

Considerations of Fusion R&D in India

by C. Sivaram

1. Spin Polarised Nuclei Can Augment Reaction Cross Sections

Recently the concept of using spin polarised nuclei to boost up the rate of thermonuclear reactions in controlled fusion reactors has been proposed. This makes use of the fact that the cross-section for the reactions between two nuclei is boosted up when they are both in the spin state; in general the fusion cross-section is dominated by only one total spin state

The nuclear forces between interacting nuclei are dependent on their spins or isospins, this being responsible among other things for the non-existence in nature of nuclei made up of only two protons (the so-called diproton) or two neutrons (the dineutron). If, however, the coupling constant of the nuclear forces had been hardly two percent stronger the diproton would have been bound and the consequences would have been quite disastrous

Under those circumstances the basic thermonuclear reaction in the sun would not have been the comfortably slow $P+P \rightarrow D+e^+ + \nu$ (which has been keeping the sun luminous for a few billion years), but the extremely rapid $P+P \rightarrow He^2 + \gamma$ (subscript p is the proton, He² the diproton, D deuterium, e⁺ the positron, ν the neutrino and γ the photon) which could make the sun explode in no time.

On the other hand, if the coupling had been about five per cent weaker, even deuterium (a loosely bound state of a proton and a neutron)

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would not have been bound. The sun and other stars would not have been able to use nuclear energy to shine, and all matter in the universe would have remained as hydrogen

The extremely slow rate of the reaction between two protons, as in the first reaction above (p+p), explains why the so-called hydrogen bomb uses the heavier isotopes of hydrogen, i.e. deuterium (D) and tritium (T). The lifetime for half the mixture to react even at several million degrees is a few billion years! It also explains why these are the isotopes which the modern Prometheus will have to use in trying to rekindle the stellar fire on earth in the form of controlled thermonuclear fusion

The Principle Involved

We can explain the principle involved in spin polarised nuclei quite simply as follows. Let the two reacting nuclei be labelled 1 and 2 and let the spin of nucleus 1 be S_1 and spin of nucleus 2 be S_2 , and further assume $S_1 > S_2$.

Then the spin of the total system of the two nuclei can take on values from $(S_1 + S_2)$ to $(S_1 - S_2)$ in steps of one. In general the fusion cross-section is dominated by only one total spin state which contributes most. Let S be this dominant spin state through which the reaction proceeds. Now associated with this spin state are $(2S + 1)$ quantum states (i.e. different orientations the state can take). Therefore the fraction of collisions between the nuclei which result in nuclear reactions are the number of states that can react, i.e. $(2S + 1)$ divided by the total number

of spin states which in this case is

$$(2(S_1 + S_2) + 1) + (2(S_1 - S_2) + 1)$$

However if it were possible to line up the nuclear spins, i.e. if it were possible to polarise them so that the total spin is always S , then we could enhance the reactivity or reaction rate, since now every collision could result in a reaction. From what has been said above, the ratio by which we would be enhancing the reaction rate would simply be the total number of spin states for the unpolarised nuclei divided by $(2S + 1)$.

We will now illustrate the idea by taking specific examples of nuclei which are being seriously considered for use in controlled nuclear fusion

Boron Reaction

One instance where there could be significant increase in the reaction rate is the p+B¹¹ system (B is the boron nucleus). This reaction produces 3 particles and releases 8 MeV of energy ($p+B^{11} \rightarrow 3\alpha + 8 \text{ MeV}$). Besides the fairly large cross-section $\langle \sigma v \rangle \sim 10^{-16}$ at 10 KeV temperature (1 KeV $\approx 10^7$ K), an attractive feature is that the products are all energetic charged particles. The power may be directly extracted by electromagnetic means without going through steam driven or vapour driven turbines which characterize reactors run on neutron producing reactants like the usual uranium water reactors. Neutrons are uncharged and therefore can only be cooled by dissipating their energy by collision conversion into heat

Unfortunately the p-B¹¹ reaction, it turns out, does not quite produce enough energy to maintain the fusion ignition unless we could somehow double the cross-section. This could possibly be done by the above idea of spin polarisation

The spin of boron eleven is $3/2 (S_1)$, the spin of the proton is $1/2$

(S_2), which means that the total spin of a B^{11} nuclide plus a proton is either 2 or 1 ($S_1 + S_2$ or $S_1 - S_2$). We must now know which one of these total spin states contributes to the resonance at 800 KeV which supplies all the reactivity. From tables of excited states of carbon it appears that it is the spin-2 intermediate state through which the fusion proceeds. Thus we should align the spins of B^{11} and p. By suitable polarisation we have $S_2 = 2$. According to our earlier formula, the enhancement factor would be

$$\frac{2(S_1 + S_2) + 2(S_1 - S_2) + 2}{2S + 1} = 8/5 = 1.6$$

(i.e. putting $S = 2$, $S_1 = 3/2$, $S_2 = 1/2$)

We would therefore increase the reaction rate by a factor of 1.6 by spin polarising the nuclei.

Now consider the thermonuclear reactions involving the isotopes of heavy hydrogen, deuterium and tritium. First take

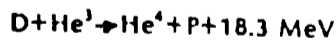


which is the favourite fuel today for most reactors for nuclear fusion mainly because it has the largest of all fusion cross-sections at the comparatively low 10 KeV temperature. The spin of D is one ($S_1 = 1$) and the spin of T is $1/2$ ($S_2 = 1/2$). The resonant reaction, i.e. the dominant spin state, comes from the spin 3/2 state for the total; i.e. $S = 3/2$.

If we take the spin 3/2 state as the one which leads to the reaction we find from the above formula, we get an enhancement factor of 1.5 for this reaction. This means we can reduce the Lawson criterion n (the product of the number density of the reacting nuclei times their confinement time in the device) by a factor of 1.5, which is a good gain as far as getting the reaction started is concerned.

Other Reactions

Similarly we also find an enhancement factor of 1.5, for the D-He³ reaction



spin of He³ ($S_2 = 1/2$, $S_1 = 3/2$). The D-He³ reaction is favoured by many as a

Fusion Report

TEMPERATURE REQUIREMENTS
FOR FUSION BREAKEVEN*
in degrees Kelvin

Fuel Cycle	Unpolarized	Polarized
D-T	100,000,000	80,000,000
D-D	350,000,000	220,000,000- 300,000,000
D-He ³	700,000,000 1,000,000,000	400,000,000- 500,000,000

*Assuming standard tokamak conditions for density confinement time

good alternative to D-T, for unlike tritium He³ is stable and already available in volcanic gases. The reaction products are all charged particles from which energy may be directly extracted by a suitable configuration of electric and magnetic fields. By contrast, with D-T the bulk of the energy, or 14 MeV, is carried away by neutrons from which the energy can be extracted only by heat via collisions.

The D-D reaction is also interesting from the spin polarisation point of view. We have $D + D \rightarrow He^3 + n$, or $T + p$ about 4 MeV energy being produced. The cross-section is much lower than for D-T, and one requires about 300 MeV to efficiently utilise the reaction, unlike only 10 KeV for D-T. The chief advantage is that D is plentifully available and one does not require the rare He³ or T which has to be bred separately.

The chief disadvantages are the very high temperatures (300 KeV, more than 30 times that for D-T) required to ignite the reaction and the large amount of energy (~40%) dissipated as neutrons. The T produced also reacts producing more neutrons of a different energy range. Thus for reactors running on D-T or D-He³—especially the latter—it would be useful if the D-D reaction is switched off. This would ensure that all of the energy of the D-He³ (18 MeV per reaction) is released in charged particles and the contaminant neutrons are not produced carrying away a large fraction of the energy.

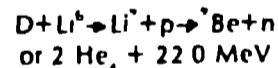
The D-D reaction mainly goes through total spin states of zero or one, the D having a spin of 1. So if the spins of the neutrons are lined up (total spin = $2 = S_1 + S_2$, $S_1 = S_2 = 1$), the D-D reaction is turned off as it cannot proceed through total spin states of 2. Thus by aligning the spins of the reacting nuclei, one can turn off the D-D reaction, and increase the reaction rates of D-T and D-He³ by a factor of 3/2.

The idea can also be extended to other reactions. For instance we have the radiative capture of neutrons by protons to form D



This reaction which may be used to regenerate part of the deuterium can have an increased reaction rate of a factor of 1.3 if the neutrons and protons ($S_1 = S_2 = 1/2$) are spin polarised.

Other reactions which could get enhanced are



the reaction producing a large number of daughter nuclei with more than 80% of the energy going into charged particles.

Several techniques are known for polarising different kinds of nuclei and neutrons, even nuclei with higher atomic numbers like rubidium and xenon.

Survival Time

However one crucial question

which may be asked is whether these polarised nuclei can survive for a long enough time in the plasma for fusion to take place. The energy associated with having the spin lined up along the magnetic field as opposed to the antiparallel case, that is, the energy required to polarise or depolarise a nucleus is very small—equivalent only to an energy difference of about 1/100 eV in a 10 KeV plasma. If we can create the polarised nuclei to begin with, they will survive long enough for the fusion to occur as there is very weak coupling between the plasma and the spin. In fact, it is so weak that depolarisation is very slow.

The cross-section for flipping the spin during collisions is only $\sim 10^{-30}$ cm², several orders of magnitude smaller than the fusion reaction cross sections. σ_{D} for depolarising turns out to be $\sim 10^{20}$ and as the fusion reactions require only $\sigma_{\text{T}} \approx 10^{15}$ there is far more than enough time for the fusion reactions to occur. Thus the nuclei would retain their initial polarised state till the fusion reaction is over. Thus by lining up all the deuterons and tritons with the magnetic field it is possible to increase the fusion rate by 50% as seen above.

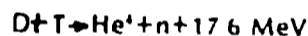
The alignment of the nuclear spins relative to the magnetic field in a fusion device can influence the direction in which the fusion products emerge from the plasma. If the deuterons in a D-T reaction are polarised the neutrons come out of the plasma perpendicular to the magnetic field. Since in a Tokamak the field runs around the toroidal container, the neutrons travelling perpendicularly through the walls of the reactor are following the shortest possible path through the wall material and thereby creating least radiation damage to the walls. Spin polarisation can also enable the fusion device to contain the fuel more easily, by pushing out α -particles parallel to the magnetic field.

The use of spin polarised nuclei opens up many new possibilities in controlled nuclear fusion research. ■

2. Fusion-Fission Hybrid Breeder Reactor Systems

The use of fission neutrons to breed more fissionable material is well known. For instance, the neutrons released in the fission of U-235 can be absorbed by a blanket of ordinary natural U-238 (which constitutes 99.3 percent of any uranium sample) to produce Plutonium-239 (Pu-239) which is fissionable. Similarly Thorium-232 (Th-232), which is not fissionable, can absorb neutrons to produce the fissionable isotope U-233. This is particularly suitable for the Indian situation where vast deposits of thorium, for example in the monazite sands of Kerala, are available. Thus even if a breeder reactor is not designed to produce commercial power it should maintain a steady intense flux of neutrons to carry out the conversion, that is, to breed fissionable material, which can later be used in other reactors.

We have seen in Section 1 how the first nuclear fusion reactors would use deuterium and tritium mixtures as fuel. A major reason for this choice is that the reaction

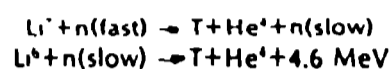


has the largest of all cross-sections even at comparatively low energies of a few KeV, and requires a temperature of only about 10 KeV to achieve the energy breakeven (energy produced > energy used to heat and confine) to start producing power. As can be seen, the reaction produces a copious quantity of neutrons (in fact the bulk of the energy, about 14 MeV, is carried away by the neutrons) even at still lower temperatures.

Fusion Breeder

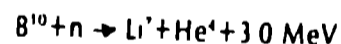
The major disadvantage is that tritium is an unstable isotope and does not occur naturally. It is therefore necessary to breed it. The usual suggestions for this are to cause part of the neutrons released in the reaction to be trapped in a lithium blanket

surrounding the reactor. In liquid form the lithium can also play the role of coolant and take away the heat dissipated by collisions between neutrons and the blanket. The reactions undergone by lithium with neutrons to breed tritium are



It is seen that the neutron survives the first reaction with the Li⁷ isotope and emerges at a much lower energy (velocity) to be captured by Li⁶. This double reaction fortunately ensures that more than one tritium nucleus is produced per neutron absorbed and thus a kind of balance is maintained between the tritium produced and the tritium consumed in the D-T reactor. This therefore would be the simplest example of the thermonuclear breeder reactor producing its own fuel. We shall see more possible examples in the next section.

One drawback with the above scheme is that lithium is also not very abundant in rocks, etc. and is not so easily mined. An alternate suggestion involves using boron, since boron is probably more easily mined occurring as borates and other salts. The neutron reactions with boron isotope (B¹⁰) provides a supply of Li⁶ also, through the reaction:

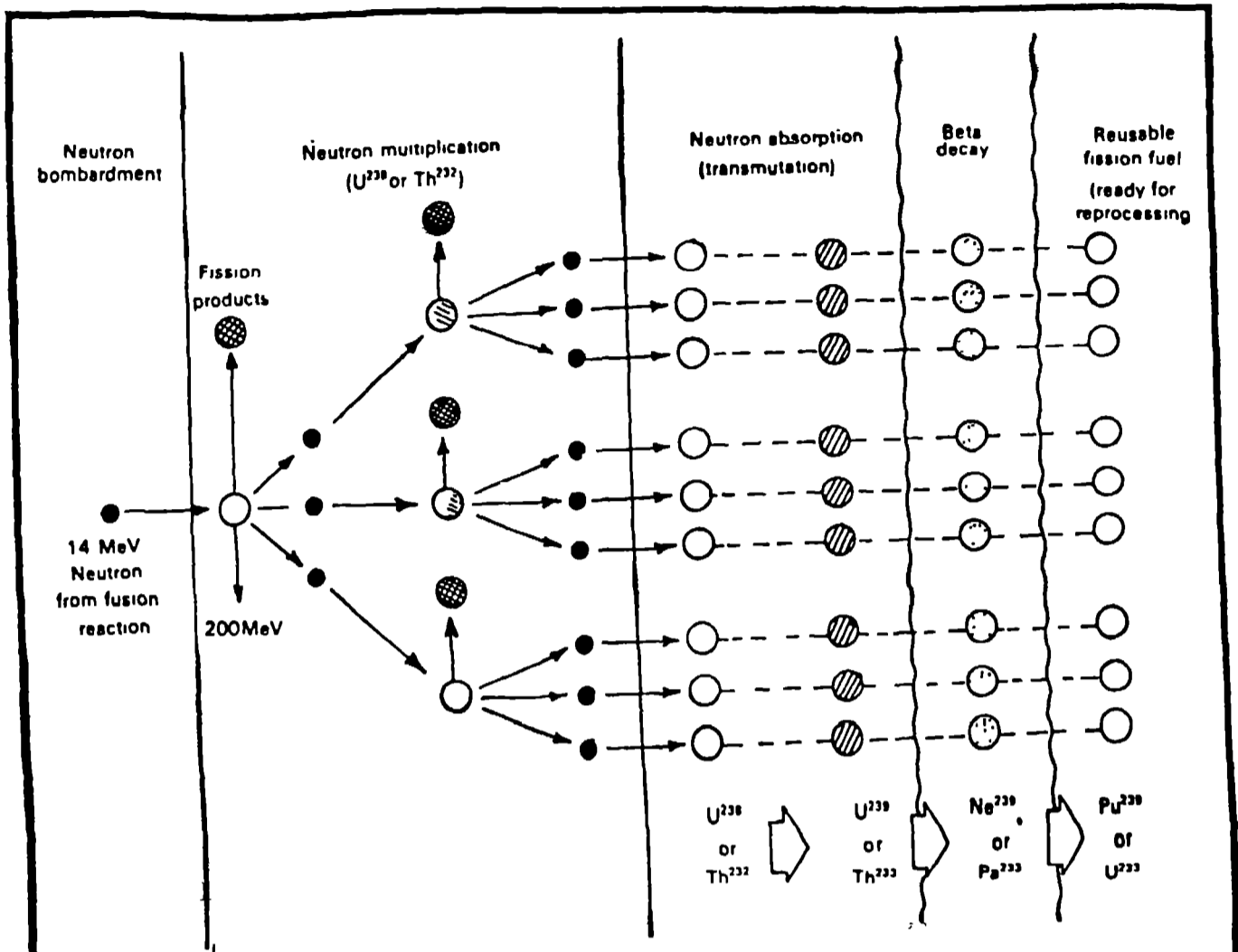


and a smaller fraction undergoes the reaction (with slower neutrons)



thus breeding tritium also.

The Li⁶ produced would of course capture neutrons and produce tritium as in the first set of reactions. If beryllium is also used in the blanket a remarkable reaction doubling the number of neutrons occurs



ENERGY MULTIPLICATION AND FUEL PRODUCTION IN THE HYBRID BREEDER REACTOR

Fast neutrons from the fusion reaction enter the reactor blanket where they trigger fission of uranium nuclei. Each such reaction releases energy (about 100 MeV) and two or three additional neutrons. The additional neutrons trigger further fission reactions, while being slowed down. When they enter the breeding region proper, the neutrons are absorbed in fertile thorium or uranium nuclei in the first step of nuclear transmutation into fissile material. In each case (uranium and thorium) two successive beta (electron emission) decays lead to the nuclear fuel Uranium-233 or Plutonium-239.



A beryllium blanket would therefore multiply the number of neutrons which would then react with a surrounding lithium blanket to produce tritium.

Thus a fusion reactor working on D-T and surrounded by a beryllium-lithium blanket would be a very copious source of neutrons. A 500 megawatt (MW) D-T reactor with such a blanket would produce about 10^{21} neutrons every second. It would

indeed be wasteful to use all these neutrons to breed only tritium; considering that lithium is not all that abundant there is a limit to the amount of tritium that could be produced.

Also Breed Fission Fuel

However the copious supply of neutrons in such a reactor naturally suggests the possibility of using these excess neutrons to breed fissionable isotopes such as U-233 by using a thorium blanket or PU-239 by using natural uranium as the blanket mat-

erial. These fissionable isotopes thus produced by using thermonuclear neutrons could then be used separately in usual fission reactors of the light water type. In the Indian context it would be ideal to breed U-233 from the abundant Th-232. In fact it would not be necessary to get pure U-233; one can mix U-233 and natural uranium to get denatured U-233 which can be used as a substitute for enriched uranium in light water reactors.

It can be calculated that a 500

MW fusion D-T reactor has the potential to produce about 3000 kilograms of fissionable U-233 every year. This much fission fuel can in turn be enough to run about a dozen 300 MW nuclear fission reactors. Thus by using the thermonuclear neutrons from the D-T fusion reactor (with appropriate blanket material) to produce fissionable fuel, one can increase the energy producing potential of the fusion reactor by a factor of at least ten—the fissionable fuel so produced can be used to operate ten or more fission reactors, each generating power comparable to the original nuclear fusion reactor. Such a hybrid system increases the power potential by a factor of ten!

Again, as light water reactors are well developed technologically no new breakthroughs in utilising the fissionable fuel thus produced would be required. Moreover if denatured uranium is used, even more fission reactors can be run with the fuel produced from just one fusion reactor. What this could mean for the country's nuclear potential can be seen as follows

Implications

At present the nuclear power programme envisages the installed capacity of nuclear power plants to be at least 10,000 MW by the end of the century, if not earlier. Most of them would be expected to be based on natural uranium and heavy water as moderator following the well developed CANDU technology. Light water reactors, such as Tarapur, which are based on enriched fuel, received a serious setback because of difficulties in procuring enriched fuel from advanced countries.

Now it can be estimated that to produce 10,000 MW of power with natural uranium reactors one requires an annual consumption of about 2000 tons of natural uranium (which contains 99.3 percent of non-fissionable U-238). It is a moot point as to whether we can produce or mine 2000 tons of uranium every year by 2000 A.D. According to the International Atomic Energy Agency (IAEA) India's attainable production would be hardly 200 tons by 1990. Moreover the amount of heavy water required during the initial installation

of such power plants totalling 10,000 MW would be about 8000 tons, requiring further an annual consumption of 1000 tons. It is again doubtful if all the heavy water plants (most of them working well below installed capacity) envisaged could deliver that much heavy water. Thus achieving even 10,000 MW of nuclear power seems a stupendous task even from the point of view of the very basic availability of the requisite materials.

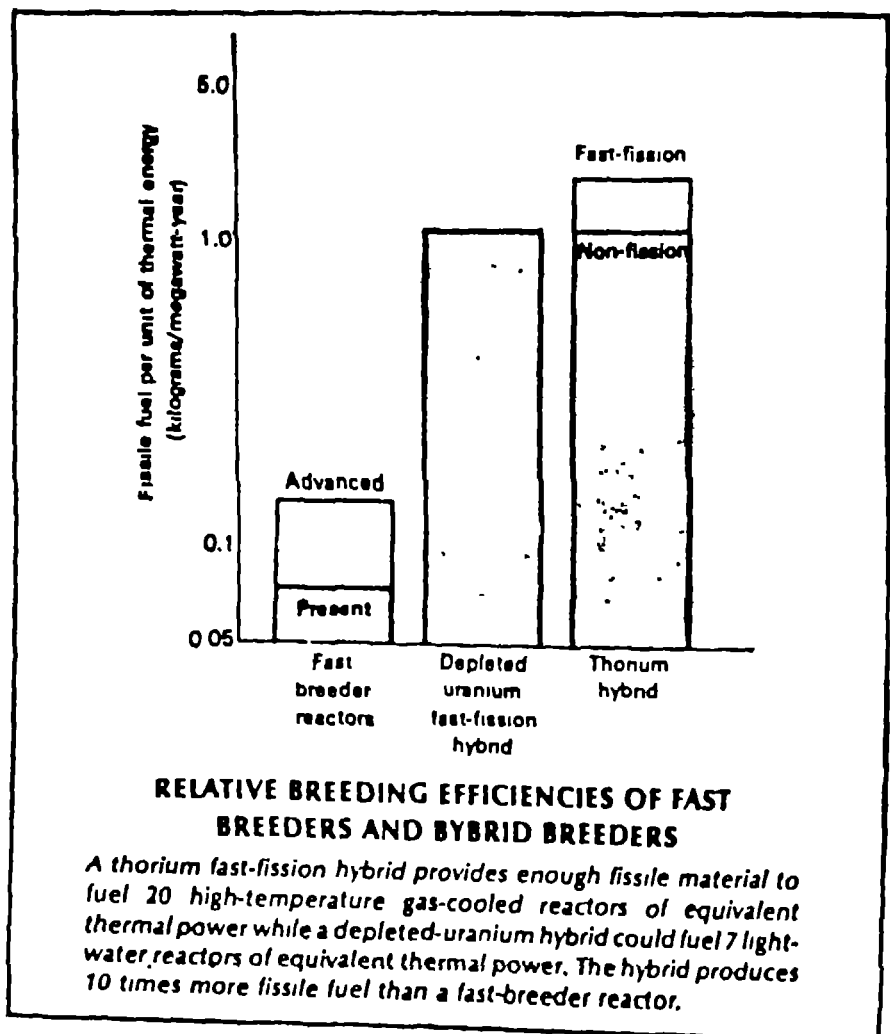
In the hybrid system described above, each 500 MW fusion reactor can give rise to enough enriched fissionable fuel to run ten or more light water fission reactors—requiring no heavy water—of the same power. The total generating potential would be several thousand megawatts, abundant thorium being the raw material for generating the enriched fuel. Thus the development of even a modest D-T fusion proto-

type reactor at just energy break-even or even a little below can mean a tremendous boost for the more conventional nuclear fission power, in terms of production of enriched fissionable fuel and the consequent multiplying of power potential.

Such a scheme should therefore receive high priority in any nuclear power programme envisaged for the country. Other possible combinations of hybrid reactor systems will be considered in the next section. Of course part of the neutrons released in the fission chain reactions can in turn be used to generate fusion fuel via reactions in the moderator (of the fission reactor) as for instance:



etc., apart from the lithium-beryllium blanket. The T obtained can in turn be fed to the fusion reactor to produce more neutrons via D-T reaction starting the process once again. ■

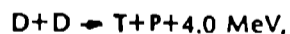
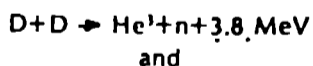


3. Other Thermonuclear Breeder Reactor Systems

In Section 2 we considered the simplest example of a thermonuclear breeder reactor. We had a D-T reactor using the neutrons produced in the reaction to build up tritium in a surrounding blanket. Thus the tritium not available in nature due to its instability is regenerated.

Here we will briefly consider more examples of such thermonuclear reactors regenerating part of the fuel consumed by them. Take first the D-D reactor, the fusion reactor running on deuterium alone. Unlike tritium, deuterium is plentifully available in nature—there is one gram of D in every 25 kilograms of water. Even if all the oceans were made of petroleum we would still be about five hundred times lower in energy potential as compared to the energy obtainable by using the deuterium available in the oceans in fusion reactors! Since lithium is comparatively rare there is a limit to the tritium which can be generated or bred. Thus the ultimate goal of controlled fusion would be to harness the D available plentifully and this can be done in D-D fusion reactors.

The D-D reactor requires about 300 KeV to keep it running to produce power in contrast to the low 10 KeV for the D-T reactor, which is of course the major reason why the D-T reaction is being attempted first. But ultimately the D-D reactor will have to be used. The D-D reactions are:

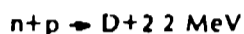


both reactions occurring with equal probability and therefore consuming equal quantities of D. Unlike T, D is of course plentifully available but still we must explore the possibility of recovering back at least some of it.

D Regeneration

The products produced in the above reactions are the proton p,

the neutron n, T and He^3 the lighter helium isotope. The neutron can be radiatively captured by the proton even at low energies in the well known reaction



This has a large cross-section. So we can get back some of the D from the products n and p without much difficulty. This will give us back 25 percent of the original D undergoing the reaction.

The remaining products He^3 and T can also react, giving

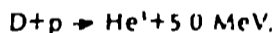


which would mean that we have recovered another 25 percent of the D. Finally we end up getting back at least half of the deuterium which underwent the D-D reaction.

We can also have a reactor running on D and He^3 . As $D+He^3 \rightarrow He^4+p$, the p can join with the neutrons from D-D or D-T to give back D.

A Number of Schemes

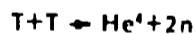
A number of such D regenerating schemes are possible. He^3 is also quite rare in nature and can be made from



the He^3 combining with D to regenerate p. Another possible reaction to regenerate T is $D+n \rightarrow T$. More advanced reactors can also undergo reactions between the He^3 and T produced from D as follows



and also



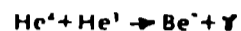
This would enable us to recover $2p+2n \rightarrow D+D$, so we have the original D we started with. Thus we can think of several fusion breeder reactors running on just the abundant D and regenerating more than half the D back.

We have more possibilities if we

incorporate Li also as fusion fuel. We would have the reactions



and at somewhat higher temperature the products react as



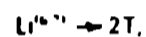
Be^7 captures the fast electrons in the plasma and we get back Li^7 .



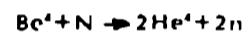
so we have a nuclear fusion breeder running on lithium. It may be added that He^3 can also capture electrons of > 18 KeV to become $He^3+e^- \rightarrow T$, so that the tritium can be fully regenerated via



$He^3+D \rightarrow He^4+p$; $He^4+D \rightarrow Li^7$, and back to T via Li.



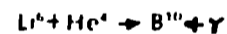
Of course the 2n can be multiplied to 4n by using



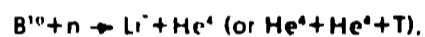
and the profuse n flux used to breed more fissionable isotopes for the hybrid reactor of Section 2. Also $He^4+T \rightarrow Li^7$ can be made use of.

Higher Temperatures

Other chains are possible at somewhat higher temperature. For instance,

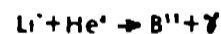


followed by



so we have recovered back both the helium and lithium. The reactions can be made to go in a cycle.

Again



and



would be another energetic sequence, which can occur with reasonably large cross-sections and also recover part of the original fuel.

Thus we see that there are a number of possible thermonuclear breeder chain reactions. The optimisation of the sequence of reactions with respect to maximal power output and maximal fuel recovery is being undertaken. ■