Technical Benefits of a Non-Tritium Breeding Hybrid Reactor

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FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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INTRODUCTION

The fusion-fission hybrid reactor consists of a fusion reactor and associated blanket which contains fertile and/or fissile material. It is an extremely versatile device because it may be designed to fulfill a variety of roles in the power economy. Among the most important ways in which a hybrid may be utilized are:

Transmutation of nuclear wastes
Fissile fuel production
Electrical power production
Synthetic fuel production

The hybrid draws its versatility from the fact that a 14 MeV fusion neutron will fission the heavy metal in the blanket, and the ensuing spectrum may be tailored by design for a specific purpose. It may be noted that two or more of the possible roles in a single reactor may be the optimum design. In a hybrid reactor, with the exception that fissile and/or fertile material would be found in the blanket, all the remaining components would be the same as in a pure fusion device.

It is generally assumed that first generation fusion reactors will be fueled by a mixture of deuterium and tritium. Since tritium occurs in nature only in trace amounts, it will have to be produced artifically, and in most conceptual hybrid reactor designs tritium is produced in the blanket surrounding the plasma by neutron reactions with lithium. Here, hybrid systems which do not produce tritium in the blanket shall be examined in order to determine those areas some advantages could possibly be obtained by devoting the entire blanket to one or more of its other uses, i.e., transmutation, power and/or fissile fuel production. It is not intended to suggest that the areas covered here would indeed be a definite advantage if incorporated in a hard engineering design. This can only be determined after a detailed engineering and economic analysis. The purpose will simply be to delineate for future study those areas in which advantages in the design and deployment of hybrid reactors might be realized if tritium is not bred in the blanket.

Historically several authors(1,2) have suggested symbiotic systems in which a fission reactor would supply all or part of the tritium needs. Other authors(3,4) have investigated the availability of tritium from production reactors and other sources, and the difficulties of converting existing reactors into tritium producers has also been considered.[4] Hybrid fuel cycle analysis[6] in which tritiumless hybrids were considered have also been investigated. Recently, a conceptual hybrid design[5] which did not produce tritium was developed, and for this design the tritium source was not specified. Likewise, for the purposes here the source of tritium is not specified; for it is immaterial in delineating those areas of study with which this is concerned.

The four main areas subject to significant change are:

Product production
Transmutation rate
Blanket design
Tritium handling equipment

Product Production

The removal of the tritium production from the blanket will result in an enhanced production of fissile fuel and/or energy. This is simply a result of more neutrons being available for use. The processes will be discussed in this section.

In the fusion process atoms of deuterium and tritium are heated and confined in a plasma where they fuse, thus liberating energy, a neutron and a resultant helium atom according to the following equation:

$$_1D^2 + {}_1T^3 \rightarrow {}_2He^4 + n + \text{energy (17.6 MeV)} . \qquad (1)$$

The process is the same, regardless of the reactor concept; that is, a magnetic or inertial confinement system. The neutron carries 14.1 MeV of kinetic energy into the blanket surrounding the plasma. The neutron is moderated and absorbed, and thus releases its energy into a working fluid which eventually drives a turbine-generator for the production of power.

If tritium is produced in the blanket, lithium is the breeding material, and tritium is produced according to the following reactions:

$$_3Li^7 + {}_0n^1 \text{ (fast)} \rightarrow {}_1T^3 + {}_2He^4 + {}_0n^1 \qquad (2)$$

$$_3Li^6 + {}_0n^1 \rightarrow {}_1T^3 + {}_2He^4 . \qquad (3)$$

Not all neutrons from the plasma are absorbed in the lithium. Some are lost through leakage, while others are absorbed in structural material. Thus, in order to produce a tritium breeding ratio of one, which implies that the amount of tritium produced in the blanket equals that consumed in the plasma, some form of neutron multiplication must occur. Often the fast neutron reaction with $_3Li^7$ (Equation 2) which produces both a tritium atom and a neutron, which may be absorbed in $_3Li^6$ (Equation 3), is sufficient to achieve breeding ratios of one. If not, special materials such as lead and beryllium which have large probabilities for multiplying the fast neutrons from the plasma through reactions in which two or more neutrons are emitted (n,2n and n,3n reactions) for each fast neutron absorbed are used in the blanket design.

In a hybrid device the blanket contains fertile and/or fissile material, for example, uranium and/or thorium. Because of the high energy of the fusion neutron, fission may occur in U^{238} and Th^{232} which are non-fissionable to slow neutrons. The probability for fission in Th is much lower than that for uranium, and thus in designs which use Th as the fertile fuel, lead or some other material is often used as the neutron multiplier rather than the fission process.

The fast fission of uranium occurs according to the following equation:

$$\begin{aligned} &n(\text{fast}) + U^{238} \rightarrow 2 \text{ fission fragments} \\ &+ \sim 5 \text{ neutrons} + \text{energy } (200 \text{ MeV}) \ . \end{aligned} \qquad (4)$$

Note that with each fission the 14 MeV carried by the neutron has been multiplied by a factor greater than 10. Not all fusion neutrons produce fission however, but still there is the probability of undergoing neutron multiplication through n,2n and n,3n reactions in uranium or other materials. Once the neutrons produced from fission and other sources are degraded in energy to below ~ 2 MeV, the principal reaction is capture. The important reaction is the capture in uranium for the production of plutonium in the U-Pu fuel cycle

$$_0n^1 + {}_{92}U^{238} \rightarrow {}_{92}U^{239} \xrightarrow{\beta-} {}_{93}Np^{239} \xrightarrow{\beta-} {}_{92}Pu^{239} \qquad (5)$$

and the capture in Th for the production of U^{233} in the U-Th fuel cycle

$$ {}_{0}n^{1} + {}_{90}Th^{232} \rightarrow {}_{90}Th^{233} \xrightarrow{\beta-} {}_{91}Pu^{233} \xrightarrow{\beta-} {}_{92}U^{233} \, . \quad (6) $$

A particular design may chose to enhance power production by increased fission in the produced Pu^{239} or U^{233} or possibly in U^{235} or Pu^{239} which was present in the initial inventory of fertile fuel.

Of particular importance is to note that fissile fuel production and fission requires neutrons, and if tritium is produced in the blanket, the reactions noted in equations 2 and 3 are in direct competition with these processes. The result is decreased power and/or fissile fuel production. Sample cases from the literature will give an indication of the reduction in fissile fuel and power production that can be expected between non-tritium and tritium producing reactors.

In Table 1 are the results for the TDHR(7), a small tokamak demonstration hybrid reactor. In one case the blanket contained only helium cooled UO_2 rods. In the second case, part of the uranium was removed and was replaced with Li_2O.

The TDHR was a small reactor and did not contain UO_2 in the inner blanket, thus a considerable number of neutrons were lost. In the tritium breeding case, liquid lithium was placed in the inner blanket complementing the Li_2O in the outer blanket. The UO_2 contained natural uranium. Note there is a considerable reduction in both power and fissile fuel production.

Another series of calculations have been made(8) in which parametric studies were done to determine the effect on Pu^{239} breeding in hybrid blankets and without tritium breeding. Sample results are shown in Table 2.

In these cases the blanket completely surrounded the plasma. Note that the tritium breeding ratio in those cases with lithium did not exceed one. If the design had been changed so that the breeding ratio was greater than one, there would have been an even greater reduction in fissile fuel production and power multiplication.

The increased production of power and fissile fuel appears to be a significant technical advantage. Whether

TABLE 1

FISSILE FUEL AND POWER PRODUCTION FOR TDHR

(REF. 7)

Fuel	Fissions Per Fusion	Tritium Atoms Per Fusion	Pu Atoms Prod. Per Fusion Net	Pu Production kg/yr	Average Blanket Power MWe
UO_2	.267	-	1.16	740	780
UO_2/ Li_2O	.200	1.10	.54	330	560

TABLE 2

Pu BREEDING IN BLANKETS WITH AND WITHOUT TRITIUM BREEDING

(REF. 8)

U/Pu Zone Thickness (cm)	^{239}Pu Enrichment	Lithium Zone Thickness (cm)	Pu^{239} Production Per Source Neutron	Tritium Breeding Per Source Neutron	Fusion Power Multiplication in Blanket
20	0%	40.	1.85	.38	7.05
60	0%	-0-	2.67	-	8.28
20	3%	40.	2.007	.703	20.22
60	3%	-0-	4.433	-	40.35

it remained so would depend on the availability and cost of tritium.

Transmutations

There have been a number of studies[9,10,11,12,13] in which CTR devices have been the driver for the transmutation of actinides or fission products. The references cited are not all inclusive, but serve as examples of the type of studies that have been made. In each of these studies it was assumed that the fission products and/or actinides could be partitioned.

The transmutation of an element involves either a neutron capture reaction or the fissioning of an actinide. Thus, the production of tritium as noted in Equations 2 and 3 is also in direct competition with these processes. Thus, elimination of the tritium production requirement will increase the transmutation rate in a hybrid, and in this section we shall examine some previous studies to determine the effect on the transmutation rate.

In the earliest study,[10] a tokamak device was used as the fusion driver. The device had a major radius of 12 meters and a blanket inner radius at 5 meters. The first zone, 5 cm thick, contained lithium for tritium production. The second region contained a moderator and actinides which were to be fissioned in a thermal flux. The integral fusion neutron source was 3.3×10^{29} neutrons/year which resulted in the fissioning of .81 MT (2×10^{27} atoms) of americium and curium per year. Note that a large number of fusion neutrons did not produce fission.

The tritium breeding ratio for this device was .6, and thus it was not self-sufficient. The authors note, however, that the introduction of the lithium zone depresses the thermal flux by a factor of 5. This is highly significant since most of the fissions occurred in the thermal flux. If the lithium zone were increased in order to have a tritium breeding ratio equal to one, the transmutation rate would decrease dramatically. Conversely, if the lithium zone was removed, we could expect the transmutation rate to increase by a factor of 5, and perhaps, even more, as a result of fast fission in the actinides since this zone would now be directly exposed to the 14 MeV flux.

A second study[12] which we shall consider is a hybrid device in which the fusion driver is a laser. In this system the blanket is divided into actinide containing and Li_2O containing segments. About 41% of the fast 14 MeV neutrons enter an actinide containing region and the remaining 59% enter a Li_2O region. The tritium breeding ratio is .73 and the initial actinide depletion rate is 7.26 MT/year. Here also, if the tritium breeding ratio is increased to 1, the initial depletion rate would fall to about 2.64 MT/year. However, if tritium production were removed, the initial actinide depletion rate would increase to about 17.7 MT/year. These results are approximations based on ratios of wall areas exposed to the 14 MeV flux to the respective depletion rate.

A second possibility for transmutation in a hybrid would be to employ a fission plate containing depleted uranium for neutron production and the subsequent utilization of these neutrons for the transmutation of selected, especially toxic, fission fragments or actinides.

We are not aware of any study in which this concept has been explored; however, an estimate of the transmutation rate may be made by a simple calculation. We assume because of fast fission (~ .5 per fusion neutron) that on the average there will be about 3 neutrons in the blanket per fusion neutron. In one study(13) using a pure fusion device, one case resulted in a transmutation rate for ^{90}Sr and ^{129}I due to capture, of ~ .5 atoms/per fusion neutron. Thus, in a hybrid device we could expect ~ (3) x (.5) = 1.5 transmutations per fusion neutron. However, because of the .5 fissions we have produced ~ 1 fission fragment per fusion neutron for a net loss of .5 fission fragments. Note, however, that on the average the new fission fragments will not be as toxic as those selected for transmutation. If, in this device, tritium is bred, the transmutation rate will decrease because of the depressed flux and loss of neutrons to the tritium breeding process.

Thus, in the case of transmutation, significant benefits arise from the elimination of tritium production. In fact, it appears that if enough tritium is bred so that the reactor is self-sufficient, the transmutation rate is depressed to the extent that only marginal benefit can be expected.

Blanket Design

The blanket, as noted earlier, of the hybrid reactor contains the fissile and/or fertile material and a working fluid for the removal of energy deposited. If the blanket produces tritium, then lithium in some form will be present.

Several conceptual blanket designs have been suggested for various hybrid devices. Typically, uranium and thorium are in the form of oxides or carbides, but sometimes are used in molten salts. Lithium is used as a liquid metal, in salts, or oxides. The working fluids have been the liquid lithium, molten salts and helium. Blanket designs using combinations of these materials try to simultaneously satisfy several blanket design criteria:

Tritium breeding ratios greater than one
Large power and/or fissile fuel production
Structural stability
Long blanket life
Adequate cooling
Easy access for maintenance

Meeting these often competing criteria simultaneously leads to compromise and complex designs.

Examples of two blanket modules(9,10) are shown in Figures 1 and 2. The modules were designed for mirror hybrids. The module in Figure 1 is designed for power production while the module in Fig. 2 produces both power and fissile fuel. Attempts to improve power and fissile fuel production can lead to even more complicated designs, for example, the blanket design for the Princeton Tokamak Fusion Fission Reactor(16) has three coolants; He, H_2O and molten salt and two separate power producing zones, one containing natural uranium and the other containing plutonium. Another blanket design(17) uses both the $U-Pu^{239}$ and $Th-U^{233}$ fuel cycles in addition to producing tritium breeding ratios greater than one.

Relaxing the criteria that the blanket breed tritium could possibly lead to similar blanket designs, for example, as shown in Figure 3. This module(14) was designed for power and plutonium production. Tritium breeding was not considered.

In addition to simplifying blanket design, removing tritium production shifts the engineering of the blanket toward known technology and materials, namely that gleaned from fission reactor technology. Alternatively, coolants and structural materials that were once

Figure 1. Power Producing Mirror Hybrid Blanket Module (From Reference 14)

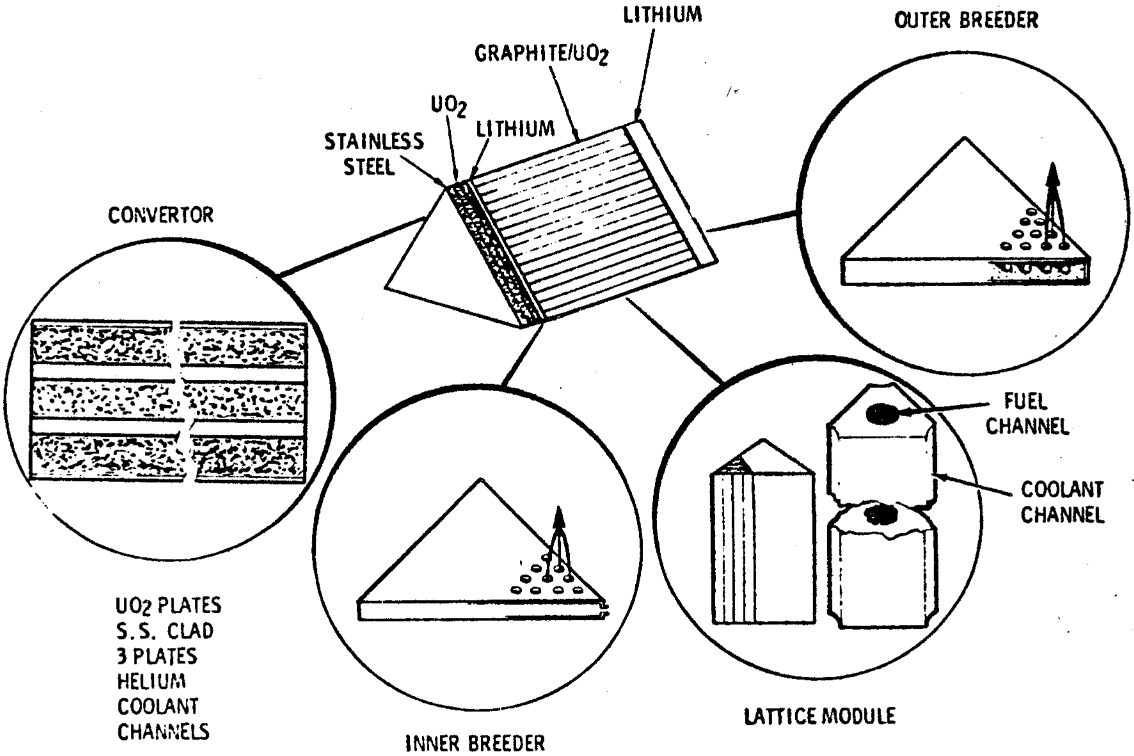
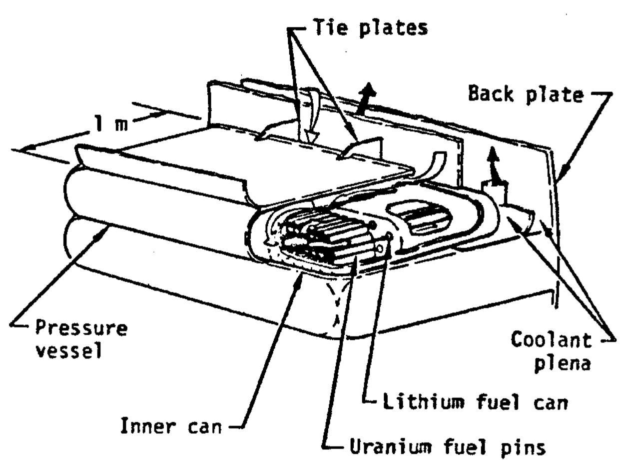


Figure 2. Power and Fissile Fuel Producing Mirror Hybrid Blanket Modules (From Reference 15)



rejected because of some undesirable characteristic in lithium or molten salt could be reconsidered. Tritium permeation through the blanket and lithium fires would be negated, relaxing material and safety constraints.

Simplicity of design, relaxed material and safety constraints, a better known technology, and a wider choice of materials could possibly lead to an earlier introduction of the hybrid into the energy economy. But as noted earlier, these speculations can be proven valid only through detailed engineering and economic analysis.

Tritium Handling

The tritium which is bred in a reactor blanket has, of course, to be removed. Usually the tritium is found in the working fluid and it is removed when the fluid leaves the reactor to deposit heat in the heat exchanger. The working fluid may be liquid lithium, a molten salt or a gas. For a gas coolant, the tritium bred in the blanket permeates the coolant tubes and enters the gas stream, where it is carried to a collector outside the blanket.

The tritium removal system for the blanket, however, is only one of several tritium handling systems associated with the reactor. Examples are the tritium storage system, fuel gas injection system and fuel gas distillation system. These systems and others required for a pure fusion reactor have been identified and it would be expected that for a hybrid, the systems would remain relatively the same.

In order to determine the technical advantages of a non-tritium breeding blanket, it is necessary to determine the reduction in the tritium inventory and tritium handling systems as compared to a tritium breeding blanket. The tritium handling system of a reactor design which uses liquid lithium as a working fluid will be examined in this section.

The UWMAK-I[19] tokamak power plant is one such conceptual design which uses liquid lithium as the working fluid. The tritium flow and inventory schematic (reference 20) is shown in Figure 4. If one examines Figure 4, it may be noted that only the tritium getter system for bred tritium may be eliminated if tritium was not bred. The divertor lithium would still be required to trap spent deuterium and tritium fuel.

Figure 3. Blanket Module for a Non-Tritium Producing Hybrid Reactor (From Reference 18)

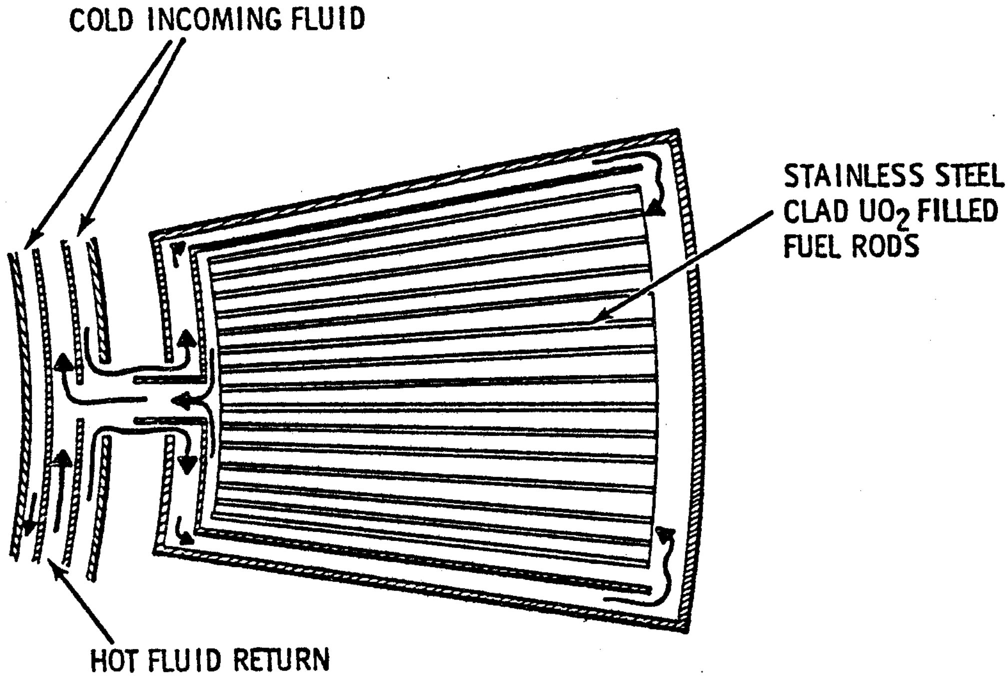
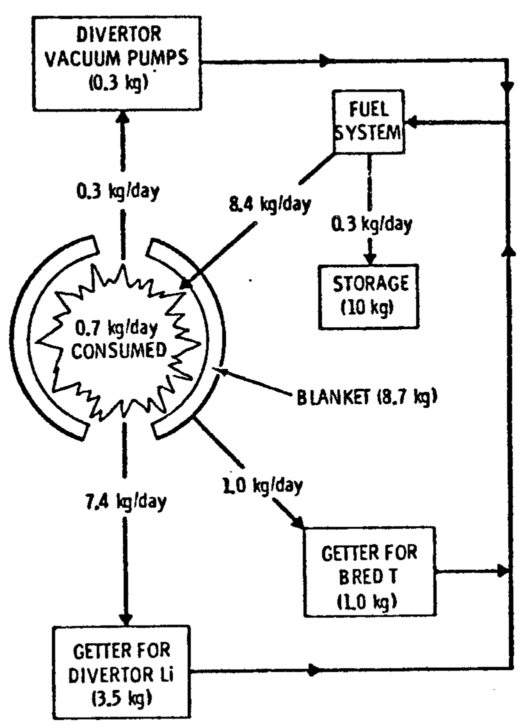


Figure 4. Tritium Flow and Inventory Schematic for UWMAK-I (From Reference 20)



The total plant inventory[20] of tritium is 23.5 kg of which 9.7 kg is blanket inventory. Thus, removal of the tritium producing blanket would reduce the inventory by less than 50%.

Similar situations[20] are found in systems which use helium as the working fluid, which carries the bred tritium.

Thus, any technical advantage in terms of tritium handling equipment and safety appear marginal if tritium is not bred in the blanket. There is to be sure some reduction in plant cost simply because less equipment would have to be purchased and developed.

Conclusions

The technical advantages of a non-tritium producing hybrid reactor have been investigated. The areas which could possibly benefit have been delineated. The advantages appear to be increased fissile fuel and power production, greater transmutation rates, simpler blanket designs and in some cases, relaxed material requirements and greater safety. There is also some reduction in tritium handling equipment and inventory. Detailed engineering and economic analysis covering not only the hybrid, but also tritium source and cost will have to be made, however, before more definite statements can be made about the viability of a hybrid which does not produce its own tritium.

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