac{I_i}{2}\right] \quad (1)$$

where

U_i = annual Be requirement, metric tons

X = metric tons Be inventory per GW(e) capacity [X = 34]

I_i = incremental installed CTR capacity in ith year in GW(e)

T_{i-1} = cumulative installed CTR capacity in (i-1) th year

a = [a = 0.004] fractional loss of Be inventory per year due to processing

b = fractional loss of Be inventory per year due to burnup [b = 0.0038]

The Be inventory outside the reactor (i.e., refabrication and processing plants) is not included in the demand figures given in Table 3. This extra Be demand is not well defined, since more detailed analysis of reactor operating conditions are required to obtain definite figures. However, it is unlikely that this effect would increase cumulative Be demand by more than ∿50%. This extra demand may be substantially reduced if it turns out that the reactor Be inventory on based the calculated breeding ratio is too high, so that less Be is actually needed.

The massive shift scenario results in the largest cumulative Be demand for CTR's, and it is still only 33,000 metric tons by 2030 AD. This is ∿50% of proved U.S. reserves and ∿12% of total (proved + projected) reserves. The maximum Be yearly demand for CTRs, 1500 metric tons/year, is not much greater than present total yearly Be consumption.

It thus appears that no serious Be resource problems exist for solid blanket fusion reactors of the type being investigated at BNL, at least at the level of CTR installed capacity contemplated for the first half of the next century. For CTR capacities much greater than 10^6 MW(e), more exact U.S. beryllium resource figures with availability determined as a function of cost are probably required to assess whether or not resource limitations exist.

Annual and Cumulative Lithium Demand

Table 4 summarizes the annual and cumulative lithium requirements for the massive shift case, i.e., the case with the largest CTR implementation. Here the processing loss is small compared to the burnup loss, whereas in the case of beryllium, the losses were comparable. The annual demand due to burnup and processing loss quickly, i.e., in a few years, exceeds the annual demand due to increasing inventory in the CTR's. In the case of beryllium, the demand for increasing inventory predominates to the end of the period under study (2030 AD).

The net demand is the lithium either actually in or burned up by the CTR's, while the gross demand is the natural lithium feed required. However, 95% of this feed is returned to other markets (e.g., Li-S batteries). The returned lithium is depleted in Li^6, but is acceptable for non-nuclear uses. The net lithium cumulative demand to 2030 is only 0.6% of the 500,000 MT U.S. resource base, and the gross demand is $\sim$10% of the U.S. resource base. Again, however, the 95% of lithium that is returned to other markets will satisfy them.

The base case scenario lithium demands are about a factor of two smaller than those for the massive shift scenario.

Alternatives to Use of Beryllium in Solid Blanket Reactors

For the long term, there appear to be four alternatives to the use of beryllium in solid blanket CTR's. All probably would involve using a mixed CTR economy, i.e., some CTR's would be solid blanket converter CTR's without Be, requiring some makeup tritium input from other CTR's which breed surplus tritium. The solid blanket converter CTR's would have a breeding ratio of $\sim$0.8 without Be. The surplus tritium breeders would be either:

1. Alternate solid neutron multipliers (e.g., Pb) for CTR tritium breeders.

2. A liquid lithium metal CTR, similar to UWMAK-1.

3. A DD reactor (probably catalyzed DD) with a tritium breeding blanket.

4. A fusion-fission reactor.

The first and second alternatives could deliver ∿0.6 surplus T atoms/20 MeV of fusion energy; the third alternative could deliver ∿1.6 surplus T atoms/20 MeV fusion energy; and the fourth alternative could deliver ∿0.2 T atoms/20 MeV energy (fusion plus fission).

The third alternative would appear to be the optimum for the very long term, provided DD reactors are practical, since it is the most efficient in that it requires the least additional energy to breed the surplus tritiums. About 8 solid blanket DT fusion reactors could operate per DD reactor of equivalent power rating. The first alternative with Pb as a neutron multiplier could readily be applied at the same time CTR converters were being constructed. Use of Pb instead of Be in solid blanket reactors would not require development of a new blanket technology which would be required if one went to liquid lithium blankets to breed surplus tritium.

The fourth alternative could be applied in the near term, since fusion fission reactors can probably be contemporary with and may even preceed pure fusion reactors. The overall ratio of fusion/fission energy in a mixed economy of fusion reactors being fed surplus tritium from fusion-fission reactors will depend on specific design of both the fusion and fusion-fission reactors. The overall ratio will probably not exceed 1.0, however, so that fission would still remain a large part of the U.S. energy economy.

Conclusions

There appears to be no serious lithium or beryllium resource problems for solid blanket CTR's in terms of projected U.S. resources, assuming a 10^6 MW(e)

CTR economy. Further, a tenfold increase in lithium total cost or in beryllium extraction costs would only have a minor effect in capital cost of the solid blanket CTR, and this increase should substantially multiply the U.S. resources, since lower grade deposits could be economically mined. The annual beryllium demand for CTRs will be comparable to present annual production and will not require massive increases in the beryllium mining industry. There appear to be practical alternates to beryllium, if necessary.

Table 1

Lithium Resource Requirements for Solid Blanket CTR's

Basis = 10^6 MW(e), CTR Capacity
80% Plant Factor
3 Year Blanket Module Life

U.S. Resources = 500,000 Metric Tons of Lithium

	First Wall Load[(a)]			
	6 MW(th)/m²		3 MW(th)/m²	
	Conventional Cycle (40% Efficient)	High Efficiency Cycle (80% Efficient)	Conventional Cycle (40% Efficient)	High Efficiency (80% Efficient)
Li Inventory in[(b)] Reactor, kg/MW(e)	0.92	0.46	1.84	0.92
Total enriched Li Inventory for 10^6 MW(e), metric tons	920	460	1840	920
% of U.S. Lithium Resource Base in Reactors as Enriched Li	0.18%	0.09%	0.36%	0.18%
Natural Lithium Base[(c)] Required to Supply Enriched lithium inventory for Reactors, Metric Tons	18400	9200	36800	18400
Burnup of Li^6 in CTR's Metric Tons Per Year	190	95	190	95
Capital Cost to Supply Enriched Li in Reactor [$1000/kg = Natural Lithium Price], $/kw(e)	18.4	9.2	36.8	18.4

a) Total energy released in reactor (including neutron absorption) divided by first wall area.

b) Same inventory as BNL reference design, adjusted for different first wall load and power conversion efficiency - Lithium in reactor is 90% Li^6.

c) 95% of this base is passed on to other markets after most of Li^6 is extracted.

Table 2

Beryllium Resource Requirements for Solid Blanket CTR's

Basis = 10^6 MW(e) CTR Capacity
80% Plant Factor
3 Year Blanket Module Life

U.S. Resources = 230,000 Metric Tons of Be [discovered plus projected].

	First Wall Load (a)			
	6 MW(th)/m^2		3 MW(th)/m^2	
	Conventional Cycle (40% Efficiency)	High Efficiency Cycle (80% Efficiency)	Conventional Cycle (40% Efficiency)	High Efficiency Cycle (80% Efficiency)
Be Inventory, (b) Kg/MW(e)	34	17	68	34
Be Inventory in Reactor for 10^6 MW(e), Metric Tons (b)	34,000	17,000	68,000	34,000
% of U.S. Resources (c) [discovered]	62	31	124	62
% of U.S. Resources (c) [discovered plus projected]	15	7.5	30	15
% of World Resources (c) [discovered plus projected]	5.7	2.8	11.4	5.7
Annual Be Consumption, Metric Tons/Year	130	65	130	65
Capital Cost of Be in Reactor [assuming only Be cost is extraction cost from ore (d)]	1.1	0.55	2.2	1.1

a) Total energy released in reactor (including neutron absorption) divided by first wall area.

b) Same inventory as BNL reference design, adjusted for different first wall load and power conversion efficiency.

c) Taken from "Beryllium", by Griffitts, U.S. Geological Survey, Paper No. 820.

d) Cost of $33/kg Be for extraction from Utah ore [Zencack, Brush-Wellman].

Table 3

Beryllium Requirements for Solid Blanket

Fusion Reactors as a Function of Time

Basis
- 6 MW(th)/m^2 Aluminum Design
- 40% Thermal Conversion Efficiency
- 34 Metric Tons Be/GW(e)
- Processing Loss 0.004/Year
- Burnup Loss 0.0038/Year

	Massive Shift				Base Case			
Year	Fusion Capacity Increment GW(e)/Yr	Cumulative Fusion Capacity GW(e)	Be Demand 10^3 MT per Yr	Cumulative Be Demand 10^3 MT	Fusion Capacity Increment GW(e)/Yr	Cumulative Fusion Capacity GW(e)	Be Demand 10^3 MT per Yr	Cumulative Be Demand 10^3 MT
2000	2.6	2.6	0.089	0.089	1.4	1.4	0.048	0.048
2002	6.1	12.7	0.210	0.439	2.7	5.9	0.093	0.048
2004	10.4	31.2	0.360	1.08	4.0	14.1	0.139	0.466
2006	17.2	61.7	0.599	2.13	7.0	26.9	0.244	0.912
2008	23.3	104.6	0.817	3.64	9.5	44.4	0.333	1.53
2010	28.4	158.8	0.997	5.54	11.5	66.4	0.407	2.30
2012	27.7	212.5	0.994	7.46	13.2	91.9	0.471	3.21
2014	30.7	272.6	1.11	9.63	14.5	120.4	0.523	4.24
2016	37.7	341.8	1.37	12.2	15.5	150.9	0.565	5.35
2018	39.2	419.7	1.44	15.0	16.0	182.7	0.590	6.52
2020	40.2	499.6	1.49	18.0	16.4	215.3	0.612	7.773
2022	40.2	580.0	1.52	21.0	16.4	348.1	0.621	8.97
2024	40.2	660.3	1.54	24.0	16.4	280.9	0.630	10.2
2026	37.7	738.2	1.47	27.1	18.0	315.3	0.693	11.6
2028	37.7	813.7	1.49	30.0	18.0	351.4	0.703	13.0
2030	37.7	889.7	1.51	33.1	18.0	387.5	0.712	14.4

Table 4

Lithium Requirements for Solid Blanket Fusion Reactors

as a Function of Time

Basis: 6 MW(th/m^2 Aluminum Design
40% Thermal Conversion Efficiency
0.92 Metric Ton Li Inventory in Reactor (90% Enriched in Li^6)
Processing loss = 0.004/year
Burning Loss = 0.206/year
Massive Shift Scenario

Year	Fusion Capacity Increment GW(e)/yr	Cumulative Fusion Capacity GW(e)	Net Annual Li Demand MT/yr	Net Cumulative Li Demand MT	Gross Annual Li Demand MT/yr	Gross Cumulative Li Demand MT
2000	2.6	2.6	2.64	2.64	52	52
2002	6.1	12.7	7.49	14.8	149.8	296
2004	10.4	31.2	14.6	40.1	292	802
2006	17.2	61.7	26.0	85.5	520	1,710
2008	23.3	104.6	39.4	156.7	788	3,134
2010	28.4	158.8	54.1	257.1	1082	5,142
2012	27.7	212.5	64.9	379.1	1298	7,582
2014	30.7	272.6	77.9	528	1558	10,560
2016	37.7	341.8	97.1	709.8	1942	14,180
2018	39.2	419.7	113.3	928.5	2266	18,570
2020	40.2	499.6	129.7	1179.7	2594	23,580
2022	40.2	580.0	145.2	1462.3	2904	29,246
2024	40.2	660.3	160.7	1776.0	3214	35,520
2026	37.7	738.2	173.6	2118.1	3472	42,360
2028	37.7	813.7	188.2	2487.2	3764	49,744
2030	37.7	899.1	202.8	2885.5	4056	57,710

Note: 1. U.S. Resources = Taken as 500,000 MT of Li.

2. Net Demand = Li used in CTR's

3. Gross Demand = Natural Li Input from which Li^6 is extracted - 95% of Gross Input is returned to other markets.

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