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Controlled Nuclear Fusion: Status and Outlook

Besides plasma confinement, technological and environmental factors are essential.

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The attempt to generate power by controlling nuclear fusion will make an interesting topic for philosophers and historians of science and technology. If such an extravagant statement sounds forced, it is just meant to say at the outset that many factors, not all scientific, and some for the first time, have helped put the state-of-the-art where it is now. I shall try to give some account of these things.

Elements of the Problem

Controlled fusion research has passed through several epochs, the first of which was initiated by four items. First came measurements of reaction energies and rates between hydrogen isotopes and other light elements, which showed that under proper conditions large energy releases would be possible. Second, the well-known laws of single particle physics seemed to show how an assembly of high energy ions and electrons could be confined in magnetic fields long enough to establish the proper conditions. Third, the radioactive ingredients and by-products of fusion appear to be much less hazardous than those associated with nuclear fission: therefore, fusion reactors would be simpler and safer than fission reactors. Fourth, deuterium is a fusion fuel in plentiful supply—one part in 7000 of ordinary hydrogen; and extraction from ordinary water is not difficult. So matters stood in the early days, say up to 1955. Only the first of these items is necessary to make H-bombs. The combination of all four items captured the imagination of a sizable and very competent fraction of the physics community. The ensuing search for controlled fusion—the ultimate power source—has sometimes taken on a moral character, possibly as a reaction to the darker uses to which nuclear energy had been put. Whatever the reason, the efforts exerted by some might be compared to those of an Everest climber who knew that Prometheus was chained to the top. And a good thing, too, for the 1953 worker didn't see the whole field of plasma physics that lay yet to be discovered between his hopes and their realization. Whether it is a field or a gulf is yet to be discovered, and attempts to cross it during later epochs are briefly accounted below.

The present consensus is that, scientifically speaking, controlled fusion is probably attainable. But if fusion reactors are to be truly practical, there are other requisites: producing large volumes of magnetic field at low cost, minimizing the effects of material damage by high energy neutrons, and so forth. All these are equally essential to success; their natural laws being better understood than those of plasma physics, less room exists either for maneuver or speculation.

These phrases introduce the several major topics: how things are now, what is still needed to demonstrate scientific feasibility, what more is needed to make a practical fusion reactor, and how fusion does or does not fit our supposed future requirements.

Several exothermic fusion reactions exist. The reaction of deuterium (D) and tritium (T)

$$D + T \rightarrow {}^4He + n + 17.6 \text{ Mev} \quad (1)$$

is the most attractive, and I build the discussion upon it. The energy is small compared with 200 megaelectron volts per reaction from uranium fission but is more per unit mass. At about 100 kiloelectron volts, the reaction cross section reaches a peak at 5×10^{-28} square meter, which is very large by nuclear standards. Of the 17.6 Mev, 3.5 appears with the ^4He nucleus, and 14.1 with the neutron.

Many difficulties in the way of developing fusion power can be derived from these simple facts. First, consider the nuclear fuel. Deuterium is almost cost-free, but tritium does not occur in nature and hence must be regenerated with the neutrons from the fusion reaction.

The worst problem is presented by the nature of the reaction itself, because the particles must have (about) 10 kev energy or more so that the D and T nuclei can overcome their mutual electrostatic repulsion and fuse. Unfortunately, the cross section for scattering via this repulsion considerably exceeds the fusion cross section at such energies; hence the particles scatter each other several times before reacting. Thus it follows that the fuel will be a randomized collection of ions whose average energy must exceed 10 kev. In conventional terms, this is a gas at a temperature exceeding 10^8 degrees Kelvin. In fact, it will be a fully ionized plasma of D^+ and T^+ ions containing an equal total density of elec-

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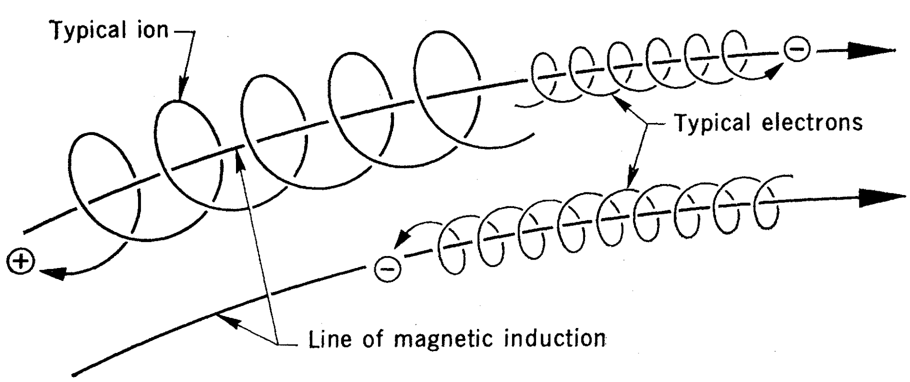

Fig. 1. Orbits of ions and electrons in a magnetic field.

trons to make the medium macroscopically neutral.

As I have implied, the principal difficulty comes in confining this plasma. A D-T nuclear explosive device stays together long enough—less than 10^{-7} second—by inertia alone for the components to react. In the process, the ^{4}He nuclei (and to some extent the neutrons) slow down in the unreacted material and heat it to an "ignition" temperature; transient pressure is millions of atmospheres. For a slower, controlled reaction, the pressure must be something that real structures can withstand; systems that we visualize will have dimensions of the order of 1 to 10 meters, and therefore pressures exceeding (say) a few hundred atmospheres are hardly believable. This restriction, plus specification of temperature already made, determines the density of the ions. Depending on the arrangement, desired D + T ion density turns out to be 10^{20} to 10^{22} m^{-3}, some 7 to 9 orders of magnitude below solid densities, and 4 to 6 orders of magnitude below that in the air around us. Required confinement time for a useful fraction of the nuclear fuel to react is 0.01 to 1 second. The most important parameter is the product of the density by the time, which should be 10^{20} sec m^{-3} or more—the so-called Lawson criterion. Total reacting nuclear mass at any one time would be only about 1 gram, even in a system that operates continuously at several thousand megawatts. All this is remote from any explosive regime.

Present Scientific Program

I will not review in depth the voluminous plasma physics underlying the schemes by which the plasma is hoped to be confined; but some acquaintance is necessary for what follows. The main schemes being developed so far involve use of large volumes of high magnetic fields. Plasma ions and electrons are hindered by magnetic forces from moving across the direction of magnetic fields, but can spiral along the field lines, as in Fig. 1. Thus (naively), confinement in the two directions perpendicular to the field direction is achieved, and one might have to worry only about confinement along the field direction.

From these simple thoughts arose in the first epoch two largely separate categories of device (*1*). In Fig. 2, field lines are curved to form a closed toroidal system; there is no escape except across field lines, and devices of this generic type are called closed systems. In the other generic type of Fig. 3, ions (and electrons) are reflected by increasing magnetic fields at each end. Here, an additional mechanism is required: each ion moving along a magnetic field line has fixed total kinetic energy U—at least until it interacts with the other ions and electrons in the system, or undergoes fusion. The total energy U can be thought of as being composed of two parts, an energy $U_\perp$ of gyrating motion perpendicular to the field line, and a part $U_\parallel$ of motion along the field line. That is

$$U = U_\perp + U_\parallel \qquad (2)$$

Now it can be shown (*2*) that the magnitude of the perpendicular component $U_\perp$ is proportional to the magnitude B of the magnetic field; that is

$$U_\perp = \mu B \qquad (3)$$

where μ is a constant (called the magnetic moment) for each particle, depending on details of its orbit. From this we find

$$U_\parallel = U - \mu B \qquad (4)$$

The consequence of Eq. 4 is straightforward—if the field B becomes high enough in the ends of the device shown in Fig. 3, then μB rises to equal U itself, and no energy $U_\parallel$ is left for parallel motion. The particle must be "reflected" from these high field regions, hence contained in the center part. The device is appropriately called a magnetic mirror (*3*).

A difficulty of these "open-ended" systems of Fig. 3 is just that—open ends. An ion or electron whose orbits happen to lie almost along the field direction in the middle of the device has a low value of the magnetic moment. Then the maximum field B at the mirrors is insufficient to reflect the particle, and it escapes out one end. Coulomb interactions continually scatter particles into such directions; hence magnetic mirrors are inherently leaky, even if no worse calamities befall.

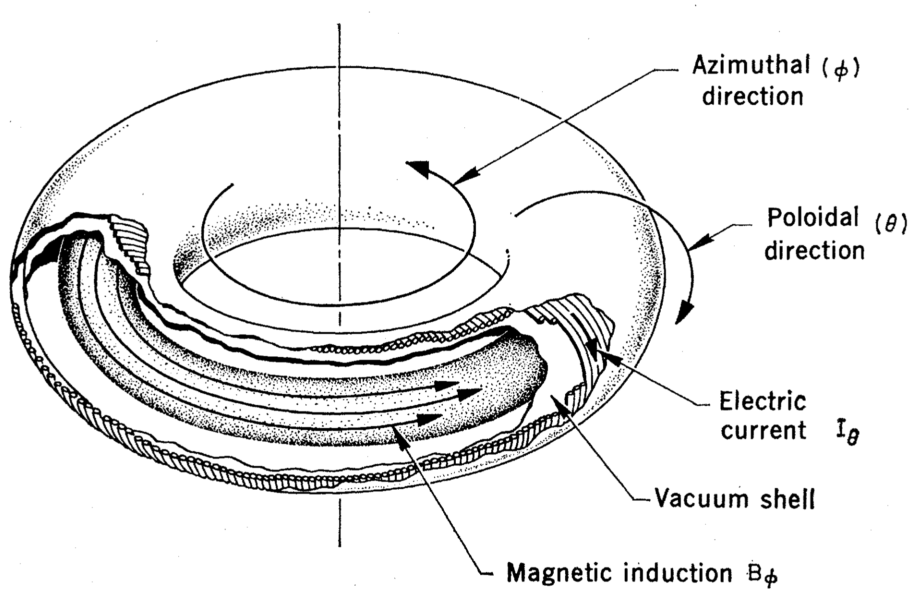

Fig. 2. Toroidal magnetic field B_ϕ made by poloidal electric currents I_θ.

In each case, the confining field might typically have a maximum strength of 8 to 10 tesla (*4*), and an equivalent magnetic pressure $B^2/2\mu_0$ (in meter-kilogram-second units) of 300 atmospheres.

The difficulty with all these truly ethereal schemes is that the plasma turns out to be unstably confined, because a number of electric effects which are negligible for a few isolated particles but important in a large assembly (that is, a plasma) were not included. Thus ended the first epoch of fusion research, a sort of age of innocence. For either the closed or open systems of Figs. 2 or 3, some field lines necessarily bow outward away from the plasma: at such places the plasma tends to develop uncontrolled aneurisms. Modifying the basic configurations (and increasing its cost and complexity substantially) will reduce these unstable growths, but it seems certain that a weak turbulence will remain. As a result, plasma could diffuse toward the surrounding vacuum walls and out the ends at a high rate.

The idea of diffusion is useful for illustrating the situation in the present second epoch of fusion research. If the plasma internal motions can be described by a diffusion theory (there is some doubt about this, which we ignore here), then a diffusion coefficient D can be assigned. The theory then states that the confinement time τ_c in (say) a long cylinder of wall radius r_w should be about

$$\tau_c = r_w^2/6D \qquad (5)$$

For long τ_c, we desire small diffusion, but even more importantly large systems. Present custom (*5*) has it that the diffusion coefficient is likely to be some small fraction of the Bohm value D_B for a fully turbulent plasma, where

$$D_B = \frac{kT_e}{e} \cdot \frac{1}{16B} \qquad (6)$$

Here, (kT_e/e) is the electron temperature measured in electron volts. Then according to this rubric, we have

$$D = D_B/A \qquad (7)$$

where the dimensionless factor A represents confinement quality, measured in "Bohm times." If $A = 1$, the plasma would be lost by diffusion with a coefficient equal to D_B. For adequate fusion system confinement, it turns out that we must have $A \gtrsim 100$ at least, the precise number depending upon the arrangement (*6*).

It is both encouraging and salutory to see where present experimental devices are in relation to these goals. There are many such, but in this summary one example must suffice. The Tokamak, one of the most promising devices today (*7*), is an easy extension of Fig. 2, developed first at the Kurchatov Institute in Moscow, now also appearing in various guises at several plasma laboratories in the United States. Figure 4 shows the arrangement: the strong azimuthal field B_ϕ remains as before; but now the toroidal plasma is itself also the secondary loop of a transformer, which accomplishes two additional purposes. First, a strong current pulse on the primary winding ionizes the gas and generates a secondary plasma current I_ϕ; that current heats the plasma by inducing weak dissipative turbulence—hopefully just enough to heat it but not lose it (Fig. 4). Second, the current I_ϕ produces a new poloidal magnetic field B_θ as shown; the two fields combined, reminiscent of the crossed plies of a tire tread, make up the confining structure. Analysis shows that the plasma should be stable against ordinary hydromagnetic instabilities in the magnetic well so formed. The remaining higher order modes might be too weak to cause excessive diffusion. One penalty for these improvements is abandonment of true steady-state operation, for the device must now be run in long pulses—vide the transformer.

At this time, hopes that a Tokamak device will establish the scientific feasibility of fusion reactors are high. The

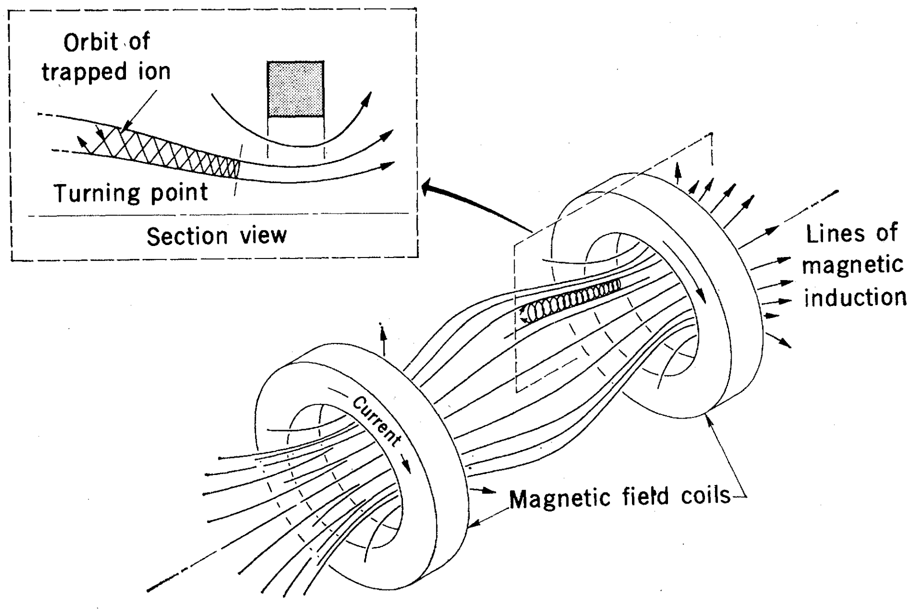

Fig. 3. Magnetic mirror particle (and plasma) confinement configuration.

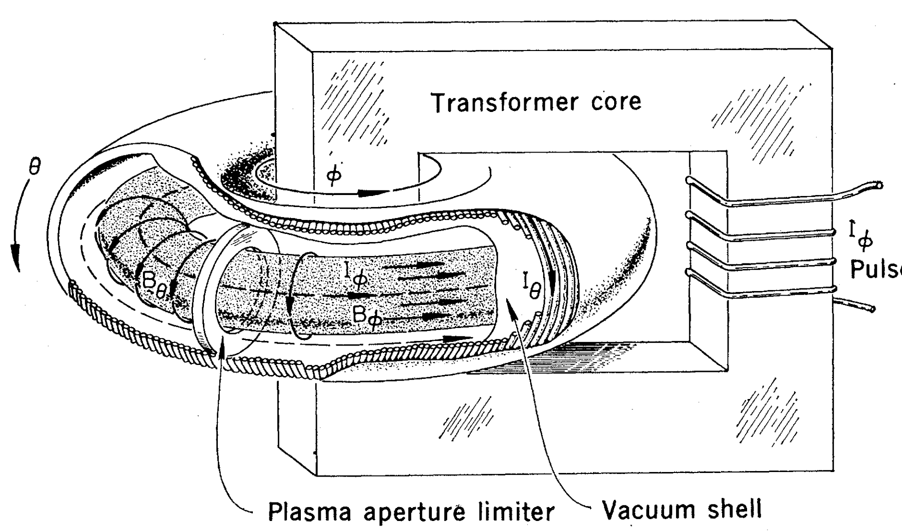

Fig. 4. The Tokamak plasma confinement scheme.

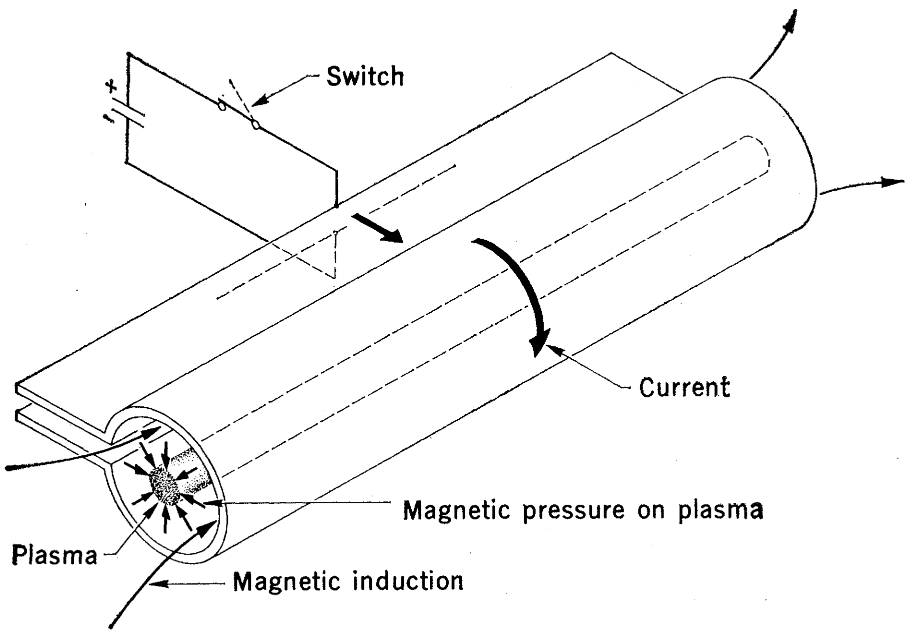

Fig. 5. Pulsed plasma heating and confinement scheme (so-called θ-pinch).

largest device operating ("T-3" at Kurchatov) has a major diameter of 2.0 m, the minor plasma diameter is about 0.3 m, the maximum field B_ϕ is 3.5 tesla, and the current I_ϕ is 10^5 amperes. For these efforts, the results (*8*) are: plasma density is $3 \times 10^{19}/m^3$, confinement time τ_c is 0.03 second, the electron temperature is > 1 kev, and the ion temperature is 0.5 kev. Each of these numbers (which has been measured both by the U.S.S.R. and a visiting team from the United Kingdom) is about a factor of 10 too low, but very good by recent standards; and there is more to the story. From Eqs. 5 to 7, we calculate $A \approx 80$; that is, the confinement time of 0.03 second is some 80 times as long as turbulent Bohm diffusion would predict. This bespeaks a fairly quiescent plasma, almost good enough (in these peculiar terms) for a fusion reactor. A respectably optimistic expert could argue that only the small size and relatively low magnetic field prevent the plasma from lasting an adequate number of seconds. Exploring whether larger or higher field devices give a closer approach to fusion reactor parameters is now an exciting activity; the next generation of experiments should tell much.

Analogous descriptions might be made about some magnetic mirror experiments [the so-called 2X experiment at the Lawrence Radiation Laboratory, Livermore, California, for instance (*9*)] or fast shock-heated plasmas [Scylla at Los Alamos, for example (*10*)]. This last device is shown very schematically in Fig. 5. The capacitor discharge through the single-turn coil generates a rapid-rising strong magnetic field ($< 10^{-6}$ second, 15 tesla). The field acts as a radial piston, compressing an initially cool plasma into a hot, dense one. In each of these various schemes, the combinations of density, temperature, and confinement time differ. For the Scylla experiment, we find densities up to 5×10^{22} m^{-3}, and temperature ≈ 5 kev, which are nearly satisfactory for fusion; but $\tau_c \approx 10^{-5}$ second is very short: plasma squirts out the open ends of the device. A longer one (Scyllac, 10 m) is being built to reduce these end effects.

General Technological Feasibility

Divinations from plasma physics may permit or deny the possibility of useful power from controlled fusion, but they cannot guarantee it. Some applied problems that are substantially independent of the particular geometric model are:

1) Plasma conditions in imagined practical devices, such as ion and electron temperatures, the fraction of fuel burned up per pass through the reactor, and radiation from the plasma surface. This might be called plasma engineering.

2) Regenerating tritium (for a D-T reactor) in a surrounding moderator-blanket by means of the 14.1-Mev neutrons.

3) Heat deposition, temperature of the moderator and vacuum wall, and heat removal.

4) Providing large quantities of high magnetic field and structure to withstand high stress.

5) Radiation damage by the 14.1-Mev neutrons, the consequences of which may be frequent and expensive replacement of much of the structure.

6) Size and cost, which are implicit in many of the above. Other problems are model-dependent; some device concepts seem to require additional developments. The list is long.

Most of the engineering-type problems that are model-independent can be described with the aid of Fig. 6, which shows a stylized fusion reactor as a series of cylinders. The main confining magnetic field is into (or out of) the paper; whether the cylinder is the center section of a stabilized mirror or is wrapped into a torus need not concern us here. The fusion plasma occupies the evacuated center, is surrounded by a neutron-moderating blanket and, at large radius, by a set of magnetic field coils. Here now are summary remarks on the problems listed above, generally slanted to a steady-state (or quasi-steady-state) device (*6, 11*).

1) *The plasma.* How is the plasma heated? What are the equilibrium temperatures and other parameters? The confinement being imperfect, we imagine plasma fuel continually being lost from the ends or sides into some suitable pump, hence also being replaced by some injection process into the center. Thus, the plasma continues in existence, but each ion or electron remains confined only for the period τ_c discussed before. Helium nuclei born in fusion reactions are also trapped for about τ_c, and deliver much (possibly all) of their 3.5-Mev energy to the plasma. Thus, the plasma is at least partly heated by its own reaction. For some fixed τ_c then, a certain throughput of plasma is needed to keep up its density; consequently, a certain calculable fraction f_b of the fuel will be burned per pass through the device; and the helium from the reaction heats electrons and ions (unequally) to temperatures T_e and T_i, respectively. As τ_c is raised, then f_b, T_e, and T_i also go up; the fuel is confined better and is not diluted by so much unreacted throughput. Fractional burnup f_b is a more useful display criterion than is τ_c. Difficulties of replenishing the fusion plasma seem to limit us to $f_b \gtrsim 0.02$; $f_b >$ 0.1 would cause too high plasma tem-

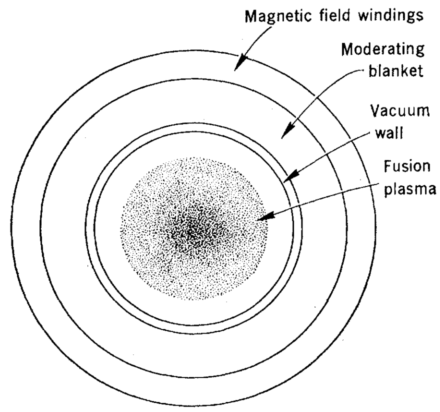

Fig. 6. Schematic controlled fusion reactor.

peratures and also demand unimaginably good confinement.

With some rather restrictive assumptions, these things can be calculated. Figure 7 shows the expected rise of electron and ion temperatures with increasing fractional burnup, for typical conditions expected in a fusion reactor. At high f_b, electron temperature falls below that of the ions. The reasons for this are that energetic electrons radiate energy, and that the ^4He nuclei tend to heat the ions preferentially, if the electron temperature exceeds about 33 kev.

Are these temperatures (once established by some startup scheme) high enough, or must more energy be added? This question lies at the heart of determining energy balance in a fusion reactor. At a given plasma pressure, the highest fusion reaction rate per unit volume occurs at temperatures of 15 to 20 kev. Then Fig. 7 appears to show ample heating if only $f_b \gtrsim 0.03$. For toroidal systems, this may be satisfactory, but an additional problem appears for open-ended systems (mirrors): the ions scatter out of the ends intolerably rapidly unless the ion temperature is very high, perhaps 100 kev or more.

For mirrors, heating the ions (probably by injecting them into the plasma at high energy) appears to be a necessary but expensive step. The expense arises both in additional equipment and in energy. Most of the energy from a D-T fusion reactor will appear as heat, which can be converted to electricity with (at most) about 50 percent efficiency. Then using large amounts of electric power to inject ions could make the system unfeasible.

These objections are serious enough so that a very different energy cycle is being investigated for mirrors (*12*). The field lines of such a device are shown ethereally in Fig. 8. Plasma escaping through the mirror (only one end is shown) is expanded radially to the periphery of a large disk, where the density is so low that electrostatic direct energy conversion can recover the plasma energy with high efficiency. This energy is used (also with high efficiency) to reinject ions. The scheme will not work well with a D-T fusion cycle, but a D-^3He cycle which produces charged particle reaction products almost entirely might be better. Such a cycle requires ion energies of several hundred kilovolts, a factor of 10 higher than for a D-T cycle. If the idea works, it would indeed make a virtue out of necessity; but the additional difficulties seem immense, and the outcome is problematical. Nevertheless, it may represent an important hope for the entire class of open-ended fusion machines.

A major difficulty with all these calculations is that they are still nebulous. The hidden assumptions may be unrealistic in serious ways. For example, how are the energy exchange rates inside the plasma affected by the presence of weak turbulence? No one knows. Will the curves of Fig. 7 be affected by inclusion of space charge effects? A subfield of fusion plasma engineering, for lack of a better phrase, needs developing before a fusion reactor can be sensibly designed.

2) *Tritium regeneration.* For a D-T reactor, tritium must be regenerated; the two lithium reactions

$$^7Li + \text{fast neutron} \rightarrow T + {}^4He + \text{slow neutron} - 2.5 \text{ Mev} \quad (8)$$

$$^6Li + \text{slow neutron} \rightarrow T + {}^4He + 4.8 \text{ Mev} \quad (9)$$

are essential and seem adequate.

The general idea in Fig. 6 is, then, to make the vacuum wall and blanket supporting structure of thin section refractory metal. Within it, there would be liquid lithium or a lithium salt coolant, plus an artfully disposed neutron moderator (probably partly of graphite). Leading choice for metals is niobium in that it can be formed and welded, retains its strength at 1000°C, and is transparent to tritium. This transparency helps in two ways: tritium generated in the lithium-bearing coolant is not trapped in the metal; and tritium can be recovered by diffusion through thin section walls into evacuated recovery regions. Some additional neutrons also come from the niobium via (n,2n) reactions, but in this particular respect molybdenum would be a better material.

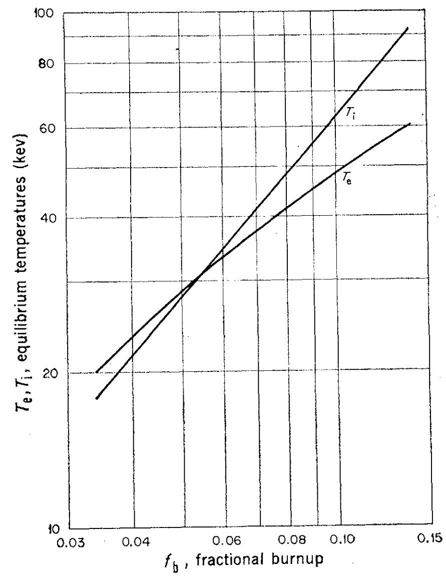

Fig. 7. Electron and ion average energies expressed as temperatures T_e and T_i, respectively, in projected fusion reactors, as a function of the fraction f_b of injected nuclear fuel that is consumed.

Liquid lithium cooling has the advantages of high heat transfer, few or no unfavorable competing neutron reactions; main disadvantage is its high electric conductivity, which makes it hard to pump through high magnetic fields—just how hard is not well enough known. In regions near the vacuum wall where the high lithium flow rate might cause excessive pumping loss, a nonconducting molten salt can be used. The likeliest candidate is Li_2BeF_4; the main penalty for its use is the presence of fluorine, which slows down energetic neutrons unprofitably, hence inhibiting the beneficial ^7Li re-

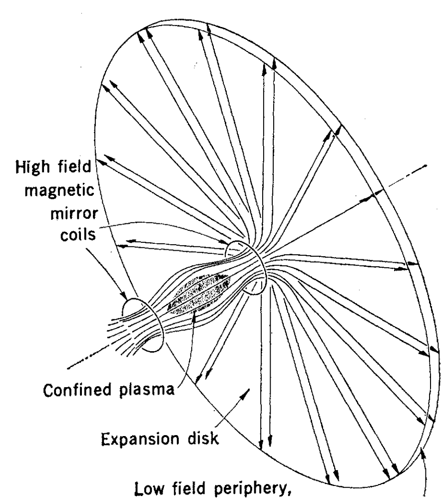

Fig. 8. Magnetic field configuration for a magnetic mirror fusion device with direct electrostatic energy recovery [after Post (*12*)].

action of Eq. 8. That is, using Li_2BeF_4 makes it harder to regenerate enough tritium.

However, with either of these schemes or a combination of them, tritium regeneration seems adequately assured. Calculations with semirealistic combinations of vacuum wall and blanket show that something between 1.1 and 1.5 tritons can be regenerated per neutron incident on the vacuum wall (*13*). Because one triton is used up per neutron generated, we have in fact a tritium breeder reactor, using the raw materials deuterium and lithium. This view of fusion as compared to nuclear fission breeder reactors has not been much emphasized in the past.

In addition to this favorable breeding ratio, present estimates put the tritium inventory in a fusion reactor at only a few weeks' supply—maybe less (*14*). Thus the tritium fuel doubling time in a fusion reactor might be much less than 1 year. Doubling time is an important measure of how quickly new reactors could be built (that is, fueled) either to match expanding power demands or to take over from a prior power-generating scheme. This short doubling time for fusion is in marked and favorable contrast to the situation with fission breeder reactors, where the doubling time tends to be uncomfortably long ($\approx$ 20 years in some designs). Here is one of the predicted large advantages for fusion.

Approximate size of the fusion reactor I have in mind comes directly from these considerations. Fairly simple nuclear calculations establish that the blanket plus a radiation shield (not shown) to protect the outer windings must be 1.2 to 2.0 m thick. This substantial thickness implies not only substantial blanket cost, but also very high magnetic field cost, to energize such a large volume. The only way to make the system pay is to have it generate a great deal of power; but nearly all this power must pass from the plasma into or through the vacuum wall. Engineering limits of power density and heat transfer then dictate large plasma and vacuum wall radii as well —between 1 and 4 m, say. Then overall size will be large, and total power will be high—almost certainly more than 1000 megawatts (electric) and perhaps 5000 megawatts.

3) *Heat deposition and the vacuum wall.* Energy is deposited in the vacuum wall facing the plasma, mainly from three sources: (i) some of the fusion neutrons suffer inelastic collisions as they pass through; (ii) gamma rays from deeper inside the blanket shine onto the back side; (iii) all electromagnetic radiation from the plasma is absorbed there. The plasma itself makes no additional load, being imagined to be pumped out elsewhere. The three sources may constitute 10 to 20 percent of the total reactor power. This is a modest fraction; but the vacuum wall region is thin, and heat deposition (and removal) per unit volume determines the power capability of the whole system. Here is a disadvantage of fusion systems compared to fission reactors; in the latter the energy is more nearly produced throughout the reactor volume and all must not pass through one critical section.

From these considerations, I imagine a total power assignment in the reactor of not more than 15 Mw per square meter of vacuum wall—say 10 Mw/m^2 being 14-Mev fusion neutrons passing through, and the rest consisting of plasma radiation and neutron captures in ^6Li. Some (*15*) imagine substantially higher energy fluxes to be possible, with the use of heat-pipe walls—about 30 to 40 Mw/m^2; but the design poses many problems. Even at 15 Mw/m^2, total reactor power is very high, as said before. If the vacuum wall radius is only 2 m, the system of Fig. 6 produces 140 Mw of heat per lineal meter (into the paper) of cylinder. If it is wrapped into a torus, the major diameter can hardly be less than 20 m. Total power of such a device would be 12,000 Mw thermal, or 5000 to 6000 electric, several times that of the largest plant now existing.

One possible way (*16*) out of this and some other difficulties is to run the reactor at substantially lower thermal stress—at $\sim$ 2 Mw/m^2. Total power is conveniently less; and because the plasma density is reduced, so is the magnetic field and the cost of it. Neutron damage (see below) is also ameliorated. Whether this option increases the cost per unit of power excessively has not yet been estimated.

The vacuum wall must support approximately a pressure of 1 atm, which is no small task for a thin-section material in such large sizes. However, preliminary designs indicate that a structure built up in depth of thin sheets (the same principle as in corrugated cardboard boxes) will have the necessary strength, and contain proper passages for coolant flow (*17*).

4) *Magnetic field windings.* Generating even 15 tesla (150,000 gauss) continuously is not the problem; superconducting coils do so routinely at low cost, a dramatic improvement from state-of-the-art 10 years ago. The problem is size: a simple solenoid generating 15 tesla has a magnetic bursting force of 900 atm on its windings. In comparison, contemporary fission reactor pressure vessels are smaller than we imagine here, and are limited to some 40 atm operating pressure. To make matters worse, the magnetic field is not a simple solenoidal one, and stresses arise that cannot be held in simple hoop tension. To be sure, no nuclear excursion impends if the coils fail structurally, but failure would still be an economic calamity. Perhaps also 15 tesla is not required, but no assurance now exists.

Almost all conceptions involve superconducting coils at 4°K, or at least cryogenically cooled ones at 10° to 20°K. This is the reason for placing them outside the blanket, outside a radiation shield; otherwise the refrigeration problem would be intolerable. To make a reinforcing structure for operation at such a temperature, with size and stress loads I have described, is a task yet to be fully contemplated. Titanium is very strong at such low temperatures; but it is also very brittle —as are most other materials under those conditions.

5) *Neutron damage.* This is a very serious problem, for either a fission or fusion reactor. In one way, fusion appears at a substantial disadvantage, as follows. One fission reaction produces 200 Mev and about 2.5 neutrons, each with no more than about 2 Mev. One fusion reaction produces 17.6 Mev, of which 14.1 Mev appears in one high energy neutron. Thus, the "energetic neutrons/watt" is an order of magnitude higher in fusion than in fission, and the structural damage caused by these neutrons is correspondingly high. For the high power levels discussed in the preceding examples, every metal atom in the vacuum wall would be displaced almost once per day (*18*). Many of these displacements anneal out at the high operating temperature; but, even with the delicate choice of materials, design, and temperature, long-term integrity of the vacuum wall against neutron damage will be a major problem facing fusion power development.

In another way of looking at the problem, fusion has an advantage. The damaging neutron flux in this high power fusion reactor is predicted to be about 10^{15}/cm^2-sec; but in reference designs for liquid metal fast breeder fission reactors, it will be an order of magnitude higher. We see here a principle of conservation of wretchedness—the fast breeder fuel elements and perhaps the components will require frequent replacement, at substantial expense.

For fusion, this problem translates into the problem of either protecting the vacuum wall (via lower power?) or replacing it. The cost of either of these options may be high; unanswered questions are whether the vacuum wall can be replaced at a cost small compared with the total reactor cost and how often replacement will be required.

Compounding the problem are the facts that probable fusion reactor conditions and materials are not in the fission breeder range of interest. Moreover, no source of 14-Mev neutrons (to test possible arrangements) now existing is intense enough—by a factor ≈ 1000.

Within the framework of fusion systems envisaged here, this damage problem cannot be circumvented, cannot be well predicted on the basis of present knowledge, and affects the feasibility of every fusion reactor scheme.

6) *Size and cost.* Size is large for lowest power cost, as I showed earlier. However, over many decades unit size has increased by a factor of 2 to 3 each 10 years. Thus, 10,000 Mw thermal is liable to be quite acceptable before 2000, when fusion might, with good fortune, come into its own.

Cost per thermal kilowatt of capacity makes a reasonable basis for comparison with other generating systems. Components stylized in Fig. 6 are equivalent to the core of a nuclear fission reactor, without some of the nuclear ancillaries (and without any of the turbines and generators of a power station). No definite cost can yet be given for what is shown there; too much is still uncertain. However, outside estimates have been made that the cost might run somewhere between 6 and 20 1970 dollars per thermal kilowatt (*6*). If neutron damage does not require too frequent replacement of the structure, the whole cost range is interesting, and the lower limit is uncontestably attractive.

Such costs warrant continuing development, but they are very perishable commodities, depending on the imperfect and changing state-of-the-art. Designs, costs, trends, and comparisons must be continually reassessed.

Model-Dependent Problems

What of the host of model-dependent problems, more specific than those hitherto listed? I mention just three, to show their kind and importance.

1) *Fuel injection into closed toroidal systems.* Plasma is lost by diffusing toward the vacuum wall and then being absorbed (no mean task, and not well understood) at specific peripheral regions. Implicit in this statement is that something replenishes the plasma at or near the middle (if the device runs on anything like a steady-state basis). Ionized particles will not move across the confining field, so neutral ones must be somehow injected. The trouble now is that the energy flux (of hot electrons) in the plasma is about 10^{14} watt/m^2, some 10^3 times that of the strongest electron beam made today. Lifetime of a neutral atom or a small cluster of atoms against being ionized in this hostile environment is about 10^{-7} second; upper limit on injected atom velocity is about 10^6 m/sec; otherwise the plasma energy balance is upset. Then the atom penetrates perhaps 0.1 m, a negligible fraction of the way in.

An alternative scheme is to inject pellets so large that they shield themselves by ablation on the way in (as a reentry vehicle into the atmosphere from a space flight). Calculation of what happens here—for example, whether the pellet must be so large that it chokes the fusion reaction—is much more difficult than calculating the fate of atmospheric reentry bodies, and not much has been done (*19*).

2) *Direct energy conversion for open systems.* The necessity for high energy injection and recovery directly as electricity was mentioned in the discussion related to Fig. 8. What cannot be illustrated well is that the diameter of the disklike expansion region may be 100 times the diameter of the mirror confinement region. Can such a structure (albeit with low magnetic field) be built cheaply enough? Can plasma stability and individual particle orbits be controlled well enough throughout this immense region? No one knows.

3) *Fast-pulsed systems.* The scheme of Fig. 5 has advantages of automatic plasma heating, apparently good stability against radial excursions, and some others. But several perplexing complications are as follows. (i) The system requires a substantial amount of stored energy to be delivered in about 10^{-6} second to the coil. At present this is done by capacitors, perhaps at a cost of $100,000 per megajoule. Some cost reduction is clearly possible, but much is necessary. (ii) The fast pulse requires that the magnet coil be next to the plasma in that it forms the vacuum wall. Then the coil must have high strength at high temperature. Electric losses in this coil reduce power output from the system. The coil also slows down and absorbs neutrons, and this process decreases the tritium yield (*20*). (iii) Pulsed operation at (say) 900 atm pressure on a microsecond basis exacerbates problems of mechanical stress failure; yet more reinforcing structure imperils the tritium breeding even more.

Fearless Forecast

To assess the relative merits of many approaches to controlled fusion is a difficult task, and disputatious. But some sort of perspective must be developed from time to time. What follows is partly opinion, partly fact; it is no one's policy but my own.

Figure 9 helps to focus and confine the discussion. In the middle is a level of achievement called Scientific Feasibility: a density-time product of 10^{20} sec/m^3 or more, and true thermonuclear temperature—say 15 kev or more, depending on the system envisaged. Whether the device looks like any eventual fusion reactor is immaterial in this context. This level of accomplishment would be crudely the analog of building the Stagg Field fission reactor in 1942: the physics is permissive, but engineering and economics are yet to come. Figure 9 has no absolute scale, but shows where each present scheme is presently situated—all are now below the feasibility waterline. Closest is the Tokamak, but the figure shows two gaps yet to be crossed. These gaps are that it is not yet known whether scaling to larger size really will work (as described earlier) or whether the ions can actually be heated enough in the device, via weak turbulence or some other means. To put some calibrating point on all this, I will bet a modest amount of even money on success of the Tokamak in the next few years.

The stellarator is a related steady-state device, where the toroidal configuration is stabilized not by induced plasma currents (as the Tokamak), but by added helical windings on the periphery of the torus. The big advantage

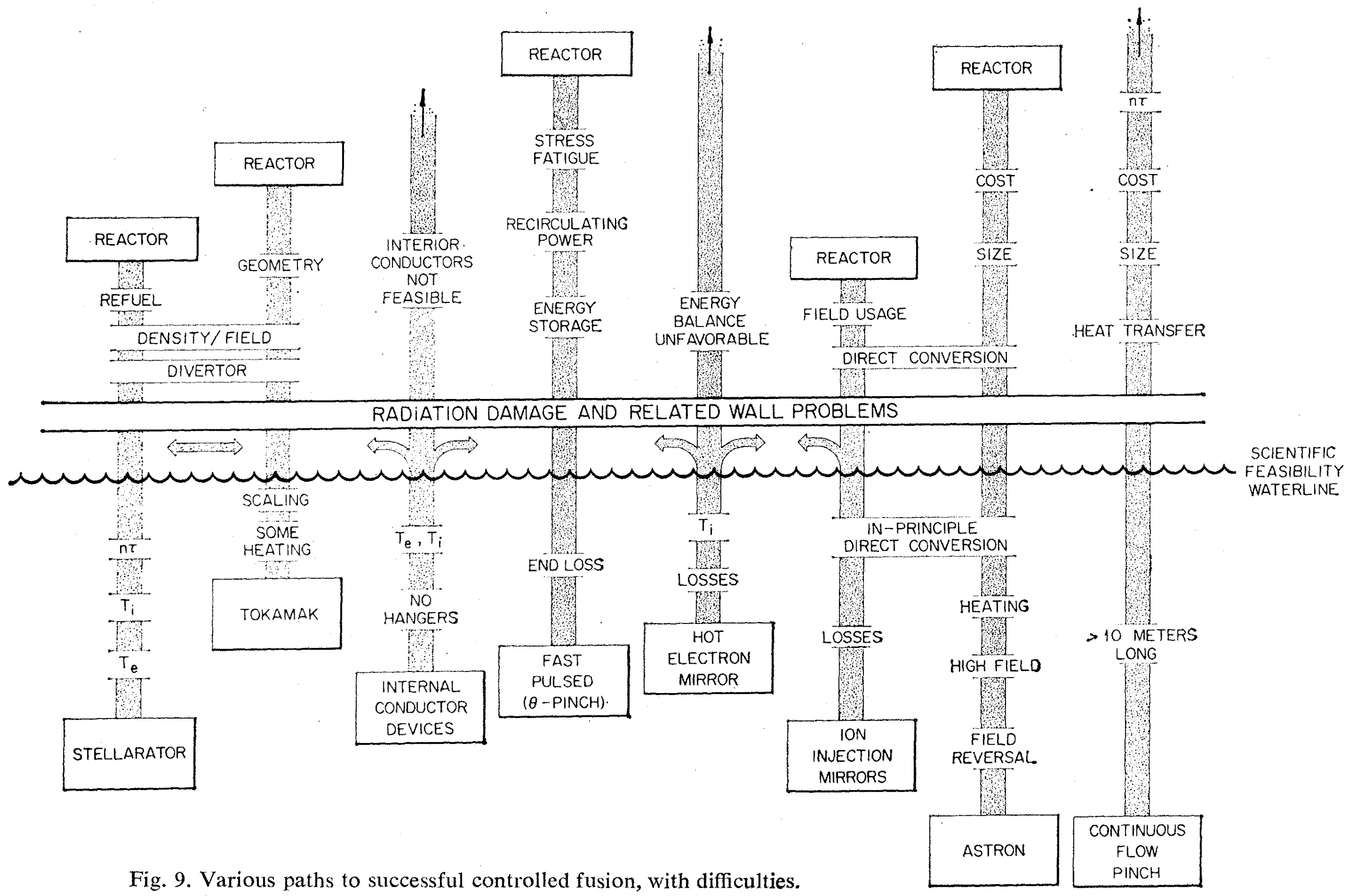

Fig. 9. Various paths to successful controlled fusion, with difficulties.

is steady-state operation. The main disadvantage is that a field configuration made this way seems to give poorer confinement. Thus the density-time product ($n\tau$ in the figure) needs more substantial improvement, and in addition both the ion temperature (T_i) and the electron temperature (T_e) will be harder to raise (*21*). The stellarator lies significantly below the Tokamak at present.

Some toroidal confinement schemes require solid conductors totally surrounded by plasma. The so-called multipoles at the General Atomic Corporation and at the University of Wisconsin, and the spherator at the Princeton Plasma Physics Laboratory are examples (*22*). These internal conductors can be (and are) made superconducting, so true levitation without supports or hangers is possible and has in fact been achieved. On the other hand, no large levitated experiment has yet been performed at high enough field. Thus in the third column of Fig. 9 we see the need to operate without hangers, and to raise both T_e and T_i by some plasma heating schemes yet to be fully developed.

Next in the figure comes the fast-pulsed devices, as shown in Fig. 5. Whether the side losses are now small and whether just reducing end losses will give satisfactory confinement are still questions, but I give the device the benefit of the doubt. One estimate is that the device needs to be 2 km long if linear and the ends are not stopped up (how?); also if wrapped into a torus, new and unresolved questions of plasma stability enter.

All open-ended mirrors suffer from high loss from the ends, and schemes to reduce these losses (by applying high frequency power at the mirrors, for example) seem not to be very effective (*23*). Heating both ions and electrons adequately is an additional problem. The "hot electron mirror" scheme uses large amounts of microwave power to produce an exceedingly dense hot electron plasma, with apparently fair confinement at least (*24*). Ions might be heated (T_i in Fig. 9) by injecting high energy neutral atoms into this "seed plasma." The chances of this scheme making a scientifically feasible fusion plasma are at least fair.

Ion injection mirrors, when the plasma is not substantially aided by hot electrons, face more difficulty. The losses are high; and, as discussed above, it seems that the high losses will require as part of the "in-principle" solution the development of "in-principle" direct energy conversion (see again Fig. 8 and the accompanying discussion).

The Astron at Lawrence Radiation Laboratory is interesting, but hard to describe (see Fig. 10). It starts out generically as a mirror (Fig. 3); but instead of confining a plasma directly there, the aim is to confine a ring of relativistic energy electrons (relativistic protons in a full-scale reactor). This is called an E layer; if dense enough, its diamagnetism actually reverses the magnetic field and sets up a new configuration of closed magnetic field lines: a torus inside the mirror. This configuration holds the fusion plasma. So far, a modest diamagnetic reduction (and no reversal) of a low field experiment has been achieved (*25*). True field reversal in a larger, high field device will be needed to set up the desired magnetic configuration. Beyond that, how the plasma is to be heated is a problem; and high end-losses may also require direct energy conversion.

The continuous-flow pinch is favored in some quarters, particularly in the U.S.S.R. The idea stems from the discovery that plasma can be focused into a small, very high density ($10^{25}/m^3$?), high temperatue (several kilo-electron volts) plasma thread a few millimeters long, at the end of a coaxial plasma gun. This is the so-called plasma focus, which is a copious source of fusion neutrons during the time scale of its pulsed operation, about 10^{-6} second (*26*). Can this very dynamic object be formed and preserved on some more steady-state basis, and spun out from the end of the plasma gun, as a thread from a spinnerette? No one knows what all the problems are, so I arbitrarily define scientific feasibility as the production of a 10-m thread.

These activities below the waterline of Fig. 9 have taken nearly all of the more than $1 billion spent around the world on fusion up to now. But how do things look for making a reactor? Above the line appear many of the problems discussed earlier. Damage to the structure by high energy neutrons may render the whole idea uneconomic, as discussed before. But besides this, the various schemes have different relative merit above and below the waterline.

Tokamaks no longer look quite so attractive. Special plasma pumps called divertors have been developed for stellarators, seem necessary for Tokamaks also (where access is more difficult), but must be vastly increased in effectiveness. Plasma stability considerations may demand that the plasma density be uncomfortably low, or the field uncomfortably high [15 to 20 tesla, or more? (*27*)]. Also, the geometry, inherently pulsed nature, and necessarily large size of the thing are hard to work with.

Some of these problems appear with the stellarator too, but with reduced intensity. Steady-state operation is easier; the additional refueling problem may be no more than moderately serious. Thus, the stellarator tends to look better, *if* we are given scientific feasibility. Stellarator and Tokamak scientific programs support each other extensively, hence the joining arrow on Fig. 9.

The internal conductor devices just will not make fusion reactors, because there is no way of cooling a levitated conductor, especially inside a fusion plasma. This is well understood; no one ever thought otherwise; these experiments are designed specifically for plasma physics and to shed scientific light on other schemes.

The theta pinches have very severe problems, as discussed in the last words of the section on fast-pulsed systems.

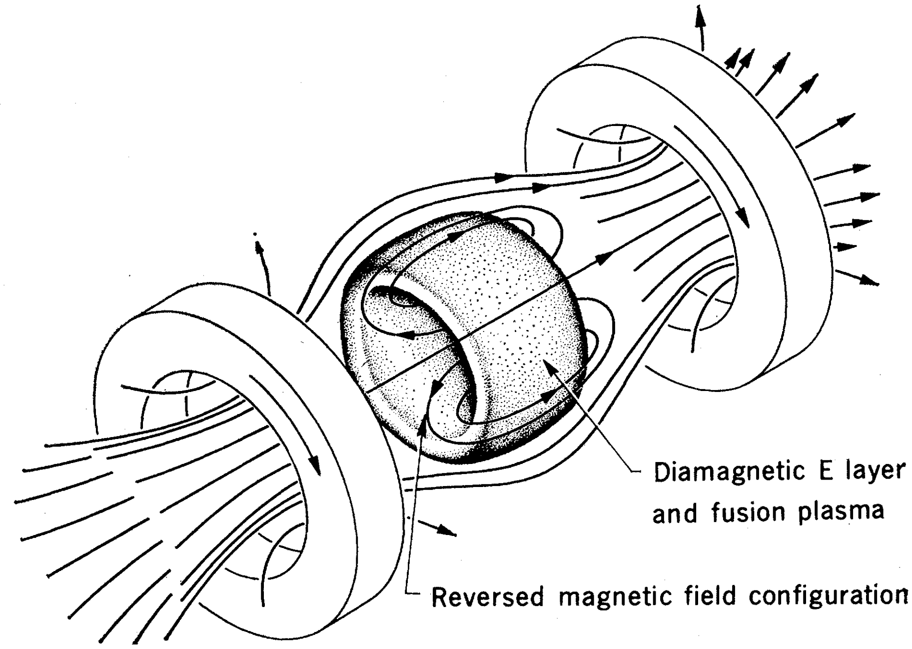

Fig. 10. The Astron configuration for obtaining controlled fusion, which aims to generate a strongly diamagnetic region inside a conventional magnetic mirror.

I am pessimistic about the outcome, as Fig. 9 shows.

Pure hot electron mirrors appear unfeasible for fusion from an energy-balance point of view, but again that is a personal opinion. As with internal conductor devices, the idea is to reach the waterline, not an economic reactor. In addition, *some* electron heating may be valuable for more conventional mirrors.

If conventional mirrors can attain scientific feasibility according to the definition given here, they should be the most likely reactor candidates. The questions are whether direct energy conversion can be developed at a reasonable price; whether the magnetic field is efficiently used (that is, cheap enough); and of course radiation damage.

The Astron seems heir to more difficulties: the size may be very large, and it is not at all clear whether relativistic-energy, high-current guns will be cheap enough. Direct conversion is still a problem.

Even if a continuous flow pinch, 10 m long, can be developed, I doubt that an economic fusion reactor can be made of it. The power density is immense, and presumably an exceedingly high magnetic field is needed to confine the plasma string. Could this ever be done without putting the field coils near the plasma, thus exacerbating heat transfer and tritium regeneration problems? There are more problems besides.

Several quite different schemes for achieving controlled fusion are not shown in Fig. 9; the so-called "laser ignition" scheme deserves mention (*28*). In that, the pulse from an ultra-high-energy laser is focused on a small pellet of solid D-T and heats it to fusion temperatures before the pellet has time to disassemble. The disassembly speed is about 10^6 m/sec at fusion temperatures, and the pellet size is the order of 1 mm. Thus the main heating pulse must be less than 10^{-9} second long. Even more, the most efficient heating scheme involves using several smaller preheating pulses to set up initial temperature and density gradients in the pellet, and these must be applied with temporal accuracy of perhaps 10^{-11} second. These requirements can be met. About 10^5 joules is the minimum estimated to be necessary for energetic break-even: enough fusion energy out to equal the laser energy deposited. Even these large values are not discouraging; what seems to me very difficult is producing power cheaply enough: for reference, 5×10^7 joules of such "explosive" raw heat deposited in (say) lithium coolant is worth about $0.01; can one do all this repetitively with an expensive and fragile device?

Many of the questions raised above will require systems research, systems development, and systems engineering to answer. These arts have been put secondary to plasma research and experimental device development up to now.

Time Scales

Present pressurized water or boiling water nuclear reactors are satisfactory as interim devices, but their relatively low thermal efficiency and inability to breed much nuclear fuel (from ^{238}U or thorium) condemn them to a brief existence in our society, unless much more uranium is found. The total installed capacity of such devices will be much less than that of fossil fuel plants, so complaints about them are and should be based on relatively local considerations—for example, thermal effects in Biscayne Bay. These words should in no way be taken as denigration of the validity of local complaints.

The view here is broader, and of longer time scales. The real question concerns second-generation fission breeder reactors (for example, a liquid metal fast breeder, or molten salt breeder) vis-à-vis the possibility of controlled fusion. At one time it was thought that fission suffered a relative disadvantage of insufficient nuclear fuel because of lack of uranium in the earth's crust, whereas deuterium is in plentiful supply. This is not true; there are adequate supplies of ^{238}U and ^{232}Th, D, or ^{6}Li for some 10^8 or more years of society based on high energy consumption. Even better, all these are resources for which little alternate use is forecast.

The real questions of fission breeders versus fusion breeders (which have to breed their tritium, as we have seen) involve feasibility, relative cost, time scales, and environmental factors, which all tend to be related. I have discussed the first of these topics and will not return to it in detail. To put the costs in some perspective, I point out that an additional penalty of $20 per thermal kilowatt—that is, doubling the maximum cost mentioned earlier—would add by itself less than $2 per month to the present average residential electric power bill. That is no invitation to adopt expensive options thoughtlessly—as electric power use increases, extra costs hurt more—but it *is* a way of saying that substantial changes could be afforded in reactor cores (fission or fusion) *if* even moderate social benefits were likely to accrue. That view will affect remarks to come later.

With regard to time scale, there is some real misunderstanding. Controlled fusion is *not* an alternative to the first-generation fission breeders, as was at one time thought. The question is whether fusion or some second-generation fission breeder will be preferable. The time scale goes like this: even if scientific feasibility is demonstrated by 1975, basic studies related to topics above the waterline in Fig. 9 will occupy several years beyond. After that, at least one pilot model fusion device would occupy our attention until the mid-1980's; then fission reactor experience shows that the lead time is long for designing and building the economic plants to follow. My own guess is that fusion power will be available in appreciable quantity by 2000, even with a fortunate outcome along one of the paths in Fig. 9. A few optimists propose 1990; pessimists propose never.

This long time before beneficial installation might seem to permit a comfortable period of grace before basic decisions about the overall feasibility and future of fusion need be taken. That is not so: other time scales enter. An important one is the fact that present gas diffusion plants for uranium enrichment may reach the end of their life by about 1990. First-generation fission breeders will have come into service well before then, but large, new, gas diffusion plants will still be needed. The question is in part whether the replacements are for an interim continuation, for a long-term continuation, or something else. Such expensive construction (several billion dollars) and the concomitant commitment bespeak a fairly clear decision by 1980 about what is to be built. For that, relative rank ordering of nuclear power systems will be needed several years earlier. Thus important decisions need to be made about the relative merits and eventual feasibility of nuclear power systems in the next few years. When the decisions start to be made, it becomes increasingly difficult to alter the course of events, because large economic and intellectual investments start to be made in the chosen course, and it usually is easier to stumble forward than to reach back. In truth, controlled fusion must from here on be subject to increasingly detailed technological assessment. To be late or unresponsive in this activity is to risk being irrelevant.

Hazards

Upon the topic of the next two sections, much arrant nonsense has been written, reminiscent of Ben Jonson's *The Alchemist*.

Almost everyone agrees that the most appreciable nuclear hazard of controlled fusion is that of tritium. A 5000-Mw (thermal) fusion plant would cycle about 10^8 curies of tritium through the plasma per day at 0.05 burnup, and actually burn 5×10^6 curies per day. How big will the inventory be? That depends on the rapidity with which unburned tritium can be reclaimed from the plasma pumps and the efficiency with which regenerated tritium can be scavenged from the moderating blanket. What little has been done on the pump problem suggests that something like 1 day's throughput may be held up in transit between exhaust from the fusion plasma and reinjection. For the blanket, more thoughtful analysis (*17*) suggests that 10 or 20 days of bred inventory may be held up in the huge bulk of lithium coolant, graphite, and so forth. At 0.05 fractional burnup, the two inventories would be about equal: a total of 2×10^8 curies.

This is a lot of radioactive material, comparable (in curies) to the amount of the most hazardous fission product ($\approx 10^8$ c of ^{131}I) expected to be found in a fission breeder reactor of the same size. But after that the comparison is not parallel. Per curie, tritium is relatively benign (9 kev average energy β^-) and in the gaseous form is only weakly biologically active. Then to this stage in the discussion, the relative hazards of fusion versus fission are perhaps $1:10^5$; on that basis fusion reactors could be installed anywhere without any containment shells (*17*). Still, extreme care must be exercised.

Complicating this story are the start-ing-to-be-assessed hazards of tritium being released as T_2O, of tritium leaking through the reactor structure, and the like (*29, 30*). For the first, T_2O enters the life cycle as does water, which increases the relative hazard considerably. For the second, hydrogen (hence tritium) delights in diffusing into and through metals, much more so than does any other element. This is no hazard of critical nuclear accident, but rather the problem of preventing the plant from having radioactive B.O. It can be solved technologically, for example, by placing vacuum barriers at critical places where tritium will migrate. But what will it cost? For example, if the fusion system cost including all such protective arrangements equals the cost of a liquid metal fast breeder plus a carefully prepared hole beneath the city to hold it, any advertised safety advantages of nuclear fusion become hard to see.

These tritium migration and scavenging problems are now starting to receive some attention, and in a few years a lot more can be said. In the meantime, I guess that fusion will retain a substantial advantage, which will be reflected in a price differential of $10 to $20 per thermal kilowatt.

Another nuclear nuisance is that the 14-Mev fusion neutrons will make the basic structure of a fusion reactor highly radioactive (*31*). Fission reactors have the same problem; the components are in no danger of being spread through the environment, so this activation poses more of a maintenance problem than a hazard.

About nonnuclear accident hazards, fusion and fission seem to be a standoff; one uses large amounts of liquid lithium or fused salts; one uses similar amounts of sodium. These hazards seem small, perhaps less than those enjoyed by people who live next to railroads on which many things are transported.

Permanent storage of long-life fission products is an additional problem for fission reactors; the advantage to fusion is modest, because total storage charges are expected not to be severe (on the scale of things discussed here).

Other Environmental and Technology Assessment Questions

Arguments about fossil as compared to nuclear power have often been made in terms of which kind of plant should be installed somewhere remote from population centers. As a corollary, the environment is imagined to be restored by having many nuclear power plants at remote locations producing electricity, which is transmitted to load centers.

That is all very well, but some kind of Sutton's Law (*32*) suggests that we look at the heart of the problem, which is elsewhere. Most people in the United States and other developed countries live in cities. Predictions vary for the energy requirements in (say) 1980, but all agree that even with the trend toward electric power accounted for, the nonelectric energy requirement will exceed the electric energy requirement by nearly an order of magnitude (*33*). Much of this nonelectric demand is for transportation. But even space heating, industrial process heat, and so forth still add up to much more than the predicted electric demand, and all this is now supplied by fossil fuels. Therefore, if fossil fuels are to be substantially traded for nuclear ones, nuclear power plants must be built in or very close to population centers. The question of hazards and the cost of assuring safety discussed in the previous section must be looked at from this point of view.

Analysis of the total social costs and benefits is complicated enough for fission breeders versus fossil plants, and is yet in a primitive stage. Including fusion as an option will make further complications. Either advanced fission breeder reactors or fusion reactors are expected to have good thermal efficiency; some propose 50 percent or more (compared with about 32 percent for present reactors, 41 percent for present fossil fuel plants, perhaps 50 percent for advanced ones). Proponents of fission breeders promote that the total environmental difficulties and social cost of nuclear power are substantially less than those of fossil fuel plants. I agree with this when the various diseconomies—those charges put upon the public sector and not now made a charge on the generating company—are included. That is, the effects of sulfur and nitrogen oxides, and of particulate emissions, place considerable burdens upon us as a whole; the country is taking steps to deal with them, and the curative costs are very large.

Beyond that, many more factors enter; here are some. Strip mining of coal can despoil large tracts of land for long periods. Deep mining of coal or uranium is hazardous; lithium mining also brings problems. Any fission reactor located on the surface in a city probably must have an exclusion area around it. Analyses show that this valuable land can be used for some agricultural purposes, very possibly in combination with some of the reactor's waste heat (*34*). But even if no direct economic use of the land is made, what large city could not do with an internal area having a pleasant vista? It is hard to quantify such social values, but surely they are substantial: recall the view down the Serpentine from Kensington Palace in London. Plant size and tradeoffs between capital cost and fuel cost can and should have substantial leverage on proper urban planning, but so far they do not. For example, large plants with low fuel cost could afford to be run with a policy of very cheap (free to some users?) off-peak power. With such a policy, different activities and living prospects can be stimulated in cities. The well-known positive feedback—via larger plant size, hence lower unit electricity cost, hence increased demand and accelerated technology change toward electricity—involves assessing much of future technology: Can transportation be based on some electric process, for instance?

Even fission and fusion are by no means mutually exclusive choices. They might complement each other, because fusion is predicted to have a large available neutron excess, and some otherwise attractive fission breeder schemes look dubious because the fuel doubling time is too long (*35*). Can fusion reactors then be used to manufacture incremental fissionable material, hence bringing about a useful symbiosis?

Yet all this does not reach the deepest layers of the problem. If we assign importance to the fact that controlled fusion could supply our energy needs for aeons, we should also see what constitutes the energy policy. Just producing more is clearly inadequate; using it sometimes brings difficulties too, such as the summer temperature rise in ghetto streets because of operating air conditioners. Then should we reduce energy dissipation by having better insulated buildings? Perhaps some principle of minimizing the entropy increase needs to be factored in. For fossil fuel utilization, this certainly seems required: jet plane travel is not wholly satisfactory, when almost as much fuel is burned per trip as if each and every passenger drove the distance by himself in his own automobile.

These are not empty phrases; if high speed intercity transport switches from aircraft to tunnel vehicles, substantial switch from fossil to nuclear (electric) power is possible. There is a lot at stake, an adequately broad assessment has not been made, and we are uncertain about what the policy ought to be. Indeed nowhere have problems of this scale—as they really exist in society—been approached in such an integrated fashion hitherto. This comment has broader implication than just to controlled fusion and relates to what appear to be very basic difficulties in how we organize ourselves to solve large societal problems. But that is another story (*36*).

It is in this broad context that controlled nuclear fusion will or will not be brought to fruition. I believe that, for fixed plant requirements, nuclear fission can be made substantially more attractive than can burning coal or oil, for most purposes. As implied in earlier sections, I also believe that the situation could be improved even more with successful fusion power. But these are still beliefs, not yet firm facts.

It would be rash to predict the outcome; not all schemes now being worked on will be adopted, which is the price in technology assessment of keeping options open. Surprises come, not all unpleasant, and a historic parallel occurs to me (*37*). In 1680 Christiaan Hüygens decided to control gunpowder for peaceful purposes, as a perpetual boon to mankind, and set his assistant Denys Papin to invent a controlled gunpowder engine. After 10 years of difficulty, Papin had a different idea, wrote in his diary,

> Since it is a property of water that a small quantity of it turned into vapour by heat has an elastic force like that of air, but upon cold supervening is again resolved into water, so that no trace of the said elastic force remains, I concluded that machines could be constructed wherein water, by the help of no very intense heat, and at little cost, could produce that perfect vacuum which could by no means be obtained by gunpowder.

then invented the expanding and condensing steam cycle, which made possible the industrial revolution.

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37. C. J. Singer, E. J. Holmyard, A. R. Hall, T. I. Williams, Eds., *A History of Technology* (Oxford Univ. Press, London, 1954–58), vol. 4, p. 171.

Language in Chimpanzee?

David Premack

Can apes be taught language? Although this question is of biological import, it may ultimately be more important to the fundamental question, What is language? The ape, when properly trained, emerges as the unclear middle case: Neither wholly comparable to man (the clear positive case) nor to parrot (the clear negative), the "talking" ape puts the question of language to its first severe test (*1*).

The approach I have taken to the twofold question of what language is and whether an ape can be taught it can be expressed in terms of two parallel lists. The first is a list of exemplars, things an organism must be able to do in order to give evidence of language. The second is a corresponding list of instructions for training the organism so that it may be taught the exemplars in question.

The exemplars I am dealing with here concern selected aspects of: (i) words; (ii) sentences; (iii) questions; (iv) metalinguistics (using language to teach

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