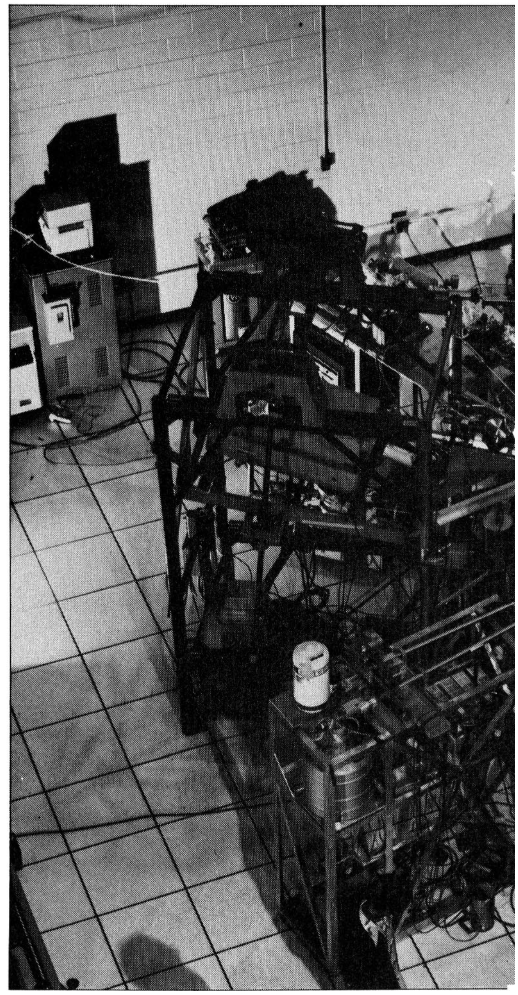

The fusion hybrid

Using fusion reactions for breeding fissile materials in addition to producing electric power may provide us with a safe and economic way to extend our energy resources.

Hans A. Bethe

In the last few years nuclear fusion by magnetic confinement has made great progress. However, an economical pure fusion power plant is still many years away. In this article I will discuss how a combination of fusion and fission power might be much closer, and might be very helpful both to fission and fusion power.

The idea of the fusion hybrid is to surround a fusion reactor (once such a machine exists) with a blanket of uranium or thorium. In the fusion of tritium and deuterium a fast neutron is produced. In the blanket, the neutrons will be captured, converting the "fertile" material, thorium-232 or uranium-238, into fissile isotopes, uranium-233 or plutonium-239, respectively. The fissile material then is used as fuel in ordinary nuclear reactors in which they undergo fission.

Such a hybrid design may multiply the energy produced in fusion many-fold, for two reasons: First, the energy released in each fission is about eleven times greater than that in a fusion reaction. Second, and more important, each fast neutron will generate several slower ones in the blanket, thus generating several fissile nuclei from fertile ones. This second property, which the hybrid shares with the breeder reactor, makes it possible for the reactor to be a net source of fuel. In a sense, the reactor's energy output is in two forms: fissile material and electricity. As we shall see, the conditions for making such a reactor economical are considerably less stringent than those for fusion reactors producing electric power alone. It also appears that hybrid reactors will raise fewer security problems than the fast breeder reactors now being planned and built.

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Fission power plants

Many of us believe that nuclear power (by fission) must contribute significant amounts to the power production both in the US and abroad. Even with a diminished rate of growth due to conservation, the demand for energy in the form of electricity will increase for a number of years. It is highly unlikely that fossil fuels will continue to be the almost exclusive source of electric power. It is also unlikely that solar-generated electricity will make a substantial contribution in the near future. Fission reactors, however, represent a power-generation system involving what is rapidly becoming proven technology, so that they can bridge the gap between decreased reliance on fossil fuels and whatever long-term power generation and distribution system is chosen.

To ensure a substantial contribution of fission power, there is need for an adequate supply of fissionable material. Basically this depends on the supply of uranium. In our present nuclear reactors (light-water reactors, or LWR) we use only the fissile isotope of uranium, U-235, which is about 0.7% of natural uranium. This being so, it takes about 6000 tons of uranium oxide to supply the fissile U-235 for one reactor through its lifetime, which is conventionally estimated to be 30 years.

There is considerable uncertainty about the supply of uranium ore. The "reserves" plus "probable" resources may be of the order of 2 million tons, but if "possible" and "speculative" uranium ores are included, the resources in the US are now estimated by the Department of Energy as over 4 million tons. This would supply about 700 reactors for their lifetimes. This is ample for the time being; it is now estimated that the total number of reactors in the year 2000 will be between 300 and 400. However, the figures mean that fairly early in the 21st century the uranium supply would come to an end, just as the supply of oil is threatening to do at an earlier time.

The most obvious way to stretch the uranium supply is by chemical reprocessing of the spent fuel, by which perhaps 25% can be added to the effective supply. A similar gain may be made by

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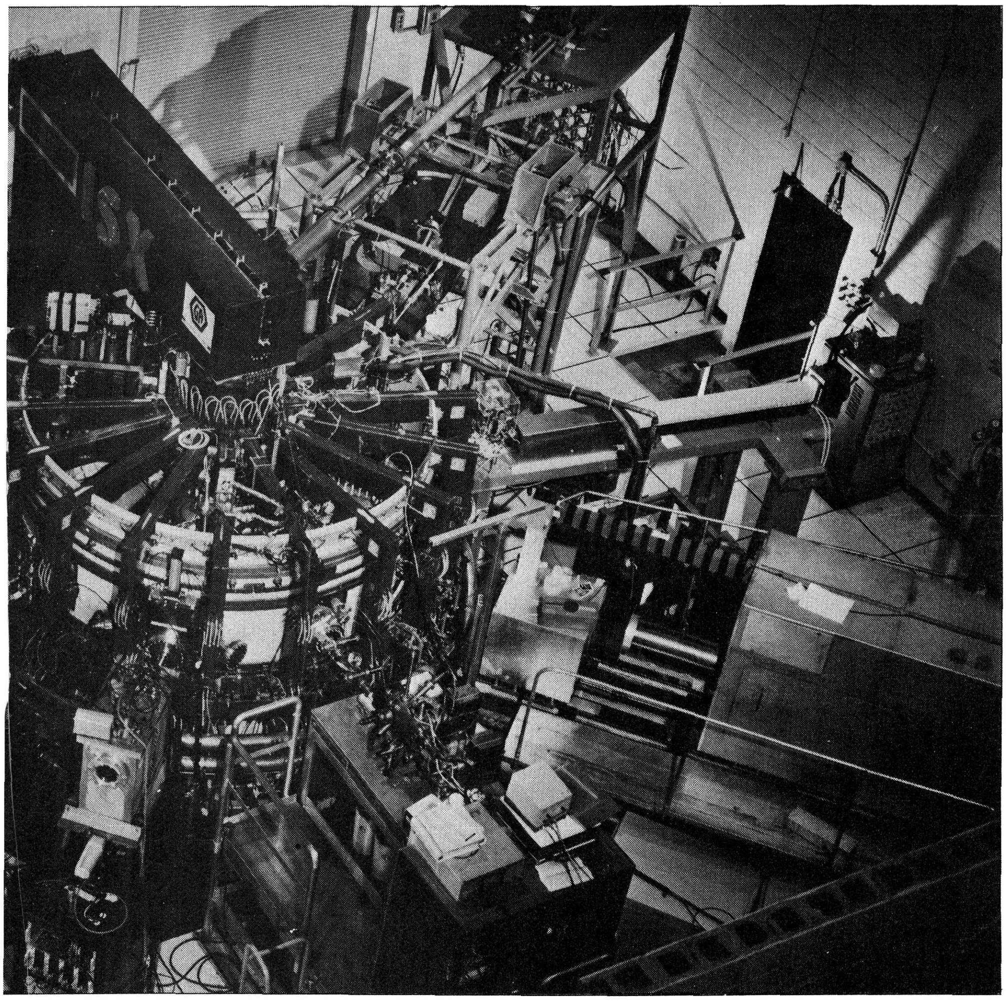


The ISX tokamak at Oak Ridge National Laboratory. It is surrounded by beam injectors and diagnostic apparatus. The toroidal vacuum chamber is within the current-carrying coils. The large iron yoke serves as the core of a transformer whose secondary is the plasma itself; the induced currents heat the plasma. Tokamak devices are among those that may be suitable for hybrid fusion–fission reactors. (Photo courtesy of ORNL)

using new methods for the separation of uranium isotopes to reduce the percentage of U-235 discarded in the "tails" of the separation process; at present the tails contain about 0.25% U-235, and this fraction might be reduced to 0.08%.

A much greater increase of the nuclear fuel supply can be achieved by the use of "advanced conversion reactors" (ACR), as has been recently emphasized[1] by Harold A. Feiveson, Frank von Hippel and Robert H. Williams of Princeton. They point out that various types of advanced converters, such as the Canadian heavy water reactor CANDU, the high temperature gas-cooled and graphite-moderated reactor (HTGR), or some modification of the light-water reactor using partly heavy water as moderator, might extend the lifetime of reactors very substantially, perhaps as much as a factor of 4. I believe this is a very good direction to go. But it must be done soon, as pointed out by Charles E. Till and his coworkers at the Argonne National Laboratory; [2] otherwise, the fissile uranium will all have been used up in ordinary light-water reactors before the advanced converters ever come into operation. Moreover, to get the full benefit from these reactors, chemical reprocessing of the spent fuel is essential.

The most commonly suggested method to extend our uranium supply is with the fast breeder. In this reactor, the fissile material is plutonium that has previously been produced in ordinary light-water reactors. In the breeder, a blanket of fertile material surrounds the reactor core, and neutrons from the core produce more fissile material in the core and blanket than is consumed in the core. Research on these reactors is well advanced, and until recently it was US policy to assume that breeder reactors would provide a long-range supply of nuclear fuel.

However, objections have been raised against reliance on fast breeders. Most importantly, President Carter fears that the plutonium produced in breeders could be misused for the manufacture of nuclear weapons. The President has therefore moved to stop construction of the breeder demonstration reactor in Clinch River, and is trying to prevail on other countries to stop their breeder development also. It is unlikely that President Carter's pressure on other countries will be successful. Already some years ago France built a very successful demonstration breeder, the Phenix, and she is rapidly proceeding toward a larger, commercial version, the Super Phenix. Whatever the outcome of the international discussions on the fast breeder may be, it is certainly desirable to avoid the spread of breeder reactors all over the world.

The fusion reactor

In this article I shall consider only fusion by magnetic confinement, not "inertial" confinement such as in laser fusion, but many of the ideas I discuss would also be applicable to the latter. At present, the technology of magnetic confinement is considerably farther advanced. In most of the successful magnetic confinement devices, energy is provided to the plasma of deuterium and tritium by the injection of neutral deuterium atoms of considerable energy, say 100 keV, well above the desired temperature of the plasma of about 10 keV. Efficient accelerators have been built so that the efficiency v_d of converting electric energy into kinetic energy of the deuterium atoms is expected to be quite high, perhaps 60–70%.

A good figure of merit of a fusion device is

$$Q = \frac{\text{energy released by fusion}}{\text{kinetic energy of injected atoms}}$$

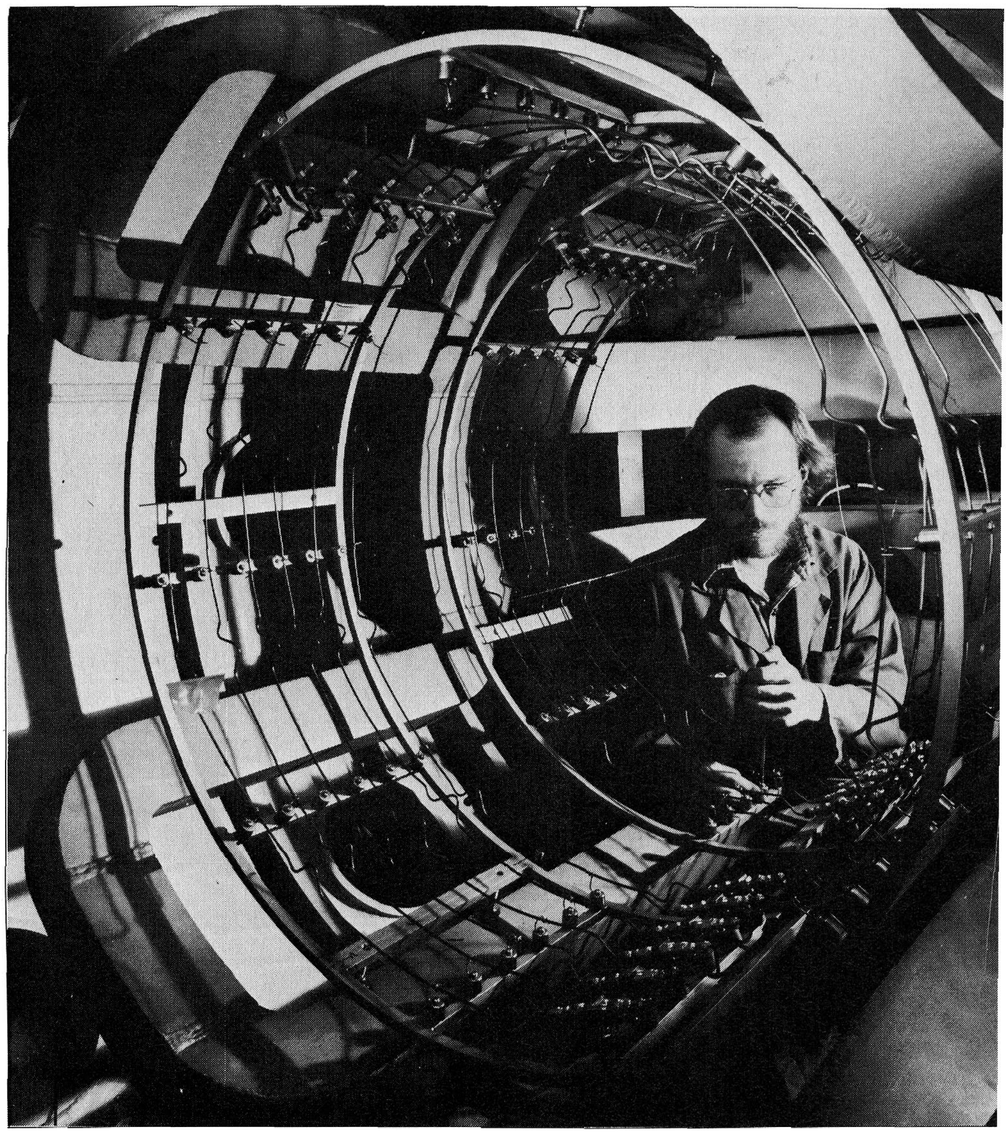
Recent progress in fusion has led to the expectation that in the 1980's fusion reactors will be able to achieve $Q = 1$. A value for Q of 1 or less is clearly of no practical use for a pure fusion power plant: More energy is put into the plasma than comes out of it in terms of fusion energy. Moreover, we must consider the efficiency v_e of converting the fusion heat into electrical energy and the efficiency v_d of converting electrical into deuterium kinetic energy; typically v_e is about 30-40% and v_d is 60–70%. The heat coming out of the fusion device is the sum of the deuterium kinetic energy and the fusion energy, or $1 + Q$ times the former, so that the ratio of electric energy output to input is

$$Q' = (1 + Q)\phi_e\phi_d \cong \frac{1}{4}(1 + Q)$$

Thus the value of Q itself must be at least 3 for a pure fusion device to break even, although by special tricks this might be reduced to about 2.

The most advanced of the magnetic-confinement fusion devices is the tokamak, which is discussed by Masanori Murakami and Harold Eubank elsewhere in this issue. Many tokamak devices have been built in the USSR, where the idea originated, the US, and other countries. Currently a large version, the TFTR, is being built at Princeton; it will probably be completed in 1982 and may begin operation the following year. Its designers expect the Princeton tokamak to reach Q = 1.

Another promising device is the tandem magnetic mirror being developed by the Lawrence Livermore Laboratory (see PHYSICS TODAY, February 1978, page 18). In this device, the magnetic field is made by coils of a complicated shape, somewhat like the seams on a baseball; the resulting field is intended to act as a "magnetic mirror," preventing the ions and electrons in the device from escaping. At present, Livermore is putting two such baseballs in tandem at the two ends of a long cylinder in which there is a magnetic field made by a solenoid. The designers hope that the ions and electrons will move freely along the cylinder, and then be reflected by the baseballs at either end. If funds are approved to construct a larger version of such a tandem mirror it may be ready soon after the tokamak. Its Q may also approach 1.



The fission–fusion hybrid

A fusion reaction between deuterium and tritium produces an alpha particle and a 14-MeV neutron. In a hybrid reactor the neutron escapes from the plasma and is absorbed in the blanket of fertile material. Its first reaction with a thorium or uranium nucleus is likely to be either one that knocks one or two additional neutrons off the nucleus or a fission reaction, in which as many as four neutrons may be released. Thus, each 14-MeV neutron provides at least two, and possibly four, neutrons that can be captured.

Some of these neutrons must be used to replenish the tritium used in the initial fusion reaction. The standard way to do this is to include lithium-6 in the blanket: The reaction between a lithium-6 nucleus and a neutron produces an alpha particle and a tritium nucleus. This reaction will compete for neutrons with the fissile material. Furthermore, some of the neutrons from the fusion reaction will escape before being captured because the blanket cannot completely surround the plasma. Even if one allows 1.2 neutrons per fusion reaction for lithium capture (to be on the safe side for regenerating tritium) and accounts for other neutron losses, calculations show that about one neutron per fusion reaction will be captured by fertile material.

The various proposed fusion reactors and the possible fertile materials differ somewhat in potential usefulness as hybrids.

The main advantage of the tandem mirror is its geometry. It will be easy to surround the cylinder by a cylindrical blanket of uranium and/or thorium to manufacture fissile material. The tokamak, on the other hand, is toroidal in shape, and it is therefore somewhat more difficult to accommodate the blanket. Nevertheless the fusion group at Westinghouse has designed a "fuel factory" blanket for a tokamak that should work reasonably well. Another advantage of the mirror tandem is that it could operate continuously, not in pulses, as the tokamak does.

The two kinds of fertile material differ substantially in the contribution of fission to the neutrons that can be absorbed in the blanket. In U-238, the cross section for fission by fast neutrons is quite large, while in Th-232 it is small (about 12% of the total cross section). This means that a uranium blanket will generate more neutrons per fusion than a thorium blanket, which is an advantage. On the other hand, the fissile nucleus produced in a uranium blanket is Pu-239, while in thorium it is U-233, a more desirable alternative for reasons that we will discuss later.

The fissions in the uranium blanket also contribute greatly to the energy generated by the fusion plant. The cost of the plant is very largely determined by the total amount of energy generated because all this energy has to be carried away from the blanket and either converted into electricity or dissipated. Therefore it is reasonable to compare fusion hybrids of a given total power, rather than given fusion power. Table 1 is based on work by a group at the Argonne National Laboratory.[3] The total power is assumed to be 3000 MW thermal energy because this is the thermal power of a "standard" fission reactor (which produces about 1000 MW electrical power). The hybrid is assumed to operate at 70% of capacity, and the blanket is assumed to subtend about 70% of the solid angle around the fusion device. As table 1 shows, the total amount of fissile material produced in the two blanket materials is almost the same, 1600 or 1700 kg per year, which is a very substantial fuel supply for fission reactors.

The two designs differ substantially in the fusion power: The blanket including uranium develops a lot of fission power, almost five times as much as is produced by the fusion reactions themselves, so that only 510 MW out of the total 3000 MW (thermal) is due to fusion. With the pure

The tandem mirror machine at Lawrence Livermore Laboratories. On the left is the interior of the central tube. A technician is tightening down the titanium "getter" wires; after each plasma pulse titanium is evaporated from these wires and deposited on the vacuumchamber walls to cover adsorbed impurities. The large coils provide a focussing field for the plasma beam. It is this part of the machine that could be surrounded by a blanket of fertile material to produce fissile isotopes for use in ordinary fission power plants. On the right is a "beam's eye view" of one of the two magnetic mirrors that are at the ends of the tube shown at left. Note that the main coil for the mirror is shaped like the seam of a baseball. (Both photos by David Proffitt, Lawrence Livermore.)

thorium blanket, the fusion power is 1150 MW; the blanket fissions in this case are only 1.6 times the fusion power.

The important point is that fission reactors require relatively little "make-up" fuel. In a "standard" fission reactor of 3000 MW(th), operating at 70% of capacity, about 1000 kg of fissile material are consumed per year, by fission or by radiative capture of neutrons in fissile nuclei. But a large fraction of this is reproduced, by other neutrons being captured in *fertile* material that is also in the fission reactor: In the present type of light-water reactors this fertile material is U-238 because the reactor fuel is 3% U-235 mixed with 97% U-238. In a future advanced converter reactor[1] the fissile material may be U-233 and the fertile a combination of Th-232 with some U-238. (The latter is added so that chemical separation of uranium from thorium would still leave the uranium unsuitable for bomb manufacture.) The fraction of fissile material reproduced in the reactor is called the conversion ratio, *C*. A light-water reactor may have a conversion ratio of 0.6 if the fissile material is U-235 or Pu-239, or perhaps up to 0.7 if it is U-233. (The difference is mainly due to the fact that radiative capture of thermal neutrons is much less probable in U-233 than in the other two nuclei, so that more than 90% of the neutrons captured in U-233 lead to fission, and thus to emission of several neutrons that can then be captured by fertile material.) In an advanced reactor, conversion ratios may be as high as 0.9 for U-233 fuel or 0.85 for U-235 or plutonium, and these may be pushed even closer to 1 by frequent reprocessing.

The make-up fissile fuel required per year by a standard-size fission reactor is

$$1000\,(1 - C)\ \mathrm{kg}$$

Assuming, on the basis of table 1, that a standard fusion hybrid produces about 1600 kg fissile material, we find then that one hybrid can provide fuel for

$$S = \frac{1.6}{1 - C}$$

fission reactors. We shall call these "satellites" of the fusion hybrid; table 2 gives their number for two types of hybrid as well as for a typical fast breeder. The considerable number of satellites is the strength of the hybrid idea: We need only a few hybrids to support many fission reactors whose operation and cost are already well known. The fast breeder. while it easily reproduces its own fuel, does not produce very much *extra* fissile material that could be used to fuel thermal reactors.

It is generally agreed that fast breeders and fusion reactors will be considerably more expensive per unit power than thermal reactors. Therefore we should think of a mixed economy, containing thermal reactors together with either fusion hybrids or fast breeders. The total cost and the total power of all the reactors in the system is relevant. If the fast breeder produces the fuel, its cost is quite important because a relatively large fraction of all the reactors would have to be fast breeders. By contrast, if we take a mixture of thermal reactors and fusion hybrids, the latter only need to be a small fraction of the total number. This permits great flexibility on cost and other characteristics of the hybrid.

The use of a fusion device to make fissionable material entirely changes the energy balance of the reactor system. If one fusion hybrid plant fuels S fission plants of the same (thermal) power (which we take as a unit), the total electric power produced by the system is

$$(S + 1)\,\nu_e$$

units. If the fraction of fusion power in the hybrid is F, then the electric power needed to accelerate the deuterons is

$$\frac{F}{Q\,\nu_d}$$

in the same units. (As before, Q is the ratio of fusion energy released to deuterium kinetic energy and ν_d is the efficiency of converting electric energy to deuterium kinetic energy.) The net electricity produced by the whole system is then

$$\left(S + 1 - \frac{F}{Q\phi_d\phi_e}\right)\phi_e$$

of our units. It is clear that $Q = 1$ will be ample to produce a lot of net electricity, due to the large value of S for hybrid reactors. It is also clear that values of Q as small as about 0.1 would not be sufficient, but that not much is gained by raising Q substantially above 1.

Advantages of the hybrid

The fusion hybrid could supply fuel for nuclear fission reactors very far into the future. The only material needed will be "fertile" material, uranium and thorium. Because the abundant isotopes U-238 and Th-232 are used, all of the uranium and thorium will be available for power production, not just a fraction of a percent as at present in light-water reactors. Much lower grade uranium and thorium ores

Table 1. Output of hybrids

Blanket	U + Th	Th
Produced U-233 (kg/yr)	1200	1600
Produced Pu-239 (kg/yr)	500	0
Fusion power, MW(th)	510	1150
Net electric power, MW, $Q = 1$	220	−750
Net electric power, MW, $Q = 2$	600	120

The quantities shown are for a 3000 MW (thermal) "standard" fusion–fission reactor, according to calculations in reference 3.

can therefore be used than at present: The price of the ore, as well as the damage to the environment due to mining, for a given amount of energy becomes negligible. This means, for example, that uranium can then be extracted from Tennessee shales and New Hampshire granite. In the United States alone, there is then probably at least 30 million tons of uranium and thorium combined. Assuming that there will be 1000 standard nuclear reactors in the US in the future, this supply would last 30 000 years, giving us a comfortable fuel assurance. This assurance, of course, could also be given by the fast breeder. The hybrid also needs lithium, which is perhaps about as available as uranium, and deuterium, of which there is an essentially unlimited supply.

Only a few fusion fuel factories will be needed. Their number depends mainly on the type of fission power reactors that are to be used. In table 2 we give the number S of fission reactors that can be supplied by one factory; it is large, between 4 and 16.

This fact makes possible a complete separation of fuel and electricity production. Such a separation is highly desirable in the case of fusion, because a fusion plant, at least in the early years, will probably be quite complicated to operate, and utilities may not be willing to face this task. The fusion fuel factories could instead be operated by the government, and could be staffed by specialists, including a large fraction of engineers. The factories would then deliver nuclear fuel to the utilities, which would use it in ordinary fission power plants whose operation by now is sufficiently standardized.

Whether the fuel factories produce or consume power is not very important because their number is relatively small. In the last two lines of table 1 we show the net power produced for different cases. It was assumed that the efficiency of accelerating deuterium is $v_d = 2/3$, and the thermal electric power efficiency of the fusion plant is $v_e = 1/3$. The combined uranium–thorium blanket has the advantage that the fuel factory itself produces some net electric energy, even with $Q = 1$, while with a pure thorium blanket, electric power would have to be bought from the grid. A value $Q = 2$ would remedy this.

All these points are rather different for the fast breeder reactor. Because a breeder can supply rather few converter reactors (table 2), it is important that the breeder itself produce power as well as fissionable material. Therefore, the reactor would normally be operated by a utility, just like any other power plant. The separation of fuel and of power production would be very difficult in the case of a system depending on fast breeder reactors.

The possible separation of fuel and power production for systems involving hybrids makes possible great flexibility in their design. Of course the fusion hybrid, like the breeder and the advanced converter, does require chemical processing to separate the U-233 formed from thorium and some fission products. But this processing would all be done at the fuel factories themselves.

The most important advantage of the fusion-hybrid system would be that the fuel factories could easily be safeguarded, just because there are few of them and they are separate from the normal utilities. If thorium is used for the blanket, then U-233 would be separated chemically once enough of it has accumulated. However, the U-233 would then again be mixed with a larger amount of U-238, so that the resulting mixture contains only 12% U-233 and thus could not be used for the manufacture of nuclear weapons Only this non-explosive mixture would ever leave the plant. If a uranium blanket is used, and plutonium produced, the best that could be done in safeguards is to mix the plutonium with a larger amount of uranium, again making a non-explosive mixture. However, this is clearly not as effective as the "denaturing" of U-233 with U-238 because plutonium could be separated by chemical means. This is one of the advantages of U-233.

The other advantage, already mentioned and used in table 2, is that U-233 is the best of all easily available nuclear fuels for use with thermal neutrons. The reason is that it has a small cross section for the capture of neutrons to form U-234; essentially every neutron absorbed in U-233 leads to fission. The best advanced converter reactors therefore would use U-233, not U-235 or plutonium.

Table 2. Number of "satellites"

Converter	LWR	Advanced
Hybrid with Th	5	16
Hybrid with U + Th	4	11
Fast breeder	0.7	2.7

The number of satellite thermal reactors supplied by fuel-producing reactors is derived from calculations in references 2 and 3.

The fact that the fuel factories would be separated from electricity producers also has a great advantage for the prevention of proliferation of nuclear weapons. In fact there would not need to be any change from the present situation; fuel would be supplied by those countries that presently supply nuclear power reactors and nuclear fuel. These countries would, in future, have fusion fuel factories under strong safeguards against diversion of the produced fuel. Since there will be few factories they would not supply an excessive amount of electricity to the countries in which they are located. On the other hand, if breeder reactors were used, the large amount of power they would deliver might be too much for the countries that supply nuclear fuel.

An advantage of the fusion hybrid, as compared with a pure fusion reactor, in the early stages of development is the reduced demand on reliability. For a reactor delivering power to the grid, it would be very detrimental if its operation were frequently interrupted by some malfunction. But for production of fuel it is entirely acceptable to have the plant operating off and on.

Cost estimate

When I first wrote about the fusion hybrid[4] I found it very difficult to estimate its cost. But now the work of the Argonne group[3] has given a reasonable basis for an estimate. They argue that the main cost is related to the removal of heat, and should therefore be proportional to the total thermal power. Fur-

Table 3. Investment cost of various nuclear power systems

Converter reactor	Fusion hybrid with blanket of U + Th, $Q = 1$	Th, 1	Th, 5	Fast breeder, with breeding ratio of 1.2	1.4	Use of U_3O_8, at $200/lb
LWR, $C = 0.6$	1.39			1.33	1.25	1.35
$C = 0.7$		1.67	1.26	1.30	1.22	
ACR, $C = 0.85$	1.40			1.36	1.32	
$C = 0.9$		1.46	1.33	1.33	1.30	1.35

The figures are estimates of the total cost of fuel factories plus converter reactors, relative to the cost of light-water reactors without fuel. In all cases the whole system is assumed to produce the same net electric power.

thermore, since heat removal from the blanket is likely to be complicated, they take the cost per unit power to be the same as for a fast breeder reactor. I then add an amount proportional to the fusion power because the costs of accelerators for the deuterium atoms, of the magnetic coils and of other parts of the reactor will be roughly proportional to the fusion power.

On the basis of these principles, I calculate the cost of a hybrid plant relative to a light-water reactor of the same power to be

$$X = B + \lambda F$$

where B is the ratio of the cost per unit power for a breeder to that of a light-water reactor, F is the fraction of power in fusion and λ the added cost of fusion per unit of power. As in my earlier paper,[4] I assume $B = 1.5$ and that the cost per unit power of an advanced converter is

$$\tfrac{1}{2}(B + 1) = 1.25$$

the latter is in close agreement with the assumption of Feiveson, von Hippel, and Williams. Using some further data in reference 3, I take $\lambda = 1.5$; then the cost of a pure fusion reactor per unit power would be

$$X_f = B + \lambda = 3$$

that is, 3 times that of a light-water reactor, which is not unreasonable.

Using these principles, I have calculated the investment cost of fusion hybrids and fast breeders, and of systems containing one such reactor and S thermal reactors, where S is given in table 2. All numbers are relative to the investment cost of a standard light-water reactor; the latter thus does not include the cost of fuel. The results are given in table 3.

Table 3 compares the cost of fusion hybrids of various types with fast breeders. If the hybrid blanket is pure thorium, we take account of superior properties of U-233 in the thermal reactor in assuming that the conversion ratio C is 0.7 for a light-water reactor and 0.9 for an advanced converter. For a combined blanket of uranium and thorium, the less good performance of plutonium in a thermal reactor is assumed to degrade C to 0.6 and 0.85, respectively. Nevertheless, if Q = 1, the hybrid with thorium in the blanket is more expensive because the fuel factory has to "buy" electric power from the converter reactors. If a Q of 5 can be achieved, this relation is reversed, because the cost of the uranium–thorium blanket is not much decreased by the higher Q.

The most striking result is that the cost of a system using a fast breeder and converter reactors is roughly the same as that involving a fusion hybrid. It should be remembered, however, that the fast breeder essentially exists (for example, the French Phenix) while the fusion hybrid is still on the drawing board. Therefore the cost figures for the fast breeder are far more reliable than for the fusion hybrid.

As I have mentioned, the unit of cost is the pure investment cost of light-water reactors of the same power, without counting the cost of the fuel. (The fuel cost for the hybrid or the fast breeder is negligible; of course in all reactor types the fuel has to be fabricated; this cost is assumed to be the same for all types and has been omitted.) The last column of table 3 gives the cost of a set of converter reactors including the fuel, assuming a price of \$200 per pound of U_3O_8 (the present price is somewhat over \$40). Conventional assumptions are made for the LWR, in other words, an investment cost of \$750 (1979 dollars) per kilowatt and a 16% annual charge on investment. With these and our other cost assumptions, advanced converters are about as cost effective as LWR's, and fuel-producing reactors (breeders or fusion factories) cost about the same as buying fresh uranium for converter reactors.

The net effect of the possibility of a fusion hybrid (or a fast breeder) is, then, that it sets a ceiling of \$200 on the price of uranium ore that is worthwhile to mine.

An important question is the cost of the initial development. It has been estimated that it would cost about \$10 billion to fully develop the breeder to a commercial-size prototype, and there are plausible arguments for supposing that a fusion plant and a fast breeder have similar development costs.

Stepping stone for fusion

While I have emphasized the use of fusion hybrids for supplying fuel to fission reactors, it is equally important as a step in the development of pure fusion. At present scientists working on fusion expect to get an energy factor, Q, around unity in the 1980's. This would suffice for a hybrid. For a pure fusion device a value of Q near 10 or higher will probably be required, taking into account the efficiency factors v_e and v_d.

Improvement in any technical process comes with experience. Building a fusion hybrid would give such experience with a large-scale fusion device, while at the same time fulfilling a useful purpose of its own. It seems important to me to have an achievable goal in the not too distant future in order to encourage continued work, and continued progress, toward the larger goal, in this case pure fusion.

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