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The Fusion Breeder

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The fusion breeder is a fusion reactor designed with special blankets to maximize the transmutation by 14 MeV neutrons of uranium-238 to plutonium or thorium to uranium-233 for use as a fuel for fission reactors. Breeding fissile fuels has not been a goal of the U.S. fusion energy program. This paper suggests it is time for a policy change to make the fusion breeder a goal of the U.S. fusion program and the U.S. nuclear energy program. There is wide agreement that many approaches will work and will produce fuel for five equal-sized LWRs, and some approach as many as 20 LWRs at electricity costs within 20% of those at today's price of uranium ($30/lb of U_3O_8). The blankets designed to suppress fissioning, called symbiotes, fusion fuel factories, or just fusion breeders, will have safety characteristics more like pure fusion reactors and will support as many as 15 equal power LWRs. The blankets designed to maximize fast fission of fertile material will have safety characteristics more like fission reactors and will support 5 LWRs. This author strongly recommends development of the fission suppressed blanket type, a point of view not agreed upon by everyone. There is, however, wide agreement that, to meet the market price for uranium which would result in LWR electricity within 20% of today's cost with either blanket type, fusion components can cost severalfold more than would be allowed for pure fusion to meet the goal of making electricity alone at 20% over today's fission costs. Also widely agreed is that the critical-path-item for the fusion breeder is fusion development itself; however, development of fusion breeder specific items (blankets, fuel cycle) should be started now in order to have the fusion breeder by the time the rise in uranium prices forces other more costly choices.

KEY WORDS: Fusion breeder; fusion/fission, hybrid; fusion/fission fuel factory.

1. INTRODUCTION

Since the beginning of the fusion program, people have been considering the use of fusion neutrons to breed fissile material ($^{233}U, ^{239}Pu$) from fertile material ($^{232}Th, ^{238}U$). The rationale behind this is simply that uranium, the only source of fissile material today, is scarce; the few rich mineral deposits will be depleted rapidly, leading to the mining of ever lower grades of ore, and as a consequence, pushing uranium prices ever higher. Any enterprise based on the use of uranium must find means for making more efficient use of it in the next few decades.

The problem stems from the fact that the fissile isotope of uranium (^{235}U) constitutes only 0.7% of natural uranium. Therefore, the idea behind the breeder reactor is to absorb the neutrons derived from fission in ^{238}U or ^{232}Th and produce as many or more fissile atoms than those consumed by fission, thus making use of all the uranium (or thorium) mined, rather than less than 1%. Thorium is four times more abundant than uranium. Neutrons from both fusion and breeder fission reactors can be used to produce fissile material at a cost which may be competitive with that of mined uranium. The breeder

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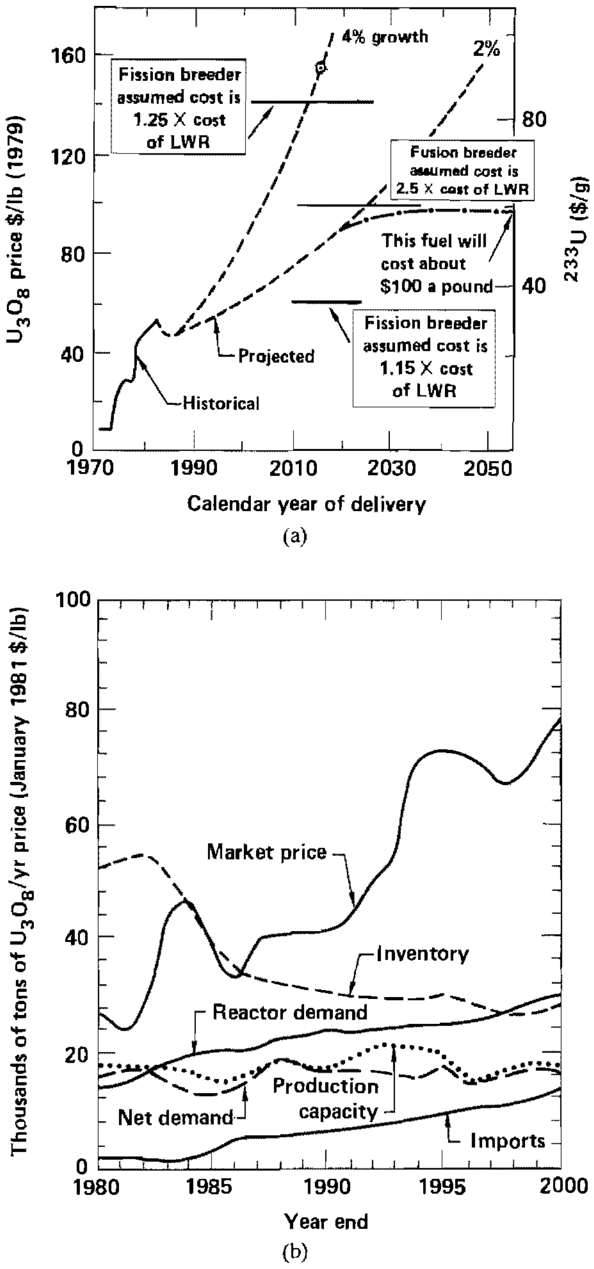

Fig. 1. (a) Future price of uranium or equivalent ^{233}U. The price of mined uranium will increase due to resource depletion until eventually either breeder reactors, fusion breeders plus conventional reactors, or both become economical. (b) A recent uranium price projection taken from the January issue of *Nuclear News*, p. 61, is consistent with (a).

uses initial inventories of fissile material, which puts additional demands on uranium supplies during the introduction phase. The fusion reactor would require an exceedingly small amount of uranium or none at all, if thorium is used to produce ^{233}U.

Figure 1 illustrates the point long recognized in the nuclear community that eventually the upward thrust of uranium prices will be stopped by breeders. That is, there will be an "indifference price" for uranium where power can be made for the same cost either by using mined uranium and fissioning the ^{235}U in conventional fission reactors (LWRs, for example) or by using ^{238}U (or thorium) to both breed and fission ^{239}Pu (or ^{233}U) in a breeder reactor. The time in the future when one is indifferent as to which way to utilize uranium to make power is the time when breeders can begin to produce benefits relative to the old ways of conventional nuclear power. The speculation is that when the fusion breeder becomes available it will result in a lower indifference price for uranium, which is one aspect of the rationale for the fusion approach to fuel production. The data for Fig. 1 are partly derived from refs. 1 and 2. The cost targets are discussed below, as are the introduction dates for the hybrid.

2. NUCLEAR REACTIONS

The two fissile material breeding reactions are:

$$^{1}n + {}^{232}Th \longrightarrow {}^{233}Th \xrightarrow[22m]{\beta} {}^{233}Pa \xrightarrow[27d]{\beta} {}^{233}U$$

and

$$^{1}n + {}^{238}U \longrightarrow {}^{239}U \xrightarrow[24m]{\rho} {}^{239}Np \xrightarrow[2.4d]{\beta} {}^{239}Pu$$

These reactions occur only for slow neutrons. The fusion reaction that is easiest to initiate is the D-T reaction:

$$D + T \rightarrow {}^{4}He + n + 17.6\ MeV$$

The T breeding reactions are:

$$n + {}^{6}Li \rightarrow T + {}^{4}He + 4.8\ MeV$$

and

$$n + {}^{7}Li \rightarrow T + {}^{4}He + n - 2.8\ MeV$$

The first reaction occurs for slow neutrons, while the second occurs only for fast neutrons. This reaction breeds tritium, and also preserves a neutron for further breeding. Thus, it is uniquely suitable for fissile breeding (as will be discussed below).

Table I. Neutron Multiplication for Each 14-MeV Source Neutron in an Infinite Medium

	^{238}U	^{232}Th	Be	^{7}Li	Pb
Number of neutrons captured (produced)	4.2	2.5	2.7	1.8[a]	1.7

[a] Of the 1.8, 1.0 is an equivalent neutron represented by a bred tritium.

3. IDEAL BLANKET CONFIGURATIONS

A neutron produced by the D-T reaction has a spectacularly high energy and can be used to produce several slower neutrons. For example, Table I shows neutron multiplication for each 14-MeV source neutron in an infinite medium(3). Uranium-238 is by far the most effective neutron multiplier due to the fast-fission reaction, which is less important in ^{232}Th. Beryllium is unique because of its large neutron multiplication with essentially no radioactivity, contrary to the case with uranium and thorium. Lithium-7 is also unique, as stated above, in that it breeds tritium and still preserves one neutron for breeding. Lead is one of the better neutron multipliers, but after subtracting one neutron for breeding tritium, it is a significantly poorer multiplier than either beryllium or ^{7}Li.

Two classes of hybrids emerge based on different characteristics of the multiplier: fast-fission and fission-suppressed. The fissile material to be bred, ^{239}Pu or ^{233}U from either ^{238}U or ^{232}Th, further specifies the class of hybrid. The most interesting combinations are given in Table II. As shown in the table, the energy released in the blanket is E, and F is the number of fissile atoms bred per fusion neutron. The values in Table II are derived from design studies where many practical considerations reduced the breeding from ideal performance, such as parasitic absorption in structural material, coolant, and leakage effect. The breeding rate per unit of fusion power and per unit of power in the blanket are also given in Table II. The relative breeding rate is defined as the ratio of the breeding rate to the breeding rate of a fission breeder whose breeding ratio is arbitrarily taken equal to 1.3. A fusion breeder will produce much more material than an equal power fission breeder, and the fission-suppressed class is extraordinary in this respect. In a recent report, Jakeman(4) discusses how various blanket types produce similar performances, and he also recommends using beryllium or ^{7}Li in a fission-suppressed mode.

By examining a number of ideal infinite-medium examples, as shown in Table III, one can get an idea of the breeding capability of various materials, and one can obtain guidance for practical blanket design. More examples are given and discussed in ref. 3. In practice, however, the results are usually degraded

Table II. Classes of Hybrids and Typical Performance Parameters

	Fast-fission U-Pu cycle multiplier, ^{238}Pu; breeder, ^{238}U, ^{6}Li	Fast-fission Th-U cycle multiplier, ^{232}Th or ^{238}U; breeder, ^{232}Th, ^{6}Li	Fission-suppressed U-Pu cycle multiplier, Be, ^{7}Li; breeder, ^{238}U, ^{6}Li	Fast fission breeder reactor
Energy released in blanket (E), MeV	154.0	70.0	22.4	200
Breeding ratio, $T + F$	2.5	1.8	1.7	1.3
F/E ($T = 1$), atoms per MeV	0.01	0.01	0.03	0.0015
Breeding rate				
kg/MW fusion yr	6.6	3.5	3.1	
kg/MW blanket yr	0.77	0.88	2.57	
kg/MW nuclear yr	0.73	0.83	2.2	0.13
Relative breeding rate	5.6	6.4	17.0	1.0

Table III. Infinite Homogeneous Results for Each 14-MeV Neutron

Case	Medium	Product atoms	Energy release (MeV)
1	$^{238}U+7.6\%\ ^{6}Li$	$3.1\ ^{239}Pu+1.1\ T$	193
2	$^{232}Th+16\%\ ^{6}Li$	$1.3\ ^{233}U+1.1\ T$	49
3	$^{9}Be+5\%\ ^{6}Li$	$2.7\ T$	22
4	$^{9}Be+5\%\ ^{232}Th$	$2.7\ ^{233}U$	30
5	$^{9}Be+1\%\ ^{238}U$	$2.4\ Pu$	29
6	$^{9}Be+3\%\ Th+2\%\ ^{6}Li$	$1.6\ ^{233}U+1.1\ T$	27
7	$^{9}Be+1\%\ U+0.4\%\ ^{6}Li$	$1.6\ Pu+1.1\ T$	28
8	$^{7}Li+0.8\%\ Th+0.02\%\ ^{6}Li$	$0.7\ ^{233}U+1.1\ T$	17
9	$Pb+5\%\ ^{6}Li$	$1.7\ T$	18
10	$Pb+5\%\ Th$	$1.6\ ^{233}U$	21

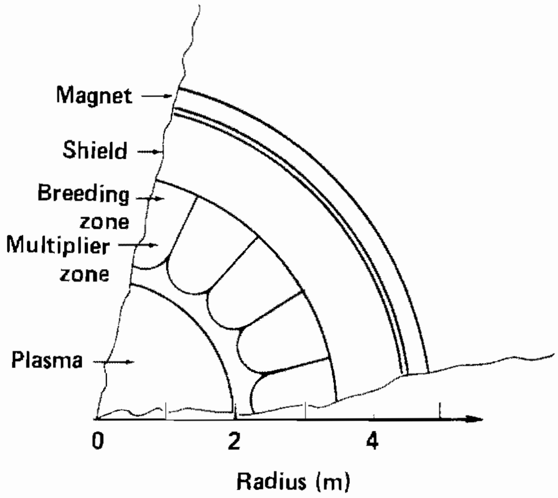

Fig. 2. Breeding blanket geometry.

due to a number of effects, such as:

1. Parasitic neutron capture in structural materials and coolants
2. Neutron leakage
3. Lack of complete wall coverage
4. Fissioning of bred fissile material before removal
5. Decay of tritium before removal
6. Heterogeneous effects (that are sometimes good)

4. ENGINEERED BLANKET CONFIGURATIONS

The geometry of the breeding blanket is shown in Fig. 2.[2] An example of a fast-fission blanket based on either the U-Pu fuel cycle or the Th-U fuel cycle is shown in Fig. 3. The fuel form is either ceramic U_3Si, a metallic alloy of uranium or metallic thorium, and is helium-cooled. The performance parameters for this blanket are given in Table IV. Note the significant loss in breeding due to reducing the wall coverage. In the case of the tandem mirror, for example, we expect the central cell to be almost 100% covered. Losses due to the ends may be as low as 5%, thus giving a coverage of 95%.

Various blanket types were considered in design studies of the tokamak configuration(1). A pressure-cylinder blanket concept was worked out for the tokamak(7). The same plate fuel concept as shown in Fig. 3 has been worked out for the tokamak in a pure fusion version in a recent paper by Huggenberger and Schultz(19) as shown in Fig. 4. An example of an engineered blanket based on a fast-fission Th-U cycle using helium-cooled metallic thorium is shown in Fig. 3 and discussed in ref. 2. The performance for this blanket is given in Table V. A fission-suppressed blanket design (Table II) using nonfissioning neutron multipliers (Table I) could use beryllium or ^{7}Li for the multiplier and could be cooled with He, Li, or molten salt. The fission suppressed blanket should have materials arranged as in Fig. 5.

The front part of the blanket should contain mostly ^{7}Li or beryllium. A small amount of ^{6}Li is used to outcompete structural materials and beryllium for slow neutron capture. To minimize fast fission, thorium or uranium should not be present in the front part. In the back part of the blanket, where the 14-MeV incident flux has been moderated and multiplied into more of the slower neutrons, ^{6}Li and thorium or uranium should be placed in sufficient concentration to outcompete structural materials for slow neutrons. Bred ^{233}U must be removed often enough to prevent captures in ^{233}U. An example of a fission-suppressed blanket cooled by molten salt is shown in Fig. 6. The performance of this engineered fission-suppressed design is given in Table VI.

The requirement for large quantities of beryllium brings up the question of an adequate resource. Since relatively few hybrids will be needed, as discussed in Section 6, present resources appear to be adequate. However, for this use alone, an increase in the production of beryllium would be required. This subject is discussed further in ref. 8.

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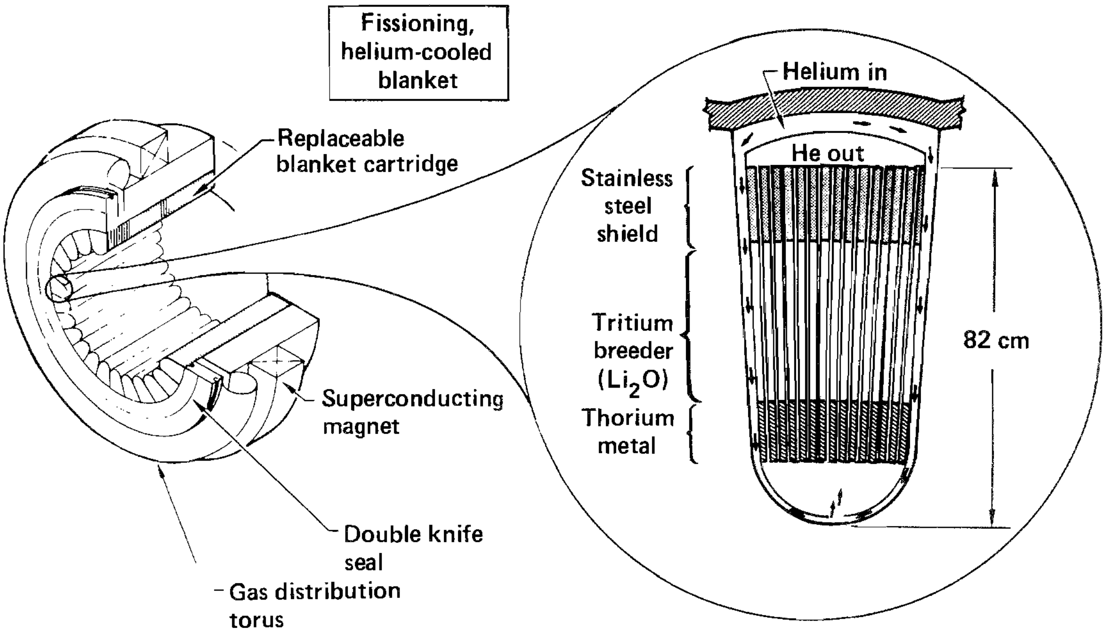
[2] This section and the next have not included work carried out in the last year.



PU PRODUCTION
2700 kg PU/YEAR
3900 MW THERMAL (MAX)
400 MW FUSION
350 W/CC PEAK FUEL POWER DENSITY
(AT WL=1.9 MW/m^2)

^{233}U PRODUCTION
2900 kg ^{233}U/YEAR
4000MW THERMAL (MAX)
800 MW FUSION
120 W/CC PEAK FUEL POWER DENISTY
(AT WL=1.5 MW/m^2)

Fig. 3. Fast-fission blanket design.

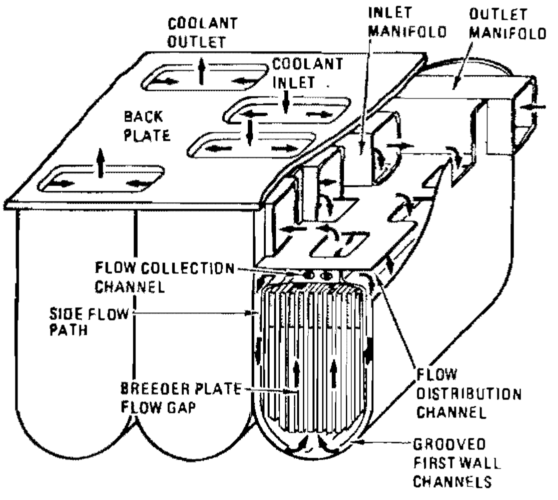
Table IV. Performance Parameters for the U_3Si Blanket

Pu[a]	T[a]	*M*	Blanket coverage (%)
1.5	1.0	11	86
1.7	1.2	13	100

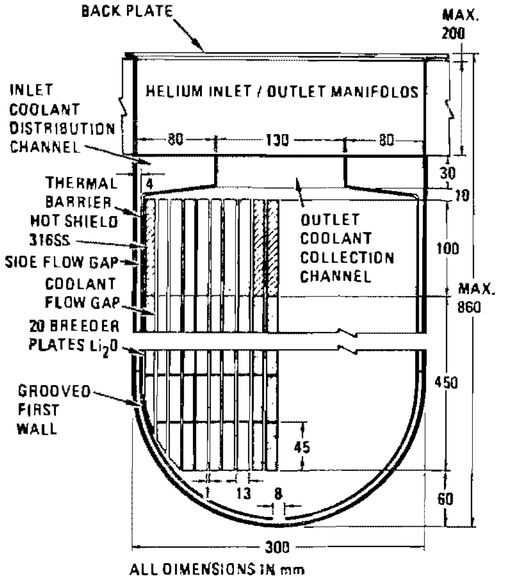
[a] Atoms bred for each 14-MeV neutron.

Note that the breeding performance of the fission-suppressed blanket is almost as good as that of the fast-fission thorium blanket, but the heat generation by the blanket is 3 times less. The fission power of the blanket is a small part of the total heat generation, and, because the thorium in the blanket is much more diluted, the fission power density is very small. Because the after-heat cooling requirements are so relaxed, we believe that fission-suppressed blankets can possibly be designed so that no active after-shutdown cooling systems will be required, as illustrated in Table VII. The subject of the safety of hybrids is further discussed in refs. 9 and 10.

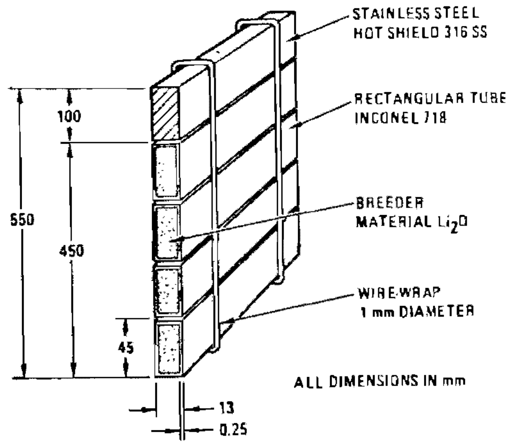
Another remarkable distinction fission-suppressed blankets have over fast-fission blankets is a very high support ratio. Support ratio is defined as the number of fission reactors one hybrid can supply with makeup fuel, when the nuclear power of the hybrid and of each fission reactor is the same. The advantage of a high support ratio is that few hybrids need to be built. The ones that are built can be located in a few nuclear fuel centers that would be well guarded and yet open for international inspection to ease diversion and proliferation problems. The support ratio for the fast-fission U-Pu cycle is 5, for the fast-fission Th-U cycle is 10, and for the fission-suppressed blankets on the Th-U cycle is about 25. For example, if a country had 300 LWRs of 1000 MWe on the Th-U cycle by the turn of the century, these LWRs could be sustained indefinitely by only 12 hybrids of the same size. Jakeman$^{(4)}$ quotes support ratios of 50–100 for advanced converter reactors



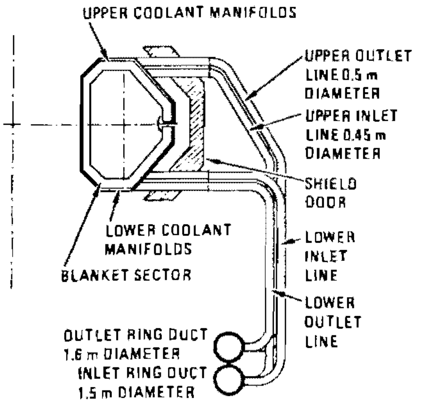
Blanket module.



Blanket module cross section.



Breeder plate design.



Blanket sector coolant supply.

fit into the STARFIRE design

Fig. 4. Example of a plate fuel gas cooled blanket worked out for a Starfire Tokamak. The fuel could be either uranium or thorium, although this example is a pure fusion design.

Table V. Performance of the Fast-Fission Thorium Blanket

^{233}U^a	T^a	*M*
0.84	1.07	5.2

^{a}Atoms bred for each 14-MeV neutron.

such as the Canadian (CANDU) reactor. The ideas behind the fission-suppressed blanket are discussed further in ref. 11.

5. RESULTS OF THE TANDEM-MIRROR FISSION-SUPPRESSED HYBRID DESIGN STUDY

The results of this ongoing study are discussed in two extensive reports(2, 12) and two summary reports.(8, 13) Related work on a fission-suppressed inertial-confinement reactor is discussed in ref. 14. The geometry of the tandem-mirror hybrid is shown in Fig. 7. The basis for the design was the conventional tandem mode (sometimes called the thermal

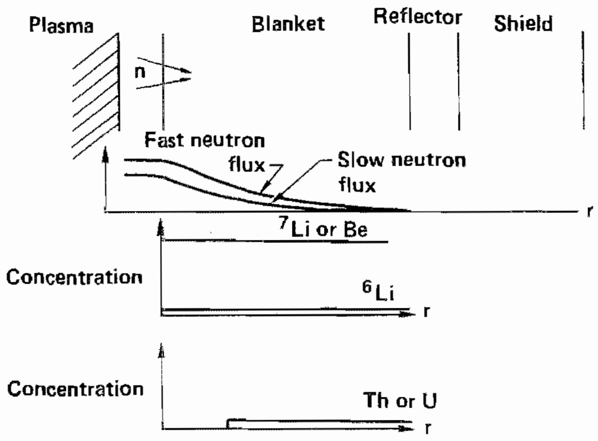


Fig. 5. Anatomy of a fission-suppressed blanket.

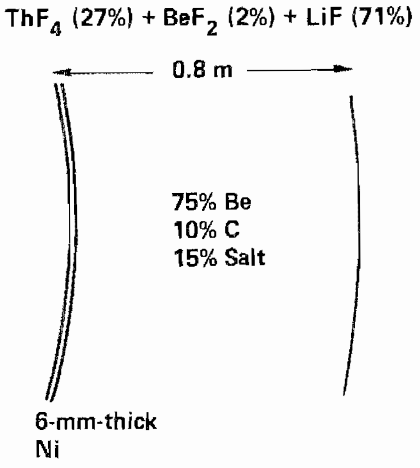


Fig. 6. Example of a fission-suppressed blanket cooled by molten salt.

Table VI. Performance Parameters of Fission-Suppressed Blanket

$^{233}U^a$	T^a	M
0.83	1.04	1.62

[a] Atoms bred for each 14-MeV neutron.

mode as contrasted to the thermal barrier mode). A parametric analysis was carried out which showed the Q value dropping with increasing Γ, where Q is the ratio of fusion power to the injected and absorbed power, and Γ is the neutron wall loading. A cost analysis showed the minimum-cost fissile fuel to occur at an intermediate value of Q shown in Fig. 8.

In order to see the sensitivity to Q and Γ separately, these parameters were varied independently of each other. This is, of course, not a real model and is sometimes called a "no-cost Q enhancer." The results in Fig. 9 show that Q should be 3 or greater and Γ should be 1 or greater. More accurately, the product $\eta_i Q$ is the proper figure of merit, where η_i is the injector efficiency. For our work, we assumed a 60% efficient injector; therefore, the product $\eta_i Q$ should be greater than about 2. The same kind of analysis was performed where Q was increased "at no cost," and we plotted the cost of electricity under two conditions: where the fuel was used in LWRs, and where the blanket produced no fuel (thus it was a pure-fusion case). These results are discussed more fully in ref. 13 and are shown in Fig. 10. The conclusions that can be drawn from Fig. 10 are threefold:

Table VII. Time for Fuel Damage with No Active Cooling After Shutdown

Blanket type	Fission power density (W cm^{-3})	Time to fuel damage
Fast-fission U-Pu cycle	350	1 min
Fast-fission Th-U cycle	105	11 min
Fission-suppressed Th-U cycle	5	16 hr

1. The hybrid can supply fuel to LWRs so that their electricity costs are increased due to fuel cost by only about 25% for Q values of 2 or more.
2. Q values need be 2 or more for hybrids, but must be 15 to 20 or more for pure fusion.
3. For pure fusion to compete economically, the reactor must have a higher power density (or the cost must be reduced) as well as have very high Q values.

The above conclusions can be substantiated by looking at cost estimates. The hybrid designed in 1979 with the fission-suppressed blanket, discussed above, was estimated to cost $6.5 billion for a 4000 MW nuclear power unit producing 7200 kg of ^{233}U each year and supplying the fuel makeup needs for 25 LWRs of the same size. The Q value was only 2 and little electricity was produced. This LWR has a 1280-MWe capacity and consumes 303 kg of ^{233}U each year at a 75% capacity factor. We have estimated the cost of each LWR at $1.15 billion. This hybrid costs 5.7 times an LWR. These 25 LWRs then would cost an estimated $28.8 billion. The cost of the system per

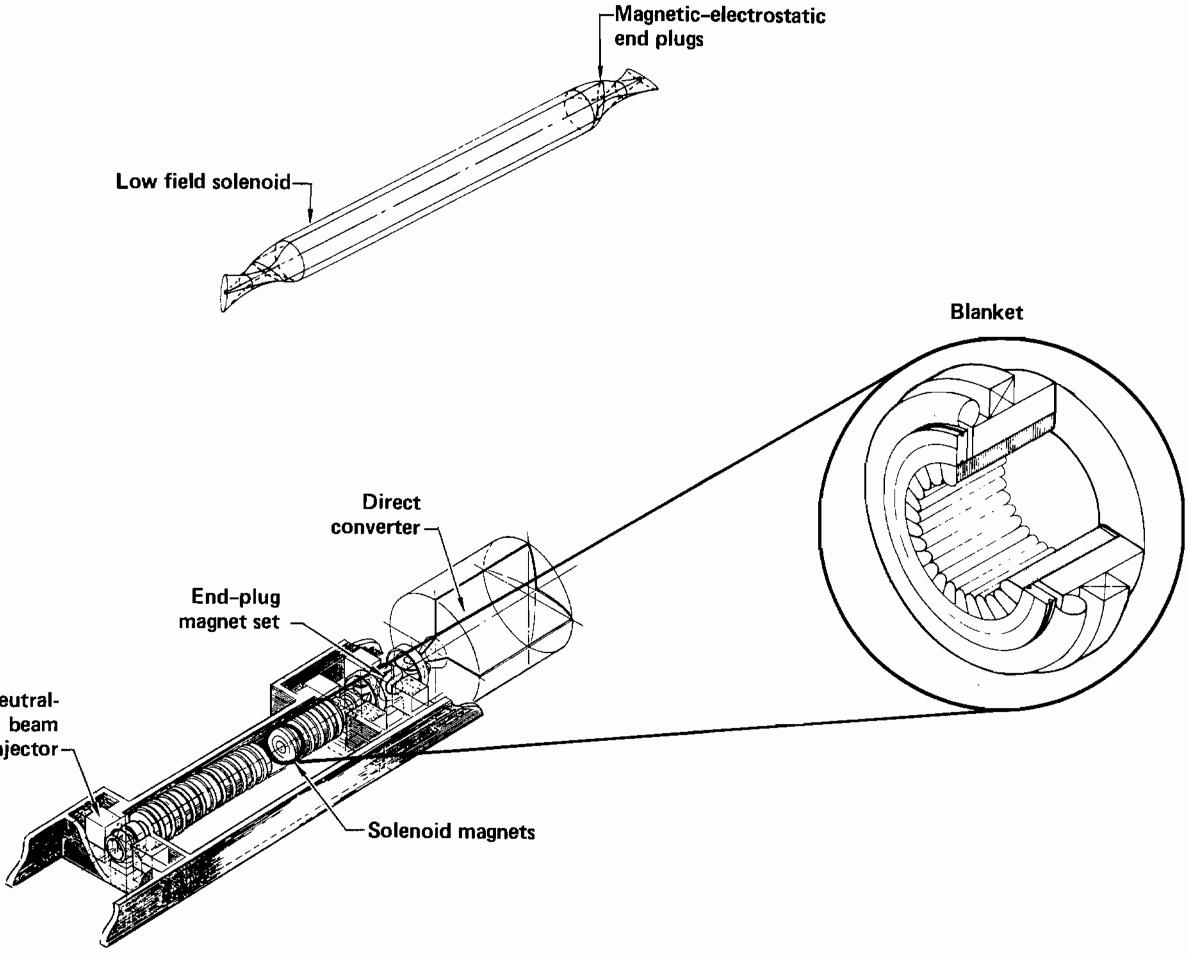


Fig. 7. Tandem mirror hybrid configuration. Top: The plasma shape is determined by the magnetic flux surface and the corresponding magnetic-field, plasma-density, and potential profiles for the conventional tandem plasma mode. Bottom: The main components of the hybrid reactor.

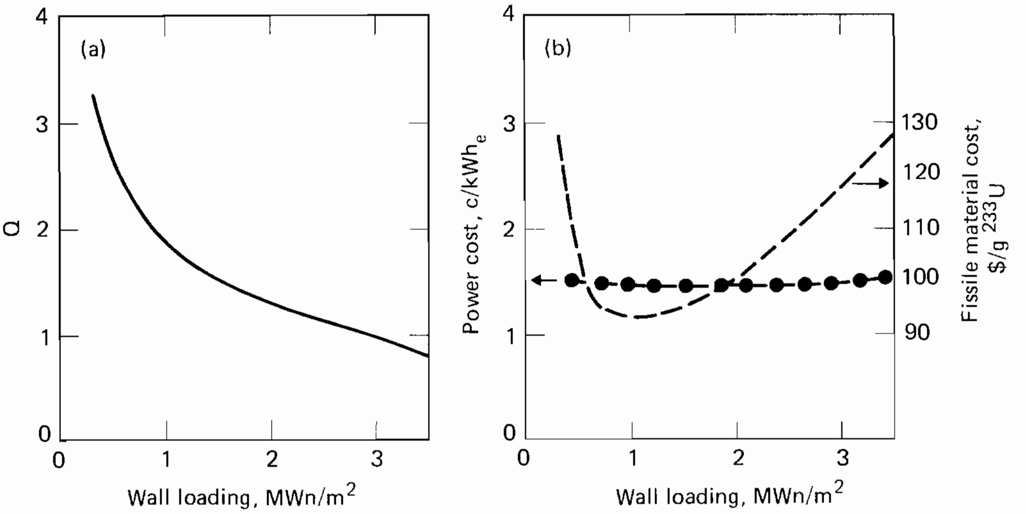


Fig. 8. Q versus wall loading tradeoff.

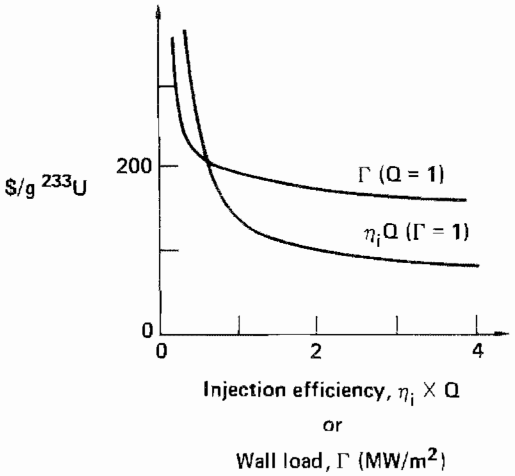


Fig. 9. Cost of fissile fuel versus $\eta_i Q$ and Γ. When the wall load Γ is varied, Q is kept fixed at 1; when Q is varied, Γ is kept fixed at 1.

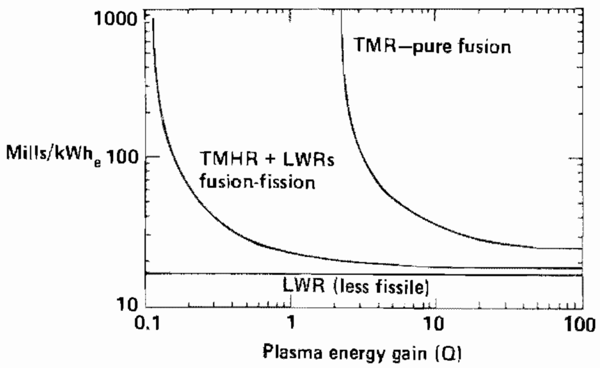


Fig. 10. Cost of electricity versus Q for the hybrid with its LWRs and for a pure-fusion tandem reactor (TMR).

Table VIII. Fusion Driver Performance Parameters

	Molten-salt blanket
Q	2.2
Γ, MW/m^2	2.0
$R_{\text{first wall}}$, m[a]	2.1
$R_{\text{solenoid magnet}}$, m[a]	4.2
L, m[a]	90
P_{nuclear}, MW (max)	4000
P_{fusion}, MW	3000
Blanket energy multiplication, M	1.4

[a] For comparison, the proposed Mirror Fusion Test Facility (MFTF-B) employs similar magnets 2.2 m in radius, 25 m long, and has a plasma radius of 0.4 m at 1.5 T (1.7 T for the hybrid).

Table IX. Hybrid Plant Parameters (with Molten-Salt Blanket)

P_{nuclear}, MW	4000
P_{fusion}, MW	2700
P_{electric}, MW	360
Electrical efficiency, %	9
kg ^{233}U/yr rate	9600
kg ^{233}U/MW nuclear year	2.4
Total estimated direct cost, millions of $	4100
Estimated $/g	59
Number of fission reactors (LWRs) (at 303 kg/GWe yr) of 4000 MW nuclear supported	25

unit of power produced is:

$$\frac{C_{\text{hybrid}} + NC_{\text{LWR}}}{P_{e\text{hybrid}} + NP_{e\text{LWR}}}$$

where N is the support ratio. If we measure hybrid costs in units of LWR costs, and hybrid electricity in units of LWR electricity, then the above equation for our example gives 1.21. That is, the power system will cost 21% more to pay for its fuel supply.

These ratios show that even for an expensive hybrid (by LWR standards), the system electricity costs are near those of the LWR without fuel charges. We can expect that the same improvements that will reduce the costs of pure fusion will also considerably reduce the hybrid cost figure quoted here of $6.5 billion. Since 1979, the concept of the thermal barrier tandem mirror has resulted in much higher Q values and lower capital cost. For a capital cost for the hybrid of twice that for the LWR, and high enough Q so the electrical power is produced as efficiently as an LWR, the cost of the system per unit of power is 1.04. That is, the fuel supply only costs 4% extra capital. If the support ratio drops to 15, the add-on is still only 6%.

We can derive the relationship of the price of U_3O_8 for which we could produce electricity at the same cost as from a system fueled from the hybrid. For example, $100/lb of U_3O_8 is the same as $118/lb of uranium metal, which is $260/kg of uranium metal. If we can remove five ^{235}U atoms per each 1000 ^{238}U atoms during isotope separation, then the $260/kg becomes $52/g of ^{235}U. An LWR uses ^{233}U about 30% more efficiently than ^{235}U, so this is worth $68/g ^{233}U. Actually U is not quite 30% more efficient, but isotope separation costs were left out, which somewhat compensates. Thus, we get the rough equivalence of $100/lb of U_3O_8 being $68/g ^{233}U. Our reactor example used 303 kg of ^{233}U each year resulting in annual fuel costs of \$20.6 M/yr. At 16% capital, this is equivalent to \$130 M capital, which is 11% of the capital of our LWR. We, therefore, conclude that a hybrid costing roughly 11% of the LWR system it supports will be cost-competitive with uranium priced at \$100/lb.

A hybrid costing 2.5 times an LWR, and producing electricity at 25% efficiency—supporting 15 LWRs—has an add-on cost of 11%; hence, it would compete with \$100/lb uranium. A breeder reactor, due to its higher burnup, is predicted to have a lower fuel-cycle cost compared to an LWR. Assume a breeder at 1.1 times the cost of an LWR is equivalent to an LWR with zero fuel cost. From the above rough analysis, each 10 percentage points of add-on cost is equivalent to about \$100/lb of U_3O_8. Hence, a breeder costing 1.15 times an LWR would be equivalent to \$50/lb, 1.20 to \$100/lb, 1.25 to \$150/lb, 1.3 to \$200/lb, and 1.4 to \$300/lb. This simple analysis is the basis for the cost targets shown in Fig. 1. We conclude these arguments by noting that fusion development might find a practical use as a fission suppressed breeder as soon as the following conditions are met:

1. $\eta_i Q > 3$
2. $\Gamma \geqslant 1.5$, $\mathrm{MW \cdot m^{-2}}$
3. Breeding ratio, $T + F \geqslant 1.7$
4. Wall coverage > 90%
5. Capacity factor > 2/3
6. $C_{\text{hybrid}}/C_{\text{LWR}} < 3$
7. The demand for LWR fuel drives the price sufficiently high (> \$100/lb)

6. INTRODUCTION RATES OF HYBRID AND LWRS

As mentioned above, the fission-suppressed hybrid with its fueled fission reactors has unique advantages in that it can be introduced at a rate that is historically unprecedented for a new technology. This is due to the large support ratio. The new part of the system is a very small part of the total. The large LWR part will be well known by the time of the first hybrid introduction. With a support ratio of 25 (^{232}Th-^{233}U cycle), we could build over 20 LWRs for each hybrid if first core-fuel loadings were provided by ^{235}U. However, this might put a strain on uranium resources. These initial cores could be provided by the hybrid with an attendant slower LWR construction rate than 20 : 1.

Table X. LWR and Hybrid Parameters for the Introduction Scenario

LWR	1000 MWe
	75% capacity factor
	239 kg ^{233}U each year
	2400 kg ^{233}U first core
Hybrid	9600 kg ^{233}U per year rate
	75% capacity factor
	7200 kg ^{233}U produced per year
	4000 MW nuclear
	2700 MW fusion

In a previous version of this paper(15), I have considered a hypothetical introduction scenario that supplied fuel to 210 LWRs of 1000 MWe each. This introduction scenario is appropriate for a medium size country. In this paper I discuss another hypothetical introduction plan appropriate to supply the world's nuclear fuel needs exclusive of the centrally planned-economy countries. The performance assumptions for the hybrids and fission reactors are given in Table 10. The assumed hybrid introduction rates are given in Table 11.

The first machine was sized at 200 MW fusion because that was close to the value assumed for the Tandem Mirror Next Step (TMNS) study(16). The next tokamak will very likely be even larger than 200 MW fusion. This machine would be a developmental machine operating only 30% of the time with an average of only 50% of the possible blanket area utilized for breeding. Construction could begin on such a machine in 1984 with fuel production beginning in 1990.[3] We assume that a 1000 MW fusion demonstration plant could be built starting in 1990. Before large expenditures are made, results from the 200 MW plant will be known.

The first commercial plant could be constructed starting in 1998; criteria for the design of this plant would be based on operational results from the demonstration plant. Under this scenario, two units are started six years later in 2004, two more units four years later in 2008, one unit one year later in 2009, one unit in 2010, and then two units per year until

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[3] When this scenario was constructed (Fall 1980), 1984 seemed like a reasonable start date given the favorable budget predictions then; however, budgets have been falling short of the predictions, but for a machine in the 50–200 MW fusion size, 1987 is probably even now a reasonable start date.

Table XI. Hybrid Introduction Rate Assumption

Number and size	Start construction (year)	Begin fuel production (year)	Begin fueling new reactor (year)	LWR fueling ^{233}U (tons/year)
1 200 MW_{fusion} 1/2 blanket coverage; CF-30%	1984	1990 (phased out by 1998)	1992	0.10
1 1000 MW_{fusion} full blanket coverage; CF-60%	1990 (by 2006)	1998 (phased out)	2000	2.13
1 2700 MW_{fusion}	1998	2006	2008	7.2
2 2700 MW_{fusion}	2004	2012	2014	21.6
2 2700 MW_{fusion}	2008	2016	2018	36.0
1 2700 MW_{fusion}	2009	2017	2019	43.2
1 2700 MW_{fusion}	2010	2018	2020	50.4
2 2700 MW_{fusion}	2011	2019	2021	64.8

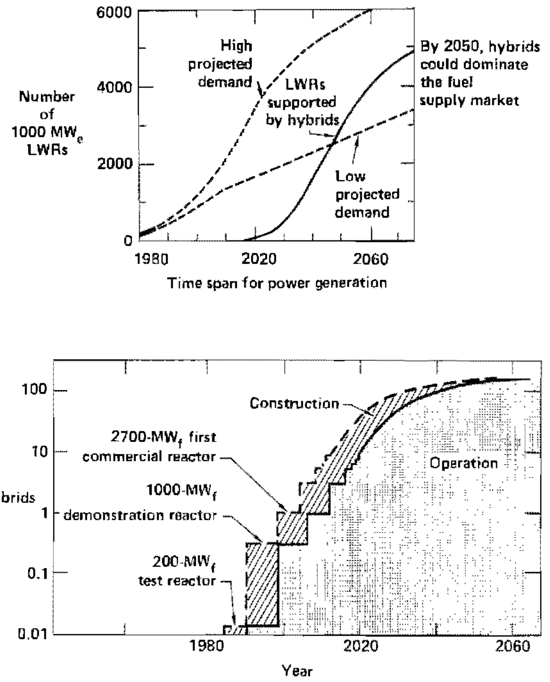

Fig. 11. Introduction rates of LWRS and their hybrid fuel suppliers.

2014. The number of hybrid construction starts per year are plotted in Fig. 11. Using data from Table 10, the introduction rates are shown in Fig. 11. The high and low demand projections were taken from ref. 17. From 2008 to 2019 the new construction starts are about 20% of the hybrids under construction. This introduction rate seems rather high and should be reexamined.

The delay time, from the introduction of the plants supplying fuel to a significant number of reactors, is apparent from Fig. 11. Small quantities of fuel (100 kg/yr) can be produced by 1990, but it will be 2014 before there is enough fuel for a significant number of reactors (~ 30). Note that this is less than 10 years after the introduction of the first commercial hybrid! There would be 100 reactors supported by 2020 and 2000 by the year 2042. The schedule could be foreshortened if a sense of urgency should develop. A group from the University of Wisconsin and Karlsruhe Nuclear Research Center(17) studied hybrid introduction rates, and they found that fission-suppressed hybrids (high support ratio) are best from an introduction standpoint. Also, they find it necessary to introduce them before the year 2020.

6.1. ^{233}U-Thorium Gas Cooled Reactors

One could develop another introduction scenario where only new plants of the high-temperature gas type would be hybrid fueled. Since these reactors use ^{233}U on the thorium cycle considerably more efficiently than LWRs and since there is no readily available alternate source of ^{233}U, this scenario has merit.

The plans for gas cooled reactors that are based on very uncertain assumptions call for a lead plant of 800 MWe to go on-line about 1995, the next one scheduled two years later, and multiple units after the year 2000. Small process heat or synfuel producing reactors would also benefit from use of high temperature gas cooled reactors using thorium and ^{233}U. As

Table XII. Goals of Future Work on Fission-Suppressed Blanket Concept

- Produce an engineered blanket design that has:
  - Outstanding safety features
    - No significant afterheat cooling problem
    - Low radioactive inventory
  - Outstanding deployment features
    - Rapid expansion possible due to high support ratio
    - Minimum development due to fission suppression
  - Economics that compete with fuel from mined uranium

we can see from the tables and figures, the first reactors would have to use ^{235}U, but one per year could be started after the year 2000 and about three a year after 2008 on ^{233}U from hybrid reactors.

More studies of hybrid introduction have been carried out in ref. 18, where it was shown that the curtailment of nuclear power would occur after 2020 if the hybrid were not introduced early enough. The effect of the fission breeder was also shown, and except for every aggressive deployment, there would still be a curtailment with the breeder alone.

7. FUTURE WORK

A study of the fusion breeder based on the tandem mirror and the tokamak is underway at the Lawrence Livermore National Laboratory; portions of the work are being carried out by industrial firms. The feasibility of the fusion breeder and its associated fuel cycle to impact the use of nuclear fission power is the paramount goal of this study. Further goals are given in Table 12.

8. RESEARCH AND DEVELOPMENT NEEDS FOR THE FUSION BREEDER

The goal of the fusion breeder R&D program is to have the appropriate technology proven in time to allow use of this technology to breed fissile material on a large enough scale to avoid problems associated with a uranium shortage. Some scenarios for the future predict the long anticipated uranium shortage will not occur before the middle of the next century. Others predict uranium supplies will be committed early in the next century. The answer to the anticipated uranium shortage has been the fission breeder, which would replace existing fission reactor types, principally the light water reactor. Such a replacement program will take so long that to avoid a uranium shortage the fission breeder should be deployed starting now. The problem with this strategy is that each fission breeder will have to be subsidized until their cost drops or uranium price rises sufficiently. For example, a fission breeder (1 GWe) costing 1.5 times an LWR would have to be subsidized by at least $400 M on its initial cost. It would break even only for uranium priced at around $400 per pound. If we could prove we had a better alternative answer to the uranium shortage, we could save billions of dollars.

Having an early answer to the technical and economic feasibility of the fusion breeder is the immediate goal of the fusion breeder program. The pacing item for the fusion breeder is fusion technology itself. The fusion breeder can be economical with fusion technology which is less demanding than the electrical power production application of fusion. One goal of the fusion breeder R&D program is to understand the differences in fusion technology for pure fusion and for the fusion breeder.

The fusion breeder program includes those things different from pure fusion technology development. In particular, breeding blankets and fuel cycles are the pacing items. In the following pages the project goals for the next year are laid out.

8.1. Project Goals for FY83

8.1.1. Plan Development and Testing Program

Experiments and studies should be planned first to give data that are needed to determine feasible fusion-breeding approaches. For example, is use of beryllium feasible? Can we use pebble fuel and beryllium? Can we use liquid metal heat coupling and coolants? Second, we must determine optimal approaches, e.g., H_2O cooling versus liquid metal cooling and aqueous reprocessing versus pyrochemical reprocessing. Third, we must provide an integrated plan for the development of the fusion breeder. This task was planned for FY82 but was not funded.

8.1.2. Experimental Tasks

There are common features of recent blanket designs, both for fission-suppressed and fissioning blankets, which have resulted in superior performance; these need experimental work rather than relying on paper studies alone. Use of beryllium, liquid metals, and pebbles are common elements where screening-type experiments or proof-of-principle experiments are needed. A preliminary list of the experimental tasks is given below:

1. 14-MeV neutronic bench mark experiment to resolve go/no go issue with beryllium-neutron multiplication
2. Liquid-metal flow experiments in a magnetic field through pebbles, insulated ducts, and baffles, etc., to better understand pressure drop and heat transfer characteristics
3. Corrosion tests: static and convective
4. Fabrication of beryllium
5. Irradiation of beryllium in a fission reactor: first, evaluate existing data; second, test and evaluate irradiated Be; third high temperature irradiation (e.g., FFTF)
6. Mock-up pebble transport experiments, non-nuclear
7. Compatibility tests of beryllium in molten salts
8. Blanket mock-up experiments in a test reactor: first, experimental data need assessment; second, test facility evaluation; third, preconceptual experimental design; fourth, plan for testing program (cost/schedule)

8.1.3. Studies

The purpose of the studies is to guide the experimental work and help define the role of the fusion breeder. The study tasks are listed below:

1. *Blanket design*: reference commercial blanket for a tokamak; demonstration blanket (e.g., for FED or TDF); generic blanket design and safety studies, including a liquid metal helium, water and salt cooled fission-suppressed and an updated fissioning blanket design
2. *Fuel cycle studies*: aqueous reprocessing plant design; pyrochemical reprocessing plant design; LWR fuel fabrication considerations
3. *Fusion-fission systems studies*: deployment and U_3O_8 resource studies; economics assessment and comparisons with fission technologies

The goal of this experimental work and systems studies is to assess the technical and economic feasibility of producing fissile (U-233 or Pu-239) fuel in tandem mirror and tokamak reactors. The work in FY83 will prepare for the FY84 work, which is an expanded testing and development program for fusion-breeder blankets and associated fuel cycles and facilities.

8.2. Proposed Research in FY84

To make breeding fuel in fusion reactors a real option on the required time scale, work needs to be done in more detail, including experimental work, and with more thoroughness than heretofore. The experimental work outlined will be much more expensive than theoretical studies alone due to fabrication of equipment and the operation of expensive, although existing, facilities. We are preparing this request under the assumption that the future need for more fissile fuel will become more widely accepted.

8.3. Goals for FY84 Work

We list FY84 goals as follows:

1. Material compatibility experiments, irradiation of samples in reactors, and liquid-metal loop experiments
2. Design studies of commercial- and demonstration-size fusion breeders
3. Systems studies to optimize designs and to determine sensitivities to technical uncertainties
4. Fuel cycle studies to include problems of bringing into practice large-scale new processes
5. Safety studies
6. Economic studies

This effort would be closely coordinated with MARS, TDF, and tokamak studies, and would be carried out largely by industrial firms. LLNL's role in the study would be: project management, fusion physics and technology, selected experiments, and systems analysis work.

9. FUSION BREEDERS' IMPACT ON THE EXPORT MARKET: AN OPPORTUNITY FOR SUPPLIERS OF REACTORS, FUEL, AND FUEL SERVICES

The U.S. has pioneered the development of peaceful uses of the atom. Indeed, U.S. industries have a lead in the nuclear business as well. However, due to a number of factors, this lead is slipping away rapidly, and in fact, many say the industry is dying. With no new reactor orders for many years and all too many cancellations, the outlook of the industry looks bleak. Three conditions could provide the climate for a strong return to nuclear reactor construction starts: an improvement in the economy, a normalization of regulatory action, and favorable government support for nuclear energy sustained over successive administrations. If coal becomes less favorable due to environmental effects (acid rain, CO_2 effects, and others), the growth in the nuclear industry could be even greater. When this return to nuclear occurs, there will have already been a great deal of experience built up in conventional reactors, and, by comparison, almost no experience in commercial fission breeder reactors. The orders would pour in for construction of and fuel cycle services for conventional fission reactors (LWRs in the U.S. and many other countries, but also HWRs and HTGRs in some countries) except for one thing—the vendors or purchasers may not be able to guarantee a supply of fuel over the economic life of the reactor. Reactors ordered in 1990 will reach their economic life in 2030!

If a new reactor type which breeds its own fuel is going to be needed (i.e., orders beginning in 1990), then the great experience built up in conventional reactors is in a sense wasted. However, if a new fuel source could be made available from the fusion breeder and already in 1990 the proposition had considerable basis even before operation of a large demonstration fusion breeder, then the conventional fission reactor and fuel cycle could be relied on and expanded rather than switching over to a new technology. To the extent one is sure the fusion breeder will provide fuel at a future date—or for that matter any new fuel source such as new ore deposits developed at a future date—then new reactors could be ordered with guaranteed fuel from existing sources up until the time when the fusion breeder is deployed.

Is it reasonable to order a fission reactor in 1990 (whose fuel cannot be guaranteed beyond 2020) based on the confident[4] prediction in 1990 that a fusion breeder will or can be operational in 2015? That is, from first operation in 2000 the owner would have 20 years to obtain secure fuel futures to cover the period 2020–2030. These futures could either be uranium ore or fuel from the fusion breeder.

The fusion breeder is used as an argument for staying with the product now being produced. Industry could sell LWRs or any other reactor types, and they could sell fuel and fuel services such as fabrication, transportation, reprocessing, waste preparation, and disposal. All these things, now rather well known, could be greatly expanded and have no connection with the fusion breeder except confidence based on the assurance of not having to make major changes in the near-planning time-frame future. Some predict that the French will sell liquid-metal, fast-breeder reactors around the world when fuel becomes scarce and expensive. This may be so, but we would argue that the reasons for the changeover would have to be compelling.[5] New sources of fissile fuel—the fusion breeder being only one—will tend to support expanded use and refinement of the present technology.

On the technical side, fusion-breeder-produced material, ^{239}Pu or ^{233}U, should be usable in LWRs, CANDUs, or HTGRs with only modest changes from present use based on ^{235}U. The opportunities for U.S. nuclear industries are:

1. Sales of conventional reactor components or licensing foreign manufacturers
2. Selling engineering services and design skills
3. Selling fissile material
4. Selling manufactured fuel assemblies
5. Buying back spent fuel, reprocessing it, and reselling it
6. Disposing of wastes for a fee

Buyers will enter into long term contracts only with reliable suppliers. Since the federal government must regulate nuclear materials, it is essential for the government to guarantee the reliability side of these long-term supply contracts for any of this to make sense. Independently of whether U.S. industries enter into the nuclear market worldwide or not, foreign-based industries surely will.

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[4] Assuming a vigorous fusion program and low-level research and development were carried out on the fusion breeder between now and 1990.

[5] The development of the fission breeder up to the point of deployment is a prudent policy. To be deployed in significant numbers, it must compete with conventional fission reactors obtaining fuel from mined uranium or from the fusion breeder. Breeders costing 30% or more than present LWRs, for example, will apparently require large subsidies.

10. FUSION BREEDERS' IMPACT ON THE FUSION RESEARCH AND DEVELOPMENT PROGRAM

Heretofore, the fusion research and development program has been supported for its ultimate use in electrical power production. Having another application—the fusion breeder—could result in more support; the earlier this application, the more urgency there is to develop the long lead time part, which is fusion itself. It is likely that early fusion reactors will cost significantly more than other power sources and this greater cost will discourage early use. Conversely, the fusion breeder can cost two to three times that of an LWR and still produce fissile fuel at costs competitive with mined uranium at about \$200/kg.

11. FUSION BREEDERS' IMPACT ON THE FISSION BREEDER PROGRAM

The fusion breeder will not be a reality until fusion is proven both feasible and economical enough to produce competitive fissile fuels. The fission breeder has already been proven feasible, while not yet economical, with mined uranium and conventional reactors. We can easily imagine scenarios in which the fission breeder would be economical. However, if the fusion breeder proves to be feasible, the fission breeder would have to compete economically not only with other types of fission reactors fueled from mined uranium, but also from fusion bred fuel, whichever was more economical. Fusion breeders may be preferred to fission breeders because they may be less disruptive and faster to deploy, and more economical. Since the fusion breeder may not succeed, we must make sure the fission breeder remains an option. One can even think of scenarios where fission breeders can compete but have too long a doubling time. If so, the fusion breeder could be used to help provide initial inventories. This would be especially important if there is high nuclear growth, if the resources of uranium prove lower than some predict, and if the ultimate breeding ratio along with other parameters results in a very long doubling time.

12. FUSION BREEDERS' IMPACT ON PROCESS HEAT AND THE SYNFUEL MARKET

In the next century when we will have had to all but abandon use of petroleum, and where coal and natural gas are unavailable or unusable, there will be tremendous incentives to develop new sources of synthetic fuels (synfuels). Already we know how to produce these fuels from hydrogen produced by water splitting at high temperatures. The processes are called thermochemical and electrochemical processes. Heat from a nuclear power source could drive such a synfuel plant. Helium-cooled fission reactors have run for years at 950°C outlet temperature. Such reactors are realistically predicted to cost within 20% of that of an LWR, which means the energy is going to be a relatively low cost (although higher than today's energy cost from natural gas). High temperature reactors (HTGRs using prismatic graphite blocks or graphite pebbles) could be nearly inexhaustible if they had a source of ^{233}U for start-up (about 2.4 tons) and for annual make-up (0.1 tons/yr for 2500 MWth) and as a fertile material used thorium. The fusion breeder could thus be used as a fuel supplier to synfuel plants. Demonstration synfuel plants could use ^{235}U, with later plants using ^{233}U after fusion breeders become deployed in fuel centers.

13. FUSION BREEDERS' IMPACT ON THE HEAVY-WATER COOLED AND MODERATED REACTOR DEVELOPED BY CANADA: THE CANDU

This reactor needs very little make-up ^{233}U on the thorium cycle (similarily for Pu on the U-Pu cycle). It has some safety advantages over LWRs because of the pressure tubes' integrity over large pressure vessels, and it has a higher availability because of on-line refueling. An almost inexhaustible fuel supply would make the CANDU reactor an attractive system for selling on the world market along with fuel services.

14. FUSION BREEDERS' IMPACT ON LWRS: THE CURRENT REACTOR OF CHOICE IN MOST COUNTRIES

A fuel supply from the fusion breeder, when mined uranium becomes too expensive, will assure LWR owners that their investment will be protected against the possibility of an expensive switch-over to another fission reactor type.

15. SUMMARY OF FUSION BREEDERS' ROLE RELATIVE TO FISSION REACTOR TYPES

If one asks what is the best fission power reactor type, the answer depends strongly on the need to breed fuel or not. Candidates for breeder fission reactors are:

1. LMFBR
2. GCFBR
3. MSBR
4. LWBR

The breeding ratio is best for reactors 1 and 2, and lowest for 3 and 4. Numbers 3 and 4 barely breed at all but are thermal reactors. For the long term, U.S. policy (as well as that of the U.K., France, U.S.S.R., and Japan) has been to rely on heavy use of the LMFBR. If an external source of fissile material existed such as ^{239}Pu or ^{233}U, and unlike ^{235}U, could be produced essentially independent of resources, then the choice of the best fission reactor types for long term heavy use could be examined in a new light. New reactor types might be considered with less changeover than would be the case if the reactor vendor production plants were at full capacity, since no new fission reactor orders have been placed for many years.

Without the virtual necessity to deploy the LMFBR, we could consider new and better strategies for fission reactor deployment as will be discussed in the next paragraphs. Rather than proceeding with the expensive deployment of LMFBRs (a recent nuclear news article reports the second generation commercial breeder in France, Super Phenix II, is expected to cost 40% more than an LWR, which is apparently only competitive with LWRs buying uranium at over \$300/lb according to the discussion at the end of Section 1), we could keep the breeder program active by designing a superior, cost-competitive breeder, but not deploy a series of inferior reactors to that of the French Super Phenix. If the French LMFBR turns out to be cost-competitive and needed, we could license the design here much like the French licensed the LWR (through FRAMATOM, from Westinghouse).

One can make the analogy to the supersonic transport. The French-British version, the Concorde, was of low technology (aluminum) and was expensive on a cost per passenger mile basis, but they proceeded with the project. The American version was based on titanium, was bigger, and would have been lower in cost per passenger mile, but we didn't proceed and in retrospect saved considerable money by building more efficient subsonic planes. A lesson may be learned from history by carefully studying the similarity between the supersonic transport and the LMFBR. I believe the LMFBR is a "bird in the hand" and nothing should be done to "take this bird out of the hand" until an alternate fuel source is assured, but just the same I believe we should also take seriously the very likely prospect for fusion providing this fuel source in a timely way and with more desirable characteristics. For the U.S. the light water reactor or slightly improved versions could be considered for long term use. Even such diverse reactor types as the graphite moderated-sodium cooled reactor should be reexamined.

The high temperature reactor of the HTGR or pebble bed type likewise could be reconsidered in the light of a new fuel source. The present government policy towards HTRs seems to be for process heat. The electricity application should be reexamined in light of no LMFBR. The question of a loss of cooling accident should be reexamined and HTRs and LWRs compared, as the HTRs seem to have much better safety features. The question of U-Pu or Th-U fuel cycle choice should be reexamined for the case of an external fuel source.

In foreign countries other reactor types could be considered with little change as the long term reactor to rely on. In Canada the CANDU is such an option. Canada should seriously consider the fusion breeder's relationship to their export market of the CANDU and fuel services. The CANDU could be built in the U.S. and surely should be given consideration. Not-invented-here syndrome, the problem of developing licensing standards, royalties, and industrial tooling would have to be considered carefully.

16. OVERALL SUMMARY

The purpose of the fusion breeder (fusion-fission reactor) is the production of fissile fuel for fission reactors. Fusion breeders whose blankets are designed using the fission-suppressed concept promise unusually good safety features as well as the ability to provide makeup fuel for a large number of fission reactors of the same nuclear power as the fusion breeder. This number, called the support ratio, is 12 for LWRs on the U-Pu cycle, 15 for LWRs using ^{233}U mixed with ^{238}U and recycling Pu (U-Pu cycle), and about 20 LWRs using ^{233}U mixed with thorium (thorium cycle). Even more heavy water- or gas-cooled graphite-moderated reactors can be supported. Such high support ratios and good safety results from the use of beryllium to multiply neutrons. If beryllium is not used, ^{7}Li can be used with about a 20% lower support ratio. The introduction of fusion breeders will require minimal changes in the fission fuel cycle because Pu and ^{233}U can fairly easily be substituted for ^{235}U.

The fusion breeder is primarily a fuel source and secondarily a power source. A fusion breeder can fuel 10–20 1 GWe LWRs while itself making 1 GWe. The high support ratio and the fact that the product is fissile fuel means a large number of fission reactors can be constructed and operated based on the knowledge of an assured fuel supply. This would allow utility planners to use mined uranium as long as it was economical and then switch over to fuel from the fusion breeders, rather than necessitate an early major commitment to fission breeders which, being prily power producers, must replace conventional fission reactors.

The critical path item in development of the fusion breeder is the neutron-producing fusion reactor. The breeding blanket and fuel cycle development are apparently modest extensions of similar developments for fission reactors.

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