Fission-Suppressed Blankets for Fissile Fuel Breeding Fusion Reactors

J. D. Lee[1] and R. W. Moir[1]

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Two blanket concepts for deuterium-tritium (DT) fusion reactors are presented which maximize fissile fuel production while at the same time suppress fission reactions. By suppressing fission reactions, the reactor will be less hazardous, and therefore easier to design, develop, and license. A fusion breeder operating a given nuclear power level can produce much more fissile fuel by suppressing fission reactions. The two blankets described use beryllium for neutron multiplication. One blanket uses two separate circulating molten salts: one salt for tritium breeding and the other salt for U-233 breeding. The other uses separate solid forms of lithium and thorium for breeding and helium for cooling.

KEY WORDS: fission-suppressed; fusion-breeder; fissile production; fusion-fission hybrid.

A fuel supply for fission reactors can be produced by using neutrons from the fusion reaction to transmute the world's abundant and low cost fertile Th232 and U238 resources into fissile fuels. Fissile fuel could be produced by using the kinetic energy of 14 MeV neutrons from the DT fusion reaction to generate additional neutrons by $(n,2n)$ reactions in the blanket (a region surrounding the fusion neutron source). The neutrons, which are in excess of those needed to breed tritium in lithium-6, can be used to convert fertile thorium to fissile U233. The fissioning of thorium can be minimized by moderating the neutrons before they reach the thorium and by limiting the thorium density. If we also remove the U233 (or its precursor Pa233) before it can fission, then we have a fissile-fuel-producing fission suppressed fusion breeder (FSFB). The FSFB would produce large amounts of fissile fuel and relatively little, if any, net power. In recent articles on fusion-fission, Bethe[1] emphasizes those concepts that maximize the fission reactor power that can be fueled by each fusion breeder. We call the ratio of fission reactor power supported to FSFB power the support ratio. Support ratios can apply to nuclear or electrical power.[2]

The two-fission-suppressed blanket concepts presented have in part evolved from earlier blanket concepts by Lidsky,[2] Lee,[3–5] and Blinkin and Norikov.[6] The objective is to find a fission suppressed blanket concept that gives good breeding at low cost with as few new materials and the least amount of chemical process development as possible.

To achieve an attractive FSFB, the blanket surrounding the fusion neutron source must have the following characteristics:

1. Fast fission of fertile material must be suppressed by limiting its exposure to fast neutrons
2. An effective nonfission neutron multiplier must be used to generate significant neutrons in excess of those needed to breed tritium to fuel the DT fusion reaction

[1]Lawrence Livermore National Laboratory, University of California, Livermore, California 94550.

[2]Nuclear power is the sum of fusion (D + T → 14 MeV neutron + 3.5 MeV alpha) power plus additional power from neutron-induced reactions in the blanket.

3. Breeding must not be compromised by parasitic neutron capture
4. Fissile material must be removed at low concentrations, economically, to inhibit *in situ* fission reactions
5. Tritium inventory must be kept low to limit its loss due to radioactive decay
6. Wherever possible, conventional technology should be used to minimize the cost, risk, and time for the necessary development program

One proposed blanket, which has the potential for making an attractive FSFB, uses beryllium for neutron multiplication and two fertile molten salts: one for fusile breeding and the other for fissile breeding. Tritium breeding occurs in an inner region containing beryllium plus the molten salt called 'flibe,' which has the following composition: LiF (47%), BeF_2 (53%). The numbers in parenthesis are mole fractions. The beryllium comprises 75% of the volume and is in a sintered metallic form clad in graphite. Fissile breeding (U233) occurs in an outer region containing a beryllium or carbon moderator plus the thorium containing molten salt ^7LiF (71%), BeF_2 (2%), ThF_4 (27%). Both molten salts are circulated for on-line reprocessing and heat removal.

The other proposed blanket concept consists of an inner region, much like pure fusion blankets, containing a lithium compound and beryllium, plus the addition of an outer region containing thorium. Both regions are helium cooled. The inner region contains mostly beryllium plus a solid ^6Li bearing compound (such as Li_2O or $Be_2Li_2O_3$). The outer region contains graphite plus solid particles or pebbles of a salt containing thorium. These solid thorium bearing salt "balls" might be encapsulated in graphite. The amount of beryllium, if any, used in the relatively soft neutron spectrum of the outer region will depend on the cost of beryllium versus performance. The solid thorium salt in the outer blanket region would be replaced during operation when the desired fissile concentration is reached. It would then be melted and reprocessed as a molten salt by the simple, low-cost fluorination process that produces UF_6. Molten salt processing has been demonstrated only on a laboratory scale and not on a commercial scale. The reprocessed salt would then be recast as solid particles and sent back to the blanket. Other material combinations are possible; such as neutron multiplication and other thorium forms such as metallic thorium slurries rather than the solid thorium salt. The concept, however, remains the same. The blanket has an inner region where neutrons are multiplied and tritium bred, plus an outer region where fissile material is bred and both the fusile and fissile materials produced are removed frequently or during operation to keep their concentrations low. Let us examine how well these conceptual blankets might meet the required characteristics of a fission suppressed blanket.

1. Fast fission of the fertile material is suppressed by moderating the neutrons in beryllium before they reach the fertile material and by limiting the amount of fertile material to just that amount required to capture the excess neutrons. According to initial calculations,[4, 5] the number of fission events per fusion neutron is 30 times lower than for a thorium fast-fission blanket and 80 times lower than for U238 fast fission blankets[7] at end of life. Peak power density can be even further reduced.

2. Neutron multiplication is accomplished by having a high atom fraction of beryllium in the inner region, and possibly, in part of the outer region as well. Beryllium is the most effective nonfission neutron multiplier we have found. The fast neutron reaction with beryllium is Be $(n,2n)$ He$-$1.67 MeV. The number of fissile atoms bred is about two times higher than for the case examined by Lidsky, which did not use beryllium.[2] The consequences of the use of large quantities of beryllium must be carefully considered beyond our preliminary work.[4, 5] If beryllium is found to be impractical, other nonfission neutron multipliers such as lead or lithium could be used, but breeding would be degraded. A recent study at Oak Ridge National Laboratory advocates a fission suppressed molten salt blanket concept without beryllium and avoids the low performance by coupling the concept to an advanced fusion device operated on the deuterium-deuterium (DD) cycle.[8] We believe DD fusion inappropriate because it is much further in the future than DT fusion.

3. The use of low-pressure molten salt or modest pressure helium and the use of graphite cladding (if needed) should lead to structural requirements that will not compromise breeding.

4. The use is recommended of either fertile-molten salt or solid-salt pebbles that can be removed, melted, stripped of U233 and Pa233 (and maybe fission products), recast, and replaced continuously or in a quick batch mode. ~~Both have~~ the potential, as economic ways, to keep fissile concentrations low. The economics look good because of low-cost[6] reprocessing and little or no down time for refueling.

5. Tritium inventory is kep low by continuously purging the lithium containing breeding material.

6. The two-region molten-salt case evolved from the single-region molten-salt blanket suggested by Lee[4] would avoid some difficult materials development problems.[5] The two-region two-salt blanket may overcome these problems by using the lower-temperature salt (flibe) in the inner blanket where the fast-neutron flux is high and using the high-temperature thorium bearing salt only in the outer region where the fast neutron flux is much less. Processing the separate salts should also be simpler, thus requiring less development. For the solid blanket, the helium cooled Li_2O inner region without beryllium is being developed for pure fusion blankets. For our purposes, this region must also contain beryllium, which will necessitate some further development. Development of the outer (solid salt) region with its low radioactive inventory, low after heat, and low temperature should be straightforward. On-line removal and reprocessing of the solid thorium salt should require only modest development. If only the U233 is to be removed, the reprocessing by fluorination needs little development. If the rare earth fission products are also to be removed, then a larger development effort appears required. Fission product removal may not be necessary. Potential advantages of fission-suppressed fissile-breeding blankets stem from their low level of fusion neutron energy multiplication (M) and low fission product generation. These advantages are:

- Low blanket power density
- Low blanket fission product inventory and after heat
- High support ratio

Low blanket power density should simplify blanket design. Low fission product inventory and after heat should greatly simplify emergency cooling and containment design and might allow heat removal after shutdown by passive means.

Low energy multiplication in the fission-suppressed fissile-breeding blanket gives a high ratio of fissile material production to energy generation. This in turn results in a high ratio of supported fission reactor power to fusion breeder power. With a high support ratio, electricity produced by the fusion breeder is small compared to electricity produced by the supported fission reactors. High support ratio has a number of potential advantages. The fissile fuel breeding fusion reactors do not have to be owned and operated by electric utilities. The fusion breeder looks more like an enrichment plant; an enrichment plant, however, that does not need power nor large amounts of ore, because it can be self-sustaining in energy and converts fertile material into fissile fuel. A relatively small number of FSFBs can make conventional fission reactors (LWRs, HTGRs, CANDUs) a long-term, large scale energy option, independent of new uranium resources. In addition to fueling conventional fission reactors, fusion breeders could also supply initial fissile inventories for fission breeders when commercial introduction of the fission breeder takes place.

A large support ratio would also make the denatured fuel cycle (U233+U238) approach, recommended by Feiveson et al.,[9] to diversion and proliferation resistance more practical. A relatively small number of internationally controlled nuclear fuel facilities consisting of fusion breeders, reprocessing facilities, and fuel fabrication facilities could supply denatured fuel to fission reactors owned and operated by other entities worldwide.

The anticipated nuclear performance of the fission-suppressed blanket is compared with thorium and uranium fast-fission blankets in Table I. There is a striking difference in support ratios and fission power densities between fast-fission and the fission-suppressed blankets. The fission-suppressed blanket can support three times more fission reactor power than can thorium fast-fission blankets and five times more than uranium fast-fission blankets. The peak fission power density of this fission-suppressed blanket is 10 to 100 times less than in the fast-fission blankets.

But what about economics? How does the suppression of fission and use of beryllium affect the fissible production cost and busbar electric power cost? This question has been answered in a preliminary way by comparing system economics with a thorium fission-suppressed blanket to a thorium fast fission blanket.[5] This comparison showed that the economics of the thorium-fission suppressed case and the thorium fast-fission case was similar. The cost of fissile fuel from the fission-suppressed and fast-fission thorium cases was found to add 20% and 24%, respectively, to the cost of electrical power from an LWR.

Since only about 20% of the cost of power from these fusion-fission systems is due to the fusion breeder component of the system, large uncertainties in fusion breeder costs will produce relatively small uncertainties in the fusion-fission system power costs.

Table I. Performance Comparison of Fast Fission and Fission-Suppressed Blankets[a]

Blanket type[b]	$U238_{ff}$ (ref. 7)	Th_{ff} (ref. 5)	Th_{fs} (ref. 5)
Fissile breeding ratio, (net) (F)	1.5 (Pu239)	0.8 (U233)	0.8 (U233)
Energy mult. (M) av./peak	11/12	5.2/5.9	1.6
Fissile production rate (kg/yr)	2700	2900	9600
Fission reactor power supported (MW)[c]	19,000	30,000	99,000
Nuclear support ratio[d]	5.2	8.5	25
Fission power density (W/cm³)[e]	350	100	1.0

[a]Tritium breeding ratio (T) = 1.0, blankets sized for breeder peak nuclear power of 4000 MW ($P_{nuclear} = P_{fusion}[0.2 + 0.8 M]$).
[b]ff = fast fusion, fs = fusion suppressed.
[c]Based on LWR with fissile makeup requirements of 444 kg Pu239/GW_e-yr and 303 kg U233/GW_e-yr and a thermal efficiency of 32%.
[d]Power of supported burners/power of fusion breeder.
[e]Peak in fuel.

Rand, in a study on alternative breeding methods, refers to this fusion-fission system power cost insensitivity as "robustness."[10] Fusion-fission systems based on fission-suppressed blankets should be very robust.

Beryllium resource and cost are important questions facing the large-scale application of beryllium containing FSFBs. Literature on beryllium indicates that both the resource and cost are quite acceptable. One FSFB supplying makeup fuel for 32 GW_e of LWR capacity has a total beryllium inventory of approximately 1000 tons and a beryllium consumption rate of only about 0.7 tons per year.

The resource estimates[11] for beryllium are 60,000 tons in known deposits and 250,000 tons in undiscovered deposits in the U.S. The estimates for other countries are 32,000 and 400,000 tons in known and undiscovered deposits, respectively.

The U.S. consumption of beryllium was 70 tons in 1978 at a cost of about \$176/kg.[12] It is clear that the beryllium mining industry would have to expand considerably if the use under discussion materializes. Also, cost can be expected to rise due to new regulations governing permissible exposure of workers to beryllium. The price of beryllium in rod form was \$226/kg in 1973 and \$276/kg in 1975.[13, 14] Escalating these prices into 1979 dollars and adding \$60/kg to account for special fabrication lead to prices over \$400/kg. This price, based on metallic rods, may be overestimated for our purpose because of the difficulty of fabricating metallic beryllium and the ease of fabricating sintered beryllium. The form we need is sintered and the price of 200-mesh powder in ton lots in 1979 was \$227/kg.

CONCLUSIONS

The fissile-breeding, fission-suppressed fusion breeder offers a unique way to help meet the world's energy needs. Based on results of preliminary work, the fission-suppressed fusion breeder can supply the fissible makeup for about 25 contemporary thermal fission reactors (LWRs) or about 50 high-gain thermal reactors (HTGRs and CANDUs), assuming that both the fusion breeder and each of the fission reactors being supported have the same nuclear power level. With such high support ratios, only a relatively small number of fusion breeders are needed to make present day commercial fission a long-term, large-scale energy option independent of limited fissile U235 resources. The relatively small number of fusion breeders required might also make the denatured fuel cycle an economically acceptable deterent to proliferation and diversion.

Low fission product inventory and low after heat inherent with fission-suppressed blankets should simplify design and operation of fusion breeders. Economic estimates indicate that fusion breeders, designed with a fission-suppressed blankets, should compare favorably with those designed with fast-fission blankets. We estimate that the fuel provided to LWRs by fusion breeders would add ~20% to the cost of power from LWRs. The development of a fission-suppressed breeder appears significantly less risky and less costly compared to fast-fission blanket breeders.

We believe the fission-suppressed breeding concept may be the best way to produce fissile fuel. The purpose of this communication is to challenge the reader to consider the concept and compare it to the methods that are now believed to be the best way to produce nuclear fuel.

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