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STRUCTURAL CONCERNS IN FUSION HYBRID REACTORS

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The concept of a fusion-fission hybrid reactor has been considered a possible application of the fusion program since the early 1950s. Three general modes of operation have been proposed. "Symbiotic" systems would breed fuel for fission burner reactors. "Hybrid" reactors would rely upon a fissioning blanket to also produce additional energy. "Augean" reactors would burn fission reactor wastes with fusion neutrons. A consensus appears to be emerging that the best mode of fusion-fission reactor operation would be that of a "fuel factory" with the production of electricity as a major and necessary by-product.

It appears that very high hybrid blanket performance may be obtained. The fusion neutron energy incident upon a uranium-based hybrid blanket may be multiplied by a factor of 10 or more by fission of ^{238}U by the 14 MeV fusion neutrons. The ^{239}Pu production rate can be as high as 6 kg/yr per MW of fusion power (0.8 kg/yr per MW_t). With a thorium-based hybrid blanket a multiplication of about 3 and a ^{233}U production rate of about 3 kg/yr per MW of fusion (1.5 kg/yr per MW_t) are possible. The lower breeding performance of thorium blankets is balanced by the higher value of ^{233}U as a fuel for thermal burner reactors.

The high performance potential of hybrid systems results in a challenging design environment. The structural design must be quite efficient because the blanket performance is a strong function of the fuel-to-structure ratio and of the thickness of the first wall between the plasma and the blanket. At expected fusion neutron wall loads, blanket power densities as high as 500 W/cm^3 may be obtained. The high blanket energy multiplication can worsen the thermal cycling problems associated with pulsed fusion systems. The power density gradient in the blanket can be quite steep, leading to steep temperature gradients and large thermal stresses. The blanket must be readily disassembled for component replacement and bred fuel removal, and may also have to serve as the vacuum-tight plasma chamber wall.

The high level of fission product afterheat will necessitate use of ASME Section III, Class 1 design code requirements and will require highly reliable residual heat removal capability.

The challenging design environment may be relieved by means of various changes in the conceptual designs of hybrid blankets but this may be achieved only at the expense of reduced blanket performance. Structural concerns will play an important role in the tradeoff between high performance and design simplicity for hybrid reactor systems.

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1. Introduction

1.1 The Fusion-Fission Reactor Concept

A fusion-fission hybrid reactor is simply a fusion reactor with a blanket of fertile and/or fissile material around it to utilize the fusion neutrons. The neutrons may cause fission, thus enhancing the energy production of the fusion reaction or may be captured in fertile materials to produce fissile fuel. In most potential applications, a combination of energy and fuel production is obtained.

The fusion-fission concept was first proposed in 1954 as a possible means of producing plutonium [1]. Next it generally was looked upon as a means of energy enhancement to allow low performance fusion drivers to achieve a positive power balance. Most recently, hybrid fusion is being looked to as a possible fuel breeder for fission burner reactors with power production as an important (and perhaps necessary) by-product. An excellent summary of earlier work may be found in Ref. 2 while more recent studies are reported in Ref. 3 through 6.

The hybrid concept is of interest today as a potential copious source of fissile fuel. The additional energy produced in the hybrid blanket can help the fusion driver achieve a positive energy balance. The energy and the fuel produced can help fusion become economically attractive. The energy and economic enhancement may allow the performance requirements imposed upon the fusion driver to be relaxed somewhat although it appears that a good hybrid reactor will require a good fusion driver. Relaxed fusion performance requirements and enhanced economics could allow earlier application of fusion power than would be possible via electrical power production alone.

The fusion-fission concept also poses potential disadvantages to fusion. The design considerations of the reactor blanket are complicated by inclusion of fission. Safety considerations are expected to be similar to those of fission reactors. The political implications of fusion power being perceived by the public as simply a means to produce fissile materials could threaten the entire fusion program. Although the technical potential of the fusion-fission concept appears good, its role in the U.S. fusion program appears to be still undecided.

1.2 Features of a Fusion-Fission Reactor

The mechanical features of a hybrid reactor are virtually identical to those of a fusion reactor. The reacting fusion plasma is surrounded by the vacuum chamber first wall beyond which a blanket region captures the fusion neutrons. Beyond the blanket lies a shield to protect reactor components from radiation damage and neutron activation. The first wall, shield, power conversion system and balance of plant can be identical to those of a fusion reactor. The blanket, however, is different. In a fusion reactor the blanket must convert the neutron energy to heat and breed tritium to sustain the fusion reaction. In a hybrid reactor the blanket must also produce fission energy and breed fissile fuel. Since the blanket is the only feature of significant difference, this paper will concentrate on the structural aspects of this region.

1.3 Fusion Drivers

Hybrid reactors based on all types of fusion drivers have been proposed. Their different operating characteristics can affect the structural concerns of the reactor.

Tokamaks. The tokamak is the leading fusion reactor concept because of its capability for high plasma power amplification (Q_p). As presently understood the tokamak will operate in a long-pulse mode with tens of seconds between pulses, allowing significant temperature fluctuation during the operating cycle with the potential for worsened structural problems. The toroidal geometry of the tokamak complicates structural design.

Mirrors. The standard mirror reactor is characterized by low plasma power amplification but can operate in a steady state mode. The low Q_p capability implies the need for a significant fission rate in the blanket to provide blanket energy multiplication. This in turn implies higher power densities, higher temperature gradients and a higher fuel burnup, all of which tend to increase structural concerns. The open magnetic configuration of the mirror means that most of the alpha particles, impurities and injected fuel ions will be swept out of the vacuum chamber and will not interact with the wall.

Inertial fusion. Inertially confined fusion would operate with very brief, intense pulses of power. By keeping the pulse repetition rate faster than the thermal time constant of the fuel ($\gtrsim$ 1 to 10 Hz), temperature oscillations may be minimized. The absence of magnetic fields makes possible the use of materials that may be more difficult to use with magnetically-confined fusion, such as ferro-magnetic structural alloys and liquid metal coolants.

2. Modes of Fusion-Fission Operation

2.1 Classification of Fusion-Fission Systems

L. Lidsky proposed classifying fusion-fission reactors as "symbiotic" if they produced fuel, "hybrid" if they produced energy and "augean" if they used fusion neutrons to burn fission reactor waste products [7]. Recognizing the continuum of modes between a fuel producer and an energy producer, this paper will use the definitions "fuel producing hybrid" for reactors whose main product is fuel, "energy producing hybrid" if the main product is energy and "fuel and energy hybrid" if both products are important. Recent concern about nuclear proliferation and diversion has prompted consideration of the "refresh cycle" concept in which fuel produced in the hybrid would be used directly in a fission burner reactor without reprocessing.

2.2 Augean Systems

Fusion can provide a plentiful source of 14 MeV neutrons which could be used to fission and transmutate long-lived fission reactor waste product actinides and fission products into stable or short-lived materials, thus helping to alleviate waste disposal concerns. A design study for a tokamak actinide waste burner was done by Westinghouse in 1976 for the Electric Power Research Institute [8] which showed that a significant exposure to fusion neutron flux was required to appreciably reduce the waste disposal concerns. This raised significant structural materials damage concerns. Basically, exposure sufficient to significantly affect the actinide inventory also significantly affected the reactor fuel and structure materials. To attempt to solve these materials problems, General Atomic in 1977, also under EPRI sponsorship, proposed use of the liner fusion concept with a rotating molten-salt fluid blanket that would operate at average wall loads of about 100 MW/m^2 [9]. With no internal structure, such a blanket would be immune to structural materials damage concerns.

The augean fusion-fission reactor studies indicate that a significant impact on the fission reactor waste disposal problem could be made, but that there are appreciable mechanical, thermal, safety, and materials problems associated with augean systems. Conventional waste disposal techniques appear to be technically quite straightforward and would be needed for disposal of augean reactor system residues. As a result, it appears that augean systems are really not worth the effort.

2.3 Energy Producing Hybrids

The energy producing hybrid would produce and consume fissile fuel in-situ, producing energy as its only external product. A hybrid reactor design study done at Princeton Plasma Physics Laboratory explored this concept [10]. Since the burnup goal of the energy producing hybrid is 100%, very high fuel fluences and burn-up levels are encountered. The fuel and structure will have to be replaced periodically. The energy producing hybrid provides a challenging design environment. A high blanket multiplication factor gives high power density, high after-heat levels and a significant radioactive inventory with concomitant safety concerns. It appears that the bred fuel would be better used in an external fission burner reactor where additional fertile conversion can improve fuel utilization.

2.4 Fuel and Energy Producing Hybrid

In the fuel and energy producing hybrid, fissile fuel is the primary product although significant amounts of energy may be produced by fast fission of the fertile material. The best overall blanket performance in terms of fuel and energy produced can be obtained from this sort of fast fission hybrid blanket [11]. Both Westinghouse [12] and the Lawrence Livermore Laboratory/General Atomic team [13] have proposed plutonium-producing hybrids based on fast spectrum uranium blankets.

Because of its excellent fuel and energy production characteristics, the fast fission fuel and energy producing hybrid blanket appears to be the "mainline" blanket concept. The design environment of this blanket is challenging due to the high temperatures, power densities, and flux levels that are present, although this reactor appears to be an easier proposition than either the augean or energy producing hybrids.

2.5 Fuel Producing Hybrids

A fuel producing hybrid would attempt to minimize the energy production in the blanket by suppressing fission. Neutron multiplication through (n,2n) reactions might be used to improve breeding performance. The intent in suppressing fission is to simplify blanket design considerations by operating at low power density with low after-heat. Although the fission-suppressed blanket has been proposed by several authors [7,14], a full design study of such a system does not yet appear to have been done. Preliminary calculations done at General Atomic with graphite-base thorium blankets and at LLL with molten thorium salt blankets indicate that ^{233}U production rates of 0.2 to 0.8 atoms per fusion neutron can be achieved with unity tritium production.

Although the fuel production capability of the fission-suppressed blankets appears modest compared to fast fission blankets, the much lower energy production allows the fuel production per unit of hybrid reactor power to be quite high. This allows a large number of fission burner reactors to be supported by one hybrid reactor. The relative advantages of high performance, high support ratio, design simplicity and potential safety concerns are still being argued. In the final analysis, the fission suppressed hybrid may prove to be more desirable than the mainline fuel and energy producing hybrid.

2.6 Refresh Cycle Hybrids

The refresh cycle concept is a unique application of fusion power to the production of fissile fuel for burner reactors under the unusual stipulation that reprocessing of the bred fuel not be allowed due to concern about nuclear proliferation and diversion. Fertile material would be irradiated in the blanket of a fusion reactor. When a sufficient concentration of fissile material had been reached, the fuel would be transferred, without reprocessing, to the thermal burner reactor. After discharge from the burner, the fuel could be returned to the hybrid reactor to have its fissile content "refreshed." When the fuel irradiation life was reached it would be retired to storage, again without reprocessing.

The refresh cycle has been investigated at General Atomic for ^{233}U fuel based on HTGR technology [15] and at the University of Wisconsin for ^{233}U fuel based on LWR technology [16]. In both cases the concept appears feasible but requires further study. The fuel consumption in a thorium cycle converter reactor without reprocessing can be three times that of the same reactor if reprocessing is allowed. The rationale for the no-reprocessing edict needs to be fully assessed. The design and performance of refresh cycle systems must be pursued in more depth. The impact on the burner reactor performance of refresh cycle fuel characteristics, particularly, needs further study. Nevertheless, if proliferation and diversion concerns rule out reprocessing, the refresh cycle fusion hybrid could still provide fuel for thermal burner reactors.

2.7 Mainline Assumption

The fast spectrum fuel and energy producing hybrid blanket concept will be used as the basis for this discussion, as it appears at present to be the mainline hybrid concept. The understanding of hybrid reactor systems, however, is advancing and serious assessment of the relative merits of the many blanket, driver and operating mode possibilities is just beginning. A strong contender for the "optimum" hybrid system may be a fission-suppressed type of fuel producer. If this proves to be the case, the design requirements of hybrid systems should be somewhat relaxed, as discussed above.

3. Hybrid Blanket Design Environment

3.1 Blanket Performance

Interaction of the 14 MeV D-T fusion neutrons with the fertile materials in the blanket of a hybrid reactor can result in significant neutron and energy multiplication. Both uranium and thorium exhibit significant (n,2n), (n,3n) and (n,fission) reactions with 14 MeV neutrons. The average performance characteristics of typical fast spectrum uranium and thorium blankets are shown on Table I [13,17]. Both blankets can produce significant amounts of fissile fuel. If this fuel is assumed to be burned in a thermal spectrum fission reactor, a large number of burner reactors could be supported by each hybrid reactor. The lower breeding performance of the throium blanket is off-set by the higher value of the bred ^{233}U as a fuel for thermal burner reactors [18]. Use of more efficient thermal converter reactors, such as the HTGR, can further enhance the hybrid reactor support ratio, as shown.

3.2 Design Environment

In addition to bred fissile fuel the hybrid blanket can also produce significant energy multiplication, by fission, of the fusion neutron energy. This can produce very high power densities in the blanket fuel material. The fuel of the Standard Mirror Hybrid Reactor, for example, experienced a peak power density of 500 W/cm^3 at 2 MW/m^2 wall load. Since the fertile blanket of the assumed mainline hybrid reactor is highly subcritical, the power density gradient in the blanket can be quite steep as shown on Fig. 1. This steep power gradient can lead to differential thermal expansion and radiation-induced swelling with resulting stress in the blanket materials. The energy multiplication of the hybrid blanket also worsens the thermal cycling problems associated with the transient response of the blanket to the pulsed nature of tokamak and inertial fusion confinement concepts.

Because the hybrid blanket can experience a significant fission power density, it can build up a fission product inventory with its associated afterheat and radiological hazard potential. As a consequence, it is expected that the hybrid blanket structure will have to be treated as a fission reactor primary containment structure under design rules such as the ASME Section III, Class 1 design code. This requirement may ultimately result in stringent design conditions because loss of ductility appears to be one of the primary limitations to the lifetime of structural materials located in areas of significant fusion fluence and this effect is strongly temperature dependent [19]. This could lead to the possibility of brittle failure of the primary coolant pressure boundary.

3.3 Performance Impact of Structural Design

Despite the severe design environment described above, the structural design of a hybrid blanket must be quite efficient because the blanket performance is quite sensitive to the amount of structural material located in the fuel zone. Fig. 2 and 3 illustrate the sensitivity of blanket performance to the structure volume fraction and to the thickness of the structural wall between the plasma and the blanket in typical fast spectrum hybrid blankets [17]. It is clearly important to minimize the amount of structure in the blanket, the thickness of the wall between plasma and blanket, and the amount of other materials, such as coolant, used in the blanket.

Systems economic evaluations indicate that it is advantageous to take the bred fuel out of the hybrid blanket at fairly low exposure, on the order of about 5 to 10 MW-yr/m^2 and ∿ 1% burnup. This has prompted interest in metallic fuels. The higher density of fertile atoms and lower density of non-fuel atoms in metallic fuels offer an improvement in the neutronic performance of hybrid blankets. Lee at LLL has investigated various uranium fuels with the results shown on Table II [4,13]. The metallic fuels offer significant performance advantage but are quite susceptible to swelling and this will have to be accommodated by the fuel structural design.

As fissile material is bred into a hybrid blanket, the energy multiplication increases. To minimize the reactor-average power variation, it is advantageous to refuel the blanket in staggered increments rather than all at one time. This, plus the low exposure, results in the desire for fairly frequent, perhaps annual, refueling. The need to refuel frequently implies the need for a blanket structural design that can be readily disassembled and reassembled. Since the blanket pressure boundary may also have to serve as the plasma vacuum chamber wall, the need for easy disassembly will require a careful structural design.

3.4 Blanket Examples

The hybrid reactor concept is still in the stage of scoping studies and preliminary conceptual designs. A number of preliminary designs have been done that illustrate some of these structural concerns. The small cylindrical module design developed by the Lawrence Livermore Laboratory/General Atomic team for the commercial Standard Mirror Hybrid Reactor is shown on Fig. 4 [13]. The helium-cooled U_3Si fuel rods give excellent breeding performance. The small module size and mechanical, double knife-edge vacuum seal allow rapid refueling without disassembling the reactor structure by use of a refueling machine inserted into the vacuum chamber. The structural design of the first wall is a nearly pure tension structure and thus the amount of material between the plasma and the fuel is minimized.

The blanket design developed by Westinghouse for the low performance, near-term Demonstration Tokamak Hybrid Reactor is shown on Fig. 5 [20]. This design has a separate vacuum chamber and coolant boundary to avoid fuel handling inside the vacuum chamber and to minimize concern about vacuum chamber leaks. The water-cooled, zircalloy-clad oxide fuel rods maximize use of LWR technology. The use of pressure tubes around each fuel rod bundle could allow the higher temperatures and pressures necessary for electricity production.

4. Conclusions

The design environment for the blanket of a hybrid reactor can be quite challenging due to the high power densities and temperature gradients that may be found. The reactor performance is sensitive to the amount of structural material in the blanket region. As a consequence, the structural design must be quite efficient to be able to operate effectively in the hybrid blanket environment without unduely penalizing blanket performance. Structural concerns will play an important role in the trade-off between high performance and design simplicity for hybrid reactor systems.

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Table I. Typical Hybrid Blanket Performance Characteristics

Characteristics	Uranium Blanket [13]	Thorium Blanket [17]
Fuel Production (atoms/fusion neutron)	1.5	0.75
Energy Multiplication (M)	10.4	3.0
Fuel Production (kg/MW fusion-yr)	6.5	3.2
Fuel Production (kg/MWth-yr)	0.76	1.25
Support Ratio* - LWR	4.0	9.6
(P_e-burner/P_e-hybrid) - HTGR	--	20.7

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*Assumed fuel consumption (kg/GW$_e$-yr): LWR-Pu, 533 kg; LWR - ^{233}U, 360 kg; HTGR - ^{233}U, 168 kg

Table II. Fuel Materials Neutronic Performance*

Material	UO_2	UC	U_3SI	U-Mo	U
Blanket Multiplication	7.1	9.3	11.1	11.6	14
Breeding Ratio (Pu/n)	1.1	1.4	1.8	1.8	2.2

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*Data normalized from Ref. 4 and 13.

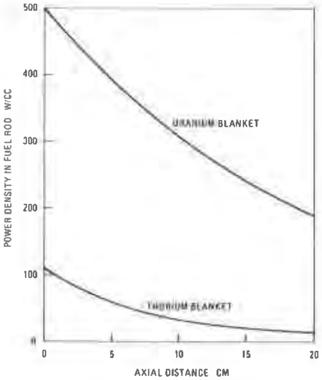

Fig. 1 Power density in typical hybrid blankets [13,17]

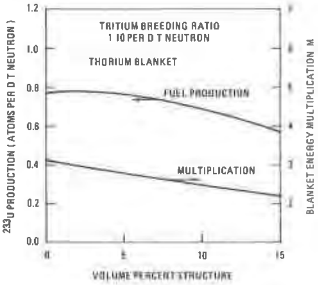

Fig. 2 Blanket performance vs structure volume fraction [17]

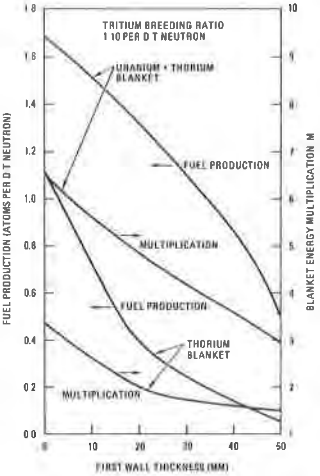

Fig. 3 Blanket performance vs first wall thickness [17]

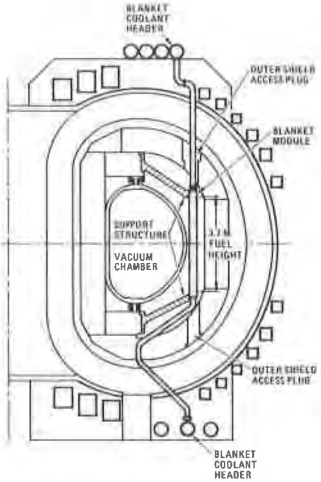

Fig. 4 LLL/GA hybrid module [13]

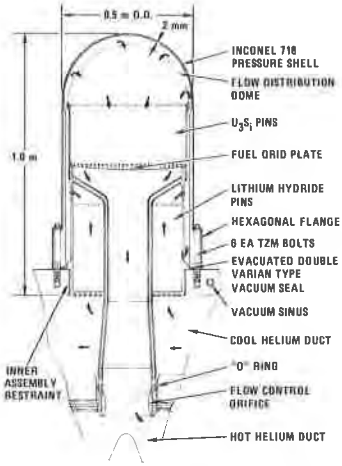

Fig. 5 Westinghouse Demonstration Tokamak Hybrid Reactor [20]