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STATUS REPORT ON THE FUSION BREEDER

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ABSTRACT

The rationale for hybrid fusion-fission reactors is the production of fissile fuel for fission reactors. A new class of reactor, the fission-suppressed hybrid promises unusually good safety features as well as the ability to support 25 light-water reactors of the same nuclear power rating, or even more high-conversion-ratio reactors such as the heavy-water type. One 4000-MW nuclear hybrid can produce 7200 kg of ^{233}U per year. To obtain good economics, injector efficiency times plasma gain ($\eta_i Q$) should be greater than 2, the wall load should be greater than $1 \cdot MW\ m^{-2}$, and the hybrid should cost less than 6 times the cost of a light-water reactor. Introduction rates for the fission-suppressed hybrid are unusually rapid.

1. INTRODUCTION

Since the beginning of the fusion program, people have been contemplating the use of fusion neutrons to breed fissile material (^{233}U, ^{239}Pu) from fertile material (^{232}Th, ^{238}U). The rationale behind this contemplation is simply that uranium--the only source of fissile material today--is scarce; the few rich mineral deposits will be depleted rapidly, leading to mining of ever lower grades of ore and hence pushing prices ever higher. Consequently, any enterprise that is based on the use of uranium must find means to make better 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. The idea behind the breeder reactor is to absorb neutrons derived from fission in ^{238}U or ^{232}Th to produce as many or more fissile atoms than those consumed by fission, thus making use of all uranium (or Th) mined, rather than less than 1%. Thorium is abundant.

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Thus, neutrons from both fusion and breeder fission reactors can be used to produce fissile material at a cost competitive with that of mined uranium. The breeder uses initial inventories of fissile material, which puts some additional demand on uranium supplies during the introduction phase. The fusion reactor needs exceedingly little uranium, and 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 (the light-water reactor, LWR, for example) or by using ^{238}U to both breed and fission ^{239}Pu 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 hybrid 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 is partly derived from Refs. 1 and 2. The introduction dates for the hybrid will be discussed later.

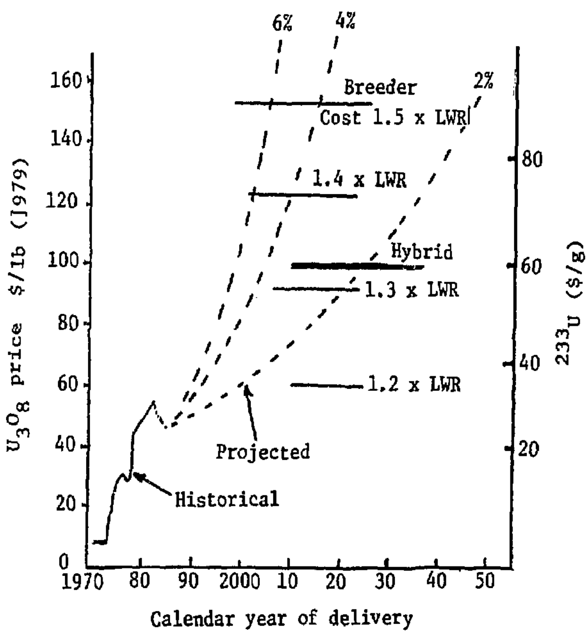


Fig. 1. Future price of uranium or equivalent 233U. The price of mined uranium will increase due to resource depletion until eventually either breeder reactors, hybrids plus conventional reactors, or both become economical.

2. NUCLEAR REACTIONS

The two fissile material breeding reactions are given below:

$$n + {}^{232}Th \rightarrow {}^{233}Th \xrightarrow[22m]{\beta-} {}^{233}Pa \xrightarrow[27d]{\beta-} {}^{233}U \quad ,$$

and

$$n + {}^{238}U \rightarrow {}^{239}U \xrightarrow[24m]{\beta-} {}^{239}Np \xrightarrow[2.4d]{\beta-} {}^{239}Pu \quad .$$

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

$$D + T \rightarrow n(14.1\ MeV) + {}^{4}He(3.5\ MeV) \quad .$$

The T breeding reactions are:

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

and

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

The first reaction occurs for slow neutrons, while the second occurs only for fast neutrons and not only breeds T, but also preserves a neutron for further breeding. Thus, it is uniquely suitable for fissile breeding (as will be discussed later).

3. IDEAL BLANKET CONFIGURATIONS

The neutron from the D-T reaction is of spectacularly high energy and can be used to produce several slower neutrons. As examples, Table I shows how many neutrons are ultimately produced from one 14-MeV neutron in an infinite medium.[3]

^{238}U is by far the most effective neutron multiplier due to the fast fission reaction, which is less important in ^{232}Th. Be is unique in its large neutron multiplication, while nonetheless resulting in essentially no radioactivity, whereas U and Th do. Li is unique, as stated before, in that it breeds T and still preserves one neutron for breeding. Lead is one of the better neutron multipliers, but after subtracting one neutron for breeding T, it is a significantly poorer multiplier than Be and ^{7}Li.

TABLE I. Neutron Multiplication in an Infinite Medium Per 14-MeV source Neutron.

	^{238}U	^{232}Th	Be	^{7}Li	Pb
Number of neutrons captured (produced)	4.2	2.5	2.7	2.0[a]	1.7

[a]Of the 2.0, 1.0 is an equivalent neutron represented by a bred triton.

Two classes of hybrids emerge based on the different characteristics of the multiplier: fast-fission and fission-suppressed. The fissile material to be bred (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.

The energy released in the blanket divided by 14 MeV is the energy multiplication M of the blanket. F is the number of fissile atoms bred per fusion neutron. The numbers in Table II are values derived from design studies where many practical considerations reduced the breeding from ideal performance. The breeding rate per unit of fusion power and per unit of power in the blanket are also given in Table II. In a recent report, Jakeman[4] discusses how blanket types obtain similar performances, and he also recommends using Be or ^{7}Li in a fission-suppressed mode.

One can get an idea of breeding potential by examining a number of ideal infinite-medium examples as shown in Table III. More examples are given and discussed in Ref. 3.

In practice, the results are usually degraded due to a number of effects such as:

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 Th-U cycle Multiplier-- Be, ^{7}Li, Breeder-- ^{232}Th, ^{6}Li
Energy multiplication, M	11.0	5.0	1.5
Fissile breeding, F	1.5	0.8	0.7
F/M	0.14	0.16	0.47
Breeding rate			
kg/MW_{fusion} year	6.6	3.5	3.1
kg/$MW_{blanket}$ year	0.77	0.88	2.57

TABLE III. Infinite Homogeneous Results per 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	2.72 T	22
4	^{9}Be + 5% ^{232}Th	2.66 ^{233}U	30
5	^{9}Be + 1% ^{238}U	2.4 Pu	29
6	^{7}Li + 0.8% Th - 0.02% ^{6}Li	0.8 ^{233}Pu + 1.1 T	17
7	Pb + 5% ^{6}Li	1.74 T	18
8	Pb + 5% Th	1.58 ^{233}U	21

- Parasitic neutron capture in structural materials and coolants,
- neutron leakage,
- lack of complete wall coverage,
- fissioning of bred fissile material before removal,
- decay of tritium before removal, and
- heterogeneous effects (sometimes good).

4. ENGINEERED BLANKET CONFIGURATIONS

The geometry of the breeding blanket is shown in Fig. 2.

An example of a fast-fission blanket based on the U-Pu fuel cycle is shown in Fig. 3.* The fuel form is the ceramic U_3Si and is helium-cooled. This design, based on the so called standard mirror, is fully discussed in Ref. 5, and is summarized in Ref. 6.

The performance parameters for this blanket are given in Table IV. Note the significant loss in breeding due to the low wall coverage in the design of only 86% resulting from space used for neutral-beam ports and for ports for the open ends of this standard, yin-yang coil mirror geometry. For the tandem mirror, we expect the central-cell solenoid to be almost 100% covered with blanket. The loss due to the ends may be as low as 5%, thus giving a very high coverage of 95%.

Various blanket types were considered in design studies of the Tokamak configuration.[1] A pressure cylinder blanket concept similar to the one shown in Fig. 3(b), but for pure fusion, was worked out for the Tokamak.[7] This configuration is shown in Fig. 3(c).

The geometry of the tandem mirror hybrid is 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. 5 and discussed in Ref. 2. The performance for this blanket is given in Table V.

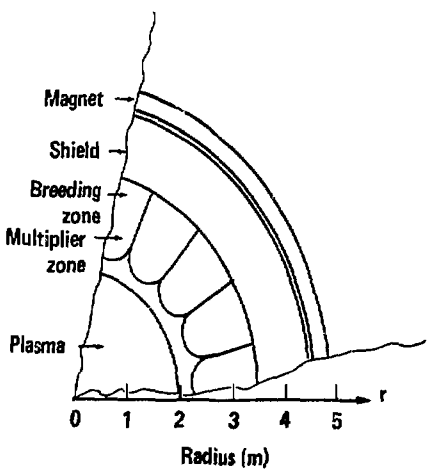


Fig. 2. Breeding blanket geometry

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

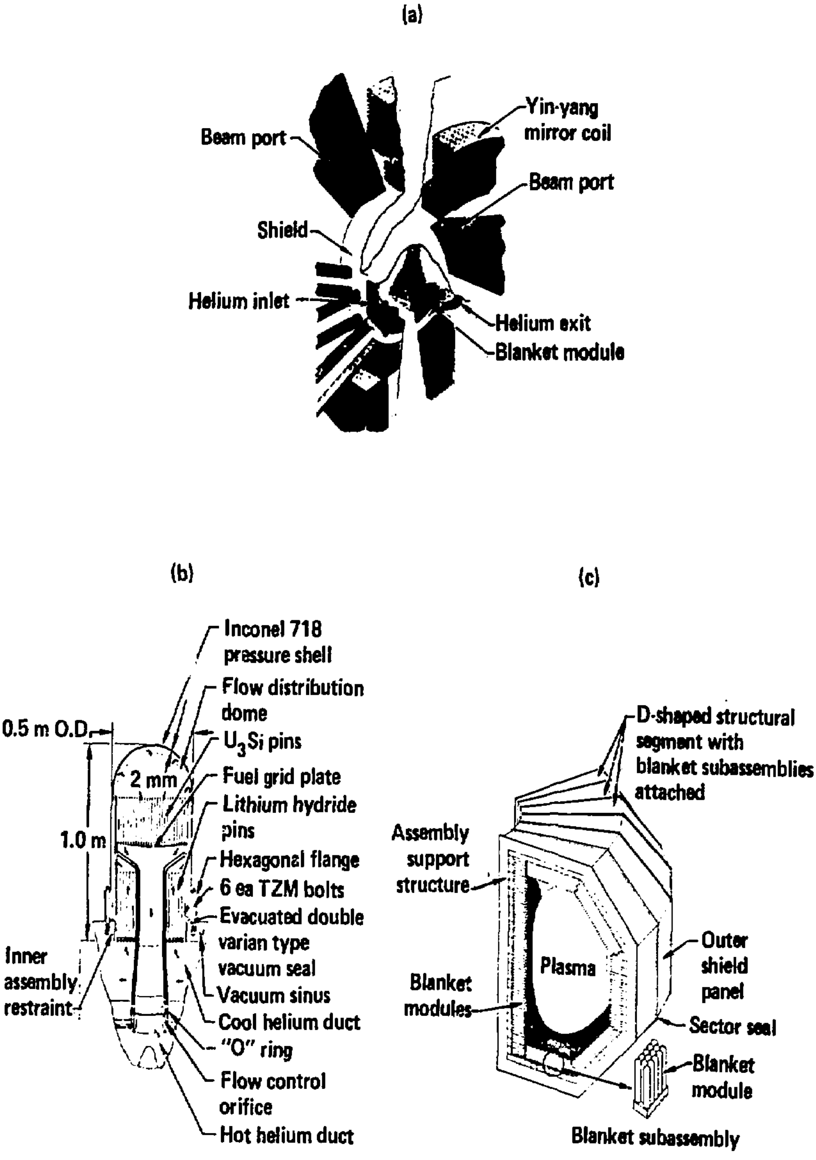


Fig. 3. Fast-fission blanket design using U^3Si: (a) the geometry of the standard mirror configuration, (b) the helium-cooled blanket modules using a pressure cylinder, and (c) the geometry of the Tokamak configuration.

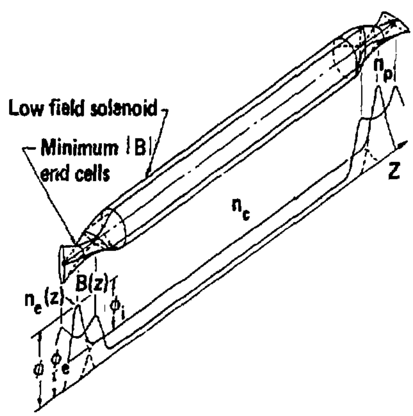
A fission-suppressed blanket design (Table II) using nonfissioning neutron multipliers (Table I) could use Be or ^7Li for the multiplier and could be cooled with He, Li, or molten salt. The fission-suppressed blanket should have materials arranged as in Fig. 6.

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 per 14-MeV neutron.

The front part of the blanket should contain mostly ^7Li or Be. A small amount of ^6Li should be there to outcompete structural materials and Be for slow neutron capture. To minimize fast fission (a safety precaution) thorium should not be present at all. In the back part of the blanket, where the 14-MeV incident flux has been moderated and multiplied into more of the slower neutrons, ^6Li and thorium should be placed in sufficient



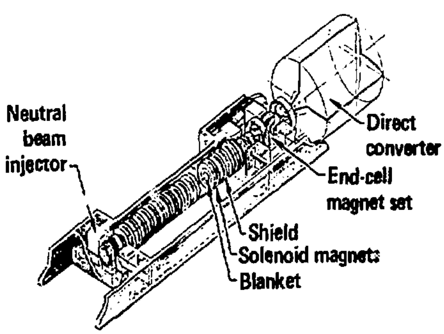


Fig. 4. Tandem mirror hybrid configuration: (a) the plasma shape determined by the magnetic flux surface and the corresponding magnetic-field, plasma-density, and potential profiles for the conventional tandem plasma mode; and (b) the main components of the hybrid reactor.

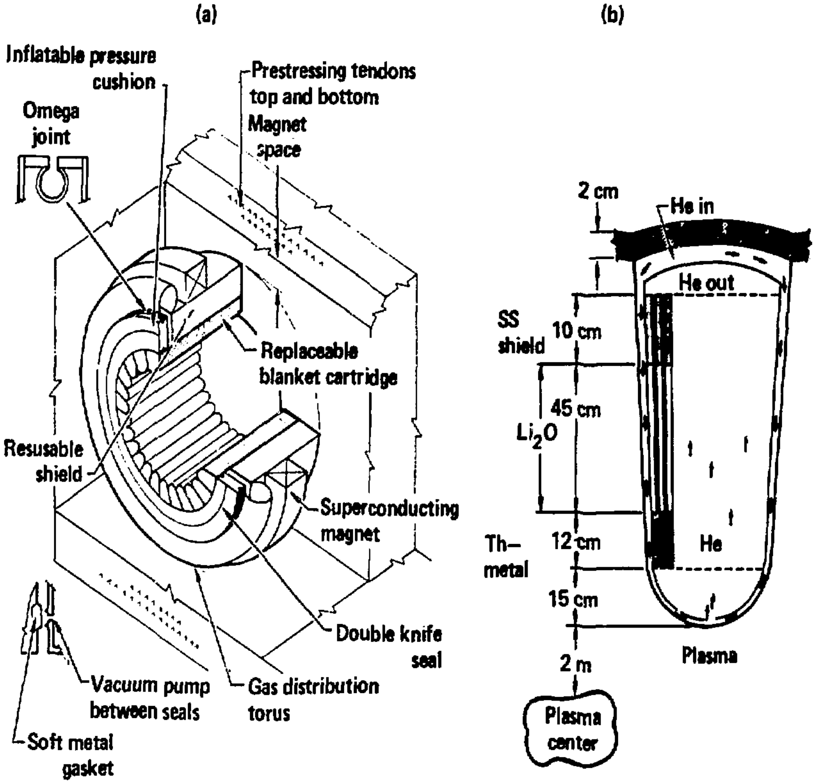


Fig. 5. Fast-fission metallic-thorium blanket: (a) the blanket module and (b) the submodule.

concentration to outcompete structural materials for slow neutrons. Bred ^{233}U and protactinium must be removed often to prevent captures in ^{233}U. We have prepared an example of a molten-salt case (Fig. 7).

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

The performance of this design is given in Table VI. 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 be designed that will need no active after-shutdown cooling systems, 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 blanket have over fast-fission blankets is a very high support ratio. Support ratio is defined as the number of fission reactors for which a hybrid can supply makeup fuel, when the nuclear power of the hybrid and of each fission reactor is the

TABLE V. Performance of the Fast-Fission Thorium Blanket.

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

TABLE VI. Performance Parameters of Fission-Suppressed Blanket.

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

[a]Atoms bred per 14-meV neutron.

same. The advantage of a high support ratio is that few hybrids need to be built, and the ones that are can be located in a few nuclear fuel centers which, because they can be well guarded and have international inspection, would 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 each 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 to 100 for advanced converter reactors such as the CANDU. The ideas behind the fission-suppressed blanket are discussed further in Ref. 11.

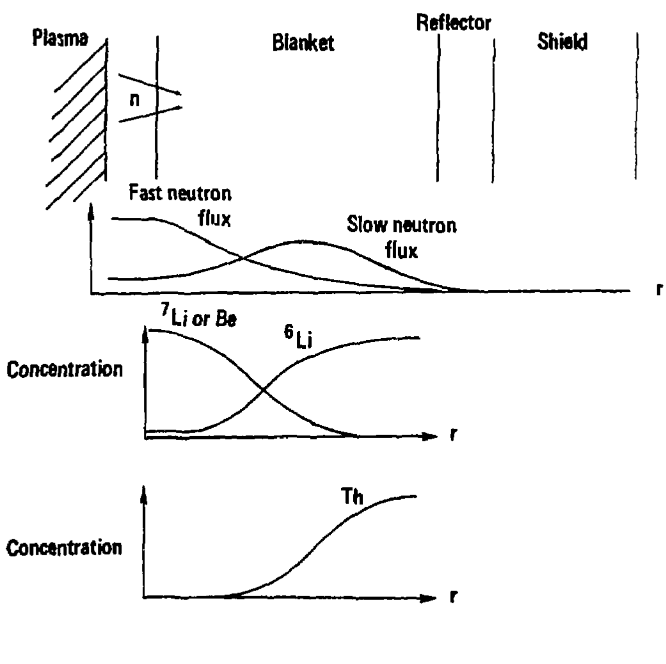


Fig. 6. Anatomy of a fission-suppressed blanket.

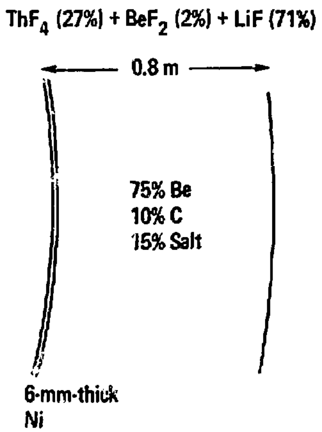


Fig. 7. Example of a fission-suppressed blanket cooled by molten salt.

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. 4. The basis for the design was the conventional tandem mode (sometimes called the thermal 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.

The design parameters that resulted from the analysis are given in Tables VIII and IX.

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 h

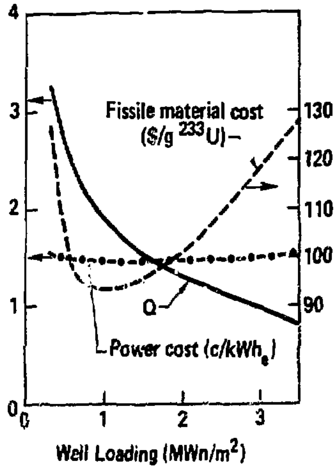


Fig. 8. Q versus wall loading tradeoff.

In order to see the sensitivity to Q and Γ separately, these parameters were varied independently of each other. That is, of course, not a real model and is sometimes called a "no-cost Q enhancer". The results shown 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 LWR's, 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.

TABLE VIII. Fusion Driver Performance Parameters.

	Molten-salt blanket
Q	2.2
Γ, MW/m^2	2.0
$R_{first\ wall}$, m[a]	2.1
$R_{solenoid\ magnet}$, 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 (LWR's) (at 303 kg/GW_e yr) of 4000 MW nuclear supported	25

The conclusions that can be drawn from Fig. 10 are threefold:

- *The hybrid can supply fuel to LWR's so that their electricity costs* are increased due to fuel cost by only about 25% for Q values of 2 or more.

- Q values need be 2 or more for hybrids but must be 15 to 20 or more for pure fusion.

- 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 points can be seen another way by looking at cost estimates. The hybrid designed with the fission-suppressed blanket discussed above was estimated to cost $6.5 billion for a unit of 4000 MW of nuclear power producing 7200 kg of ^{233}U each year and supplying the fuel makeup needs for 25 LWR's of the same size. This LWR has a 1280-MW_e 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. These 25 LWR's then would cost an estimated $28.8 billion. The capital cost ratios are interesting where, by the symbol C, we mean cost per unit power:

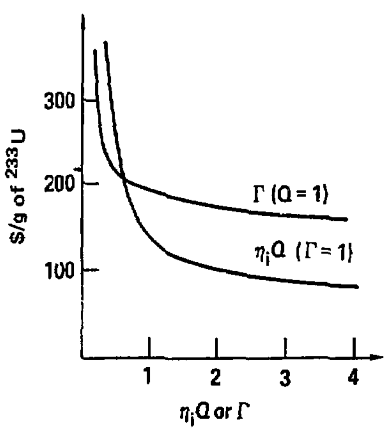


Fig. 9. Cost of fissile fuel versus niQ and r. When the wall load r is varied, *Q is kept fixed at 1*; when Q is varied, r is kept fixed at 1.

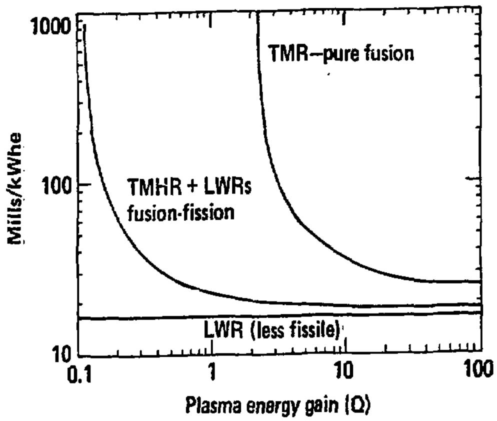


Fig. 10. Cost of electricity versus Q for the hybrid with its LWRs and for a pure-fusion tandem reactor (TMR).

$$\frac{C_{hybrid}}{C_{LWR}} = \frac{6.5}{1.15} = 5.7 \quad ,$$

and

$$\frac{C_{hybrid} + 25\ \mathrm{LWR's}}{C_{LWR}} = \frac{6.5 + 28.8}{28.8} = 1.23 \quad .$$

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. We conclude these argyments by noting that fusion development might find a practical use as soon as the following conditions are met:

1. $\eta_i Q > 2$
2. $\Gamma > 1$
3. Wall coverage $\gtrsim$ 90%
4. Capacity factor $\gtrsim 2/3$
5. $C_{hybrid}/C_{LWR} \lesssim 6$
6. The demand for LWR fuel drives the price of uranium sufficiently high (maybe as low as \$200/kg)

6. INTRODUCTION RATES OF THE HYBRID AND LWRs

As mentioned before, the fission-suppressed hybrid 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, and the large LWR part will be well known by the date of hybrid introduction. With a support ratio of 25 (Th-^{233}U cycle), we could build over 20 LWRs for each hybrid if first core-fuel loadings were provided by ^{235}U. This might put a strain on uranium resources. These initial cores could be provided by the hybrid with

TABLE X. LWR and Hybrid Parameters for the Introduction Scenario.

LWR	1000 MW_e
	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

an attendent slower LWR construction rate than 20:1. As an illustration, I have constructed a purely hypothetical introduction schedule designed to supply first cores and makeup fuel for 210 LWRs at 1000 MW_e each on the Th-U fuel cycle. The key assumptions are given in Tables X and XI.

The results of this hypothetical introduction rate are shown in Fig. 11.

The first machine was sized at 200 MW_{fusion} because that was close to the value chosen for the Tandem Mirror Next Step (TMNS) study.[15] By the year 2018, just 12 years after introduction of the first commercial hybrid, 10 LWRs can be introduced per year. Only 7 hybrids are needed to produce this introduction schedule.

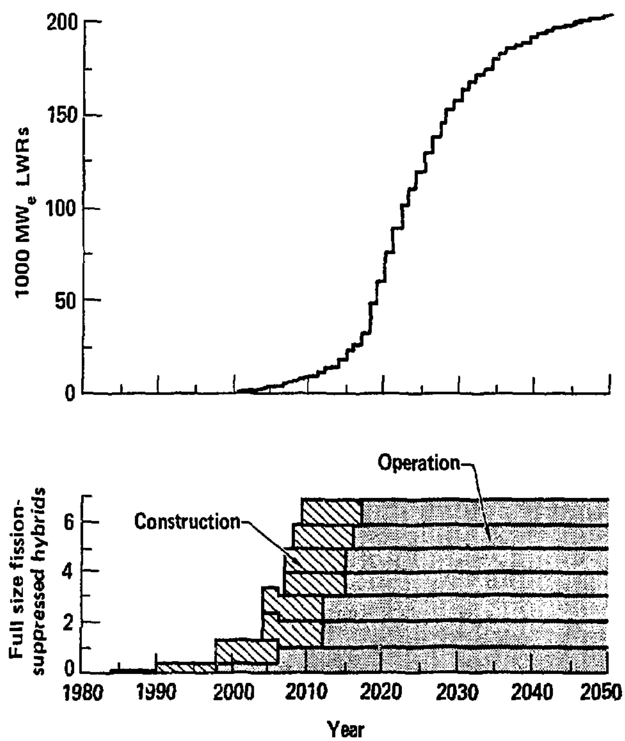


Fig. 11. Introduction rates of LWRs and their hybrid fuel suppliers.

TABLE XI. Hybrid Introduction Rate Assumption.

Number and Size	Start construction (year)	Begin fuel production (year)	Begin fueling new reactor (year)	LWR fueling (tonnes/year)
1-200 MW_{fusion} 1/4 blanket coverage 30% capacity factor, (CF)	1984	1990 (phased out by 1998)	1992	0.05
1-1000 MW_{fusion} full blanket coverage; CF-60%	1990	1998 (phased out by 2006)	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	43.2
1-2700 MW_{fusion}	2009	2017	2019	50.4

The delay time from the introduction to the supply of fuel to a significant number of reactors is apparent from Fig. 11. Small quantities of fuel (50 kg/yr) can be produced by 1990, but it will be 2018 before we have enough fuel for a significant number of reactors (~30). After 2018 the rate is sufficiently large. The schedule could be foreshortened if a sense of urgency should develop. Recently a group from the University of Wisconsin and Karlsruhe[10] studied hybrid introduction rates; they find that hybrids of the fission-suppressed type (high support ratio) are best from an introduction standpoint. Also, they find it necessary to introduce them before the year 2020. It would be instructive to expand the present hypothetical model in order to compare it to their various conclusions.

7. FUTURE WORK

A study of the fission-suppressed hybrid based on the tandem mirror is underway at the Lawrence Livermore National Laboratory, with portions of the work being carried out by industrial firms. The feasibility of the fission-suppressed hybrid concept is the paramount goal of this study. Further goals are given in Table XII.

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

ACKNOWLEDGMENTS

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