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Report

AN INTRODUCTION TO HYBRID FUSION

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AN INTRODUCTION TO HYBRID FUSION

by

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ABSTRACT

This report gives a brief introduction to some hybrid fusion proposals. The idea is to take advantage of the high neutron energy in fusion compared to fission either to breed fuel more efficiently than in a fast reactor, or increase the power output by fission of U^{238} or transmute radioactive waste. The penalty is an increased cost and complexity of the blanket and the loss of environmental and safety arguments for fusion systems which rest on their low inventory of radioactive materials.

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1. INTRODUCTION

The aim of hybrid fusion is to combine favourable aspects of fusion and fission into one system. Compared to fusion, fission power has the advantages of high power density, low capital cost, small unit size, technical simplicity, greater reliability, better energy economics and, for thermal reactors, a large investment in an established system. Known uranium resources are sufficient only for some decades at forecast rates of exploitation, after which the intention is to breed fuel in fast reactors. Unfortunately the neutron energy spectrum in fast reactors, particularly sodium cooled ones, is not very hard (peaking at ∿ 0.1 MeV) so the efficiency of fuel production is low. On the other hand D/T fusion produces a much harder neutron energy which can be used for comparatively rapid production of fissile fuel.(5) Systems involving the use of fusion reactors to produce fuel for fission reactors are known as symbiotic systems, and represent the main area of interest in hybrid fusion. Two other uses proposed for fusion neutrons are hybrid fusion power where the blanket is used directly for power production, and systems in which fission waste is incinerated. This note gives a brief introduction to these applications of fusion neutrons.

2. THE SYMBIOTIC SYSTEM

In the symbiotic system the fertile materials U^{238} and Th^{232} are incorporated into the fusion blanket. Neutron multiplication (n,2n or n,3n) by the U^{238} (and to a lesser extent by Th^{232}) increases the neutron flux by a factor of ∿ 5, and the resulting lower energy neutrons are captured (n,γ reactions) producing U^{233} from Th^{232} or Pu^{239} from U^{238}. Thus abundantly available fertile material is converted into fissile fuel for thermal reactors. Allowing for up to one neutron required to produce tritium by capture in lithium (also in the blanket) and losses, each thermonuclear neutron produces at least one fissionable atom. The gain can be compared to the LMFBR performance in which each high energy neutron produces ∿ 2.2 fission neutrons (again allowing for losses), one of which is needed to sustain the fission and another is needed to produce plutonium to maintain fuel balance. Thus only ∿ 0.2 neutrons are left to produce more plutonium - a factor of ∿ 5 less than in the symbiotic system.

The above estimates apply to a D/T fusion driver. D/D is also of some interest as a driver because on a long timescale the application will not be limited by lithium resources and neutrons do not have to be used to produce tritium in the blanket. This is because, at high burn-ups, the spectrum is hardened above 2.45 MeV by D/T reactions involving tritium formed in the plasma(2), and the fissile production rate and the energy per 14 MeV neutron remain economically attractive. D/D drivers are more difficult to ignite than D/T drivers because of the lower fusion cross section but once ignited they may be attractive hybrids.

Some symbiotic proposals(6,7) eliminate fuel processing by using fusion neutrons to produce fuel from Th or U^{238} in fuel elements without removing the reaction products before use in a fission reactor.

The presence of U^{238} causes power to be produced by fast fission in the blanket. For example, in one proposed arrangement(3) a combined hybrid power/symbiotic fuel producer of 3000 MW thermal energy generates 1600 kg per year of fissile fuel from U^{238} and Th^{232}. Only about 15% of the overall power is due to fusion. In such a system 5 LWRs can be fuelled from each symbiotic fusion reactor compared to only 0.7 LWRs fuelled from each LMFBR of the same power. The power from fast fission of U^{238} in the blanket may produce formidable cooling problems in normal operation. To reduce the fast fission power, some proposals include further neutron multipliers or an increased thorium content, although this reduces the overall breeding.

Symbiotic systems have commercial, economic, security and some safety advantages. These can be summarized as:

(a) They can feed an already established system of thermal fission reactors which will have a large investment of capital and expertise by the time fusion systems are available. By the year 2000 there will be at least 300 thermal reactors with a capital investment of $\sim$ £2.10^{11} at present money values.

(b) They can be placed in remote secure areas away from the fission power reactors. Fuel can be prepared in these areas and only exported in a "spoilt form" suitable only for use in fission reactors.

(c) Because of the complications of fusion reactors it is reasonable to expect that they will not be as reliable as fission power systems. However if the fusion reactor is part of a symbiotic system and not producing essential power, breakdown periods lasting a substantial fraction of a year are tolerable because the refuelling time scale of fission reactors is longer than this.

(d) There is a possible safety advantage over fast reactors in that there is no critical assembly of fissile material in the symbiotic system, although provision must still be made to cool fission products in the blanket after an emergency shutdown.

(e) The rate of introduction of hybrid breeders is not constrained by plutonium doubling times, as with the LMFBR. For a particular country, this advantage depends on the existing plutonium stocks.

(f) The use of hybrid breeders to produce U^{233} would lead to a more rapid utilization of thorium as a fuel.

(g) Since one fusion hybrid can support a number of LWRs the cost of the hybrid is relatively unimportant.

3. HYBRID FUSION POWER

Hybrid fusion can increase the overall energy efficiency compared to fusion alone. A figure of merit for the efficiency of fusion reactors is Q, the ratio of fusion energy released divided by the energy needed to start the fusion. Allowing for the efficiencies of electricity generation, ignition energy production, magnetic field production, vacuum pumping etc., a $Q \geq 10$ is required for breakeven with fusion alone; reference reactor designs have $Q \sim 25$. If the energy required to construct the fusion reactor is included, a greater Q is required. TFTR tokamak and larger versions of the tandem mirror may achieve $Q \sim 1$.

In hybrid fusion power, the fission of U^{238} in the blanket by fast thermonuclear neutrons is optimized, so the reactor does not operate in conjunction with thermal fission stations, as in the symbiotic system. This enhances the Q; for example in one design(9) the energy multiplication was 7 to 14 times so, for example, TFTR could break even or a reactor based on confinement using magnetic mirrors(19) may be practical.

Looked at in various ways, the inclusion of a power producing fissile blanket could reduce $n\ \tau$ required for break even, increase the tolerable impurity level, allow operation at lower β, reduce first wall loading or even make driven systems marginally economic. One attraction of hybrid fusion power is that it may be possible to burn depleted natural uranium to 10 to 15% burn-up thereby eliminating the need for reprocessing.

4. ACTINIDE INCINERATION

For actinide incineration(11) the fusion reactor provides a source of fast neutrons to transmute actinide waste products from fission reactors into relatively harmless substances. It is difficult to transmute lighter fission products such as Cs^{137} and Sr^{90} because a higher neutron flux is required. The general safety is formidable because of the high inventory of fission products and their transport to the fusion reactor incinerator. There are also design difficulties because the fast neutron dose has to be so high that internal structural damage can occur.

5. COST

The overall capital cost per unit thermal power of a symbiotic system to be about equal to a LMFBR(13), which at present is around ∿ 1.3 times LWR costs.(14) It should be remembered that the fusion component of costs is far more speculative than the thermal fission reactor costs, although, since a number of thermal reactors is involved, the overall cost is not strongly sensitive to the cost of the fusion component.

6. DIFFICULTIES

The performance of hybrid systems depends vitally on the blanket design, which requires careful optimization. Neutronics and engineering of the blanket becomes even more complicated than with pure fusion. The blanket must breed tritium and plutonium or uranium in a stable manner while acting as a heat exchanger operating at very high power densities (up to 500 MW/m^3 is envisaged, which is similar to that in LMFBRs). Also it must shield the super-conducting magnetic coils from neutron flux and provide a support structure. Further, development of the fuel cycle will be very costly.

Superimposed on these factors are problems of accessibility, material damage, thermal stress caused by high temperature gradients, and thermal fatigue in pulsed toroidal systems. Further, the volume must be minimised because of the high cost of magnetic field flux in the blanket.

The presence of heavy atoms in the hybrid system removes the safety advantage of pure fusion compared to fission reactors. Care must be taken that radioactive products cannot escape in accident configurations involving loss of geometrical integrity which could result from explosions by the release of electromagnetic energy, chemical fire or fission product meltdown by accidental loss of cooling.

7. CONCLUDING REMARKS

In spite of formidable problems there has been persistent interest in hybrid systems particularly in the US and USSR. Essentially, the hybrid combines neutron-rich but power-poor fusion with power-rich but neutron-poor fission. Among the earliest publications concerning hybrids are those of Imhoff(15) and Lawson(16) in the 1950's. Proponents in the US are Bethe(13), Lidsky(4) and Werner(20) and examples of studies based on a particular fusion confinement devices are those of Tenney(10) for Tokamaks and Bender(8) for Mirrors. In 1974 there was a conference on hybrid fusion at Germantown(17) organized by ERDA, and in 1976 there was a US-USSR symposium at LRL. In the USSR, Golovin(12) and Velikov(18) have been active in hybrid systems studies.

The general consensus of opinion seems to be that of the three systems, symbiotic systems have the most chance of success, and they may even be realizable before pure fusion. There is, however, much work to be done to establish a convincing case for hybrid fusion, and although there are some very attractive features there remain many formidable technical and engineering problems and the safety acceptability is not clear.

The views expressed in this report are the author's and do not necessarily reflect the policy of the UKAEA.

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