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NUCLEAR FUSION BY MAGNETIC CONFINEMENT*

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SUMMARY

The concept of a nuclear fusion reactor based on magnetic confinement is becoming scientifically credible, following two decades of research devoted to the solution of complex problems in plasma physics. Barring setbacks, current research programs surveyed in this paper could lead to demonstrations of scientific feasibility within a decade. Although the present research is concentrated on the confinement problem, increasing consideration is being given to the engineering and technology problems expected to arise in the design of fusion reactors based on the three main present approaches to the fusion confinement problem. These approaches are: 1) closed or toroidal systems of the "tokamak" type, 2) pulsed high density systems called "theta-pinch", and 3) open-ended magnetic configurations utilizing the magnetic mirror principle for plasma confinement. The status, remaining problems, and potential as a reactor of each of the above approaches is discussed.

I) INTRODUCTION

Fusion power does not exist today. What exists is a well-grounded worldwide research effort specifically aimed toward achieving it, plus recent evidence that says this research effort is on the right track. There is growing acceptance of the proposition that power from fusion not only will be achieved but that fusion offers an almost ideal answer to our future energy needs. There is also a feeling on the part of many that not only is fusion a highly desirable goal, but that it is not necessarily a distant one. Certainly it is one that would be brought nearer by an intensified effort. In response to our mounting concern over sources of energy such an intensification is clearly warranted.

Controlled fusion research began about 20 years ago, in secrecy and essentially simultaneously in the U.S., the United Kingdom and the USSR. Secrecy was ended by international agreement in 1958 and since that date an unusually high degree of international cooperation has existed in this field. Based on scientific manpower involved the present worldwide fusion effort can be estimated to be roughly 200 million dollars equivalent - about 40% being in the Soviet Union, 20% in the U.S. and the rest in the U.K., Western Europe and Japan.

Before discussing details, some fusion basics: Fusion research seeks ways to extract useful power from nuclear reactions among light elements. The primary fuel for fusion is deuterium - heavy hydrogen. Deuterium exists in sufficient quantity to satisfy any conceivable energy demands for thousands of millions of years. The cost of obtaining it by isotope separation from water is so low that as a fuel deuterium would cost less than 1% of the present cost of coal, on a per-unit-of-energy basis.

Nuclear fusion is nuclear combustion, the process

that heats the sun and the stars. To achieve controlled fusion on earth we must carry out the following steps: First heat a small quantity (how small will be discussed later) of fusion fuel above its ignition point - about 100 million degrees kinetic temperature. Second maintain this fuel in a heated condition long enough for the release of fusion energy to exceed the heat input, and third convert the energy released to useful form - namely electricity.

The requirement for high temperatures to achieve fusion is unavoidable; except for practical restrictions the choice of operating fuel density is open. For example, in a large reactor operating in steady state the fuel density would likely be quite low - about one one-hundred-thousandth of the density of the atmosphere - practically a vacuum. Even so the fusion power released per unit volume would be about 10 megawatts or more per cubic meter of reacting fuel. Higher fuel densities would be possible, but since fusion power increases as the square of the fuel density reactors working at densities much higher than these must necessarily operate in a pulsed mode, that is with an intermittent combustion cycle, like an internal combustion engine. In any fusion reactor, however, the total amount of fuel present at any one time would be at most a fraction of a gram.

II) Magnetic Confinement

Confinement of the hot fuel gas, that is isolating it from physical contact with the reactor chamber walls, has always been the central problem. At first this problem seemed insolvable even in principle. Then it was realized that the high temperature necessary for fusion itself could help solve the problem. At fusion temperatures matter exists only in the plasma state - ions and electrons. These can be controlled by magnetic fields. Thus since the earliest days of fusion research the main approach has been to use intense magnetic fields to control the plasma - in other words to attempt to confine it within a magnetic bottle. This paper will be concerned solely with the magnetic approach to fusion. The recently proposed alternative - laser pellet irradiation - is discussed in another paper.

As implied by the words "attempt to confine", the stumbling block for fusion research in the past has been the failure of magnetic bottles to live up to expectations. This single circumstance dominated the research picture for many years. This is the circumstance that has now changed so radically.

To anticipate matters later discussed, the present situation in fusion is that the origins of the past failures of magnetic confinement - namely plasma instabilities - are well understood, and that effective means for dealing with these instabilities have been devised and proved out in the laboratory. In fact the present state of optimism in the fusion community stems from the circumstance that the stabilization principles involved are being found to remain effective in plasmas whose properties are not far below those needed in a fusion reactor. Furthermore, new experiments are coming up that should push these limits even farther. Many in fusion research look on these new

*Work performed under the auspices of the U.S. AEC. This paper represents a revision and extension of a paper delivered by the author at the Symposium for the Future, April 26, 1971, National Academy of Sciences

experiments as being the likely immediate predecessors of what might be called "scientific feasibility demonstrations" for fusion - that is experiments in which the principles of magnetic confinement would be proved at fusion reactor densities, temperatures and confinement times.

Again, some basics about magnetic confinement: Charged particles immersed in a magnetic field execute helical coil-spring-like orbits in that field. If the field is sufficiently intense the diameter of the helices will be small compared to that of the reactor chamber. When this is true particles should only be able to reach the chamber walls by a step-by-step collision-induced "random walk", at the so-called classical rate of diffusion of plasma across a magnetic field. At fusion temperatures and in a straight tube this classical rate calculates to be several powers of ten slower than that needed to satisfy fusion requirements. This result - namely that a strong magnetic field in a straight tube should effectively prevent the flow of particles across that field has been around for at least 30 years. It represents both the starting point and the reference standard for magnetic confinement.

To convert this basic idea into a useful plasma confinement system is another story. This kind of magnetic confinement is good for stopping transverse flow but is obviously worthless in inhibiting flow along field lines. There are three ways to resolve this dilemma: Either, (1) make the tube so long that its open ends don't matter - this means a kilometer or so at high density pulsed reactor conditions or hundreds of kilometers for a steady-state reactor - not a very attractive possibility. Or (2) restrain the flow of plasma along the field lines - this is the "mirror machine" idea or, (3) (and this one is the most popular choice for many reasons) return the field lines on themselves within a doughnut-shaped chamber, so that plasma particles, though moving freely along the lines, cannot immediately escape. The last two ways gave rise during the earliest days of fusion research to two simple, neat and intuitively obvious forms - the so-called open and closed magnetic bottles shown in Fig. 1. The open system is called a mirror machine since it works by trapping particles between magnetic mirrors (the mirrors are the strong field regions at the ends). The closed bottle is a primitive forerunner of the stellarator idea discussed later.

Like many simple solutions to difficult problems these two approaches are virtually worthless as originally proposed. Nevertheless they embody the basic confinement principles of later magnetic bottles that have proved to be effective.

III) The Problem of Plasma Instabilities

Why did the systems described above fail? They failed because they were subject to the simplest and most catastrophic of all plasma instabilities - the MHD or hydromagnetic instability - one in which the plasma moves as a whole across the confining field - in the downhill direction on any average magnetic gradient that happens to be present. This kind of instability is like that of a ball perched on a hill - the ball is the plasma. Let it go and it rolls off the hill - in this case meaning the field. In the simple toroid the field weakens away from the central axis of symmetry at every point on every magnetic line; confinement is not possible and the plasma slides to the outer wall in microseconds. In the simple open system a similar catastrophe can happen - here it occurs sideways between the mirrors.

MAGNETIC CONTAINMENT CONFIGURATIONS

Fig. 1 Open and Closed Magnetic Containment Configurations

The first major success of fusion research - accomplished about a decade ago - was the suppression of MHD instabilities. This success was achieved in both open and closed systems by reshaping the confining fields. From this work emerged two basic principles of plasma stabilization now used in one form or another in almost every modern fusion experiment. These two principles are magnetic shear and the magnetic well.

Fig. 2 shows the idea of magnetic shear. In a sheared field the lines are all helices (except for the one down the axis). But what is important is that in a field with shear the helical pitch angle varies between successive layers of field lines (if you can think of layers of such things). This means the lines form a kind of multi-layered basket-weave pattern.

Fig. 2 Concept of magnetic shear

The helical nature of the field lines in a closed toroidal system with magnetic shear actually has two

important consequences; First, all field lines (except the one in the middle of the tube - the magnetic axis) spiral as they go around the tube - sometimes being nearer to the outside wall, sometimes nearer to the inside wall. This effect is called rotational transform and it was first used in the stellarator. Its effect is to average out the "downhill magnetic gradient effect". The second effect is that shear can also inhibit other plasma instabilities (other than MHD) that could cause losses across the field. Field shear in effect "shorts out" the localized unstable accumulation of charges by taking advantage of the high electrical conductivity of plasma along field lines.

Strong shear is one basic principle - the magnetic well is the other. Magnetic wells are made by shaping the magnetic field within and around a plasma so that the plasma sits at a point of relative minimum in the field. If this trick can be accomplished then it is always "uphill" on the magnetic gradient no matter what direction the plasma tries to move. Therefore in deep magnetic wells MHD instabilities are energetically impossible.

Magnetic well fields can be made either by modifying the field coils or by a combination of currents flowing in conductors floated inside the plasma. Perhaps the best known application of the magnetic well idea is to the mirror machine. The first experimental test was carried out by Ioffe and his co-workers in Moscow in 1961. Fig. 3 shows the general shape of the field lines and the confined plasma in a modern version of the magnetic well type of mirror machine as made by a "baseball coil" - one shaped like the seam on a baseball.

Fig. 3 Magnetic well field produced by baseball coil

Suppressing MHD modes does not end the instability story, however. When they are controlled some less violent but still worrisome modes may remain. Even though these residual modes cannot expel the plasma bodily they can cause it to diffuse excessively rapidly across the field lines of a torus - or out the ends of a mirror machine. On a time scale where MHD modes dump plasma in microseconds these weaker modes may dissipate it in milliseconds. However in all but very high density systems milliseconds confinement is too

short. In a steady-state reactor tenths of a second to a second or so are likely to be required.

The instability modes now being discussed are loosely describable as plasma turbulences. They generally involve laser-like wave amplification effects that lead to unstable plasma oscillations. They represent the last known hurdle before scientific feasibility - and it is in their control that major recent progress has been made.

The bad effects of turbulence modes were probably first noticed in closed systems. There earlier experiments strongly suggested a fundamental limitation on confinement, proposed by Bohm about 30 years ago to explain some peculiar effects in gas discharges in magnetic fields. According to this dismal law (dismal for fusion that is) in the presence of turbulence magnetic confinement should get progressively worse with increasing plasma temperature - rather than getting better as in classical diffusion. Not only that but confinement was predicted to vary only as the first power of the magnetic field, rather than improving as the square as in classical diffusion. Thus high magnetic fields would be of little help. For years experimental evidence in toroidal systems seemed to support the Bohm law. Fig. 4 shows the accuracy with which this law was found to hold in the Princeton Model C stellarator - at that time the largest and most powerful toroidal experiment in the world.

Fig. 4 Bohm diffusion-limited losses in Model C stellarator

Faced with the fact of Bohm diffusion the fusion community went back to the drawing board. Probably the first ray of light came when magnetic wells were tested in toroidal geometry. Special experiments were set up in which ring conductors inside the plasma chamber were used to shape the field. Though few today think of these suspended ring experiments as leading to reactors they do provide critical tests of stabilization principles in closed confinement systems. A clear cut example of plasma stabilization in such a torus is provided by the Princeton "spherator" experiment, where both shear and magnetic well depth can be varied. Fig. 5 shows the stabilization achieved. The upper scope traces and the density curve indicate stable confinement; the lower ones show turbulence and loss of confinement.

TEST OF MAGNETIC FIELD CONFIGURATIONS IN A PPL SPHERATOR

Fig. 5 Stabilizing effects of shear and magnetic well in Princeton spherator

IV) Plasma Beta And Its Importance

Before discussing recent fusion developments there is another important aspect of fusion plasma confinement yet to be mentioned. It has to do with the "beta value" of a fusion plasma. Beta measures the energy of density of the plasma - as compared to the energy density of the confining field. When β is small the plasma hardly perturbs the magnetic field by its presence; when it is large it may markedly weaken it. Beta equal one is the limit; there the plasma has pushed out the field entirely, magnetic fields can hold no more. Although beta is not too important in academic studies of confinement, it would be very important in a fusion reactor since it measures how effectively the magnetic field is being used - therefore it involves dollars - since magnetic fields cost money. Since fusion power varies as beta squared, high β is desirable from an economic standpoint.

Experiments have now been performed that exhibit both high β and classical diffusion in a tubular plasma. These experiments are called "theta pinches" since they work by magnetically squeezing the plasma with currents flowing in coils wound around it (in the theta direction). A striking example of a stable high beta plasma column is shown in Fig. 6. The device is the Los Alamos Scylla IV and the picture shows a laser interferometer picture of the compressed plasma. In a similar experiment in the U.K. it was shown that such columns diffuse classically - not by Bohm law. Fig. 7 shows the evidence - theory and experiment.

One very important additional aspect of high beta plasmas is that they can dig their own magnetic well, thus in some cases they can actually help stabilize themselves. This idea is also implicit in the Astron concept under investigation at the Lawrence Livermore Laboratory and at Cornell, where the well is to be dug with high energy electrons.

A fine experimental example of both stable high beta confinement and self-dug magnetic wells is shown in Fig. 8 from the Oak Ridge National Laboratory. The upper half shows contour lines of magnetic intensity as modified by mirror trapped high energy electrons. The lower half of the figure shows the magnetic field contours without plasma. Comparison shows that the plasma electrons indeed have dug a well for themselves and are quite happy to stay there.

V) The Present Status of Confinement Experiments

As discussed up to this point, where do matters stand? Magnetic confinement, at first a wobbly and

Fig. 6 End-on laser interferogram in Los Alamos 3 meter theta pinch; schematic view of apparatus used.

RESULTS OF DIFFUSION EXPERIMENT

Fig. 7 Confirmation of classical diffusion in theta pinch experiment at Culham Laboratory, U.K.

poorly understood business, has been refined to the point where it can be made to work? But is it good

Fig. 8 Magnetic well produced by mirror-contained high energy electrons, Oak Ridge National Laboratory

enough for fusion reactors?

First one must recognize that, with one exception, experiments mentioned so far have been preparatory ones - that is they were conducted with non-fusion (that is low density or low temperature) test plasmas. The exception was the theta pinch, where the plasma was both hot and very dense. Beyond that experiment what else is known about confining real fusion plasmas? At this point we will discuss two more experiments, plus their follow ups, that have encouraged fusion researchers to feel in their bones that magnetic confinement really should work for fusion reactors. The first of these is the Tokomak T-3 experiment in Moscow. A tokomak is a toroid in which magnetic shear and magnetic well effects are produced by a combination of the usual external fields with fields from a heavy induced electrical circulating currents flowing in the plasma itself. In T-3 plasma ion temperatures of about 10 million degrees were achieved, at densities (3×10^{13} ions/cm³), close to those required for a reactor. The confinement time was about 10 milliseconds - a world's record at that time at the density and temperature achieved. But what excited the fusion community most was the fact that the measured confinement time was within about a factor of 3 to 5 of the calculated classical lifetime in a torus, and was obviously far above the Bohm value. The Soviet results have since been confirmed at Princeton and have recently been extended even further in new experiments at that Laboratory.

The second experiment to come within shooting distance of classical confinement - in this case a mirror experiment - is the 2X experiment at the Lawrence Livermore Laboratory. In this experiment the plasma was hotter than in T-3 - nearly 100 million degrees, the density was the same. Being a mirror system the classical time was not as long. Fig. 9 shows a historical sequence of plasma confinement curves in 2X, showing the improvement in confinement caused by the progressive elimination of instabilities over the years, and the approach to classical confinement (top curve). Recent experiments (in 2XII) have yielded an even closer agreement.

The third fusion plasma confinement result has already been mentioned - the Scylla IV theta pinch at Los Alamos. These three experiments, T-3, 2X and Scylla IV and their recent extensions represent the visible basis for present optimism in fusion. Less visible but no less important is a massive accumulation of prior experiments and theory. While plasma theory is a very difficult business increasingly there are found cases where theory and experiment agree closely. In fact prediction based on theory is becoming more of a science and less of an art.

Fig. 9 Sequence of plasma decay curves in 2X experiment (Lawrence Livermore Laboratory)

As mentioned earlier there are new generation experiments, based on the successes of the old ones, that are about to come on line in the near future. These experiments are in preparation in the U.S. and in other laboratories around the world - including some new and larger tokomaks in the USSR. Will these new generation experiments prove successful? - all of them? - any of them? We don't know for sure.

VI) Visions of Fusion Reactors

Though the problems of fusion research have up to the present time been mainly scientific ones, the vision of being able to build a fusion reactor following the solution of these problems has never been lost. It is not possible to predict today with assurance how or when this vision will be for the first time realized, but guesses can be made, based on plausible reactor concepts already in hand.

Fusion Fuel Cycles

The starting point for discussing fusion reactor concepts is the matter of fusion fuels and possible fuel cycles. The primary fuel for fusion is deuterium. Four reactions which involve deuterium and which represent the main candidates for fueling a reactor are listed below.

- 1) $D + D \rightarrow T + p + 3.25 \text{ MeV}$
- 1') $D + D \rightarrow {}^3\text{He} + n + 4.0 \text{ MeV}$
- 2) $D + T \rightarrow {}^4\text{He} + n + 17.6 \text{ MeV}$
- 3) $D + {}^3\text{He} \rightarrow {}^4\text{He} + p + 18.3 \text{ MeV}$

Note that these reactions define a sequence. Starting solely with deuterium one can visualize a fusion cycle in which the nuclear combustion of deuterium, together with the recycling and combustion of its reaction products, results in a total energy release of 7.2 MeV/deuteron. This is more than 3 times the energy release per gram that that released in the fission of

uranium. Furthermore at today's prices the fuel cost represented would be less than 1% that of coal. Such a cycle, which would tap the enormous reservoir of deuterium in the waters of the earth, represents the ultimate energy potential of fusion, a potential that could not be exhausted for billions of years. However in the first exploitation of fusion power other considerations will likely be more important. This circumstance is illustrated in Fig. 10, which shows the relative reaction probabilities of the reactions above as a function of ion temperature (1 keV ion temperature = 1.12×10^7 degrees Kelvin kinetic temperature).

Fig. 10 Fusion reaction rate parameters vs plasma ion temperature

In addition to having a large energy release the DT reaction has the highest reaction probability at low ion temperatures, thus would be the easiest to initiate. But tritium, being a radioactive isotope, is not available from natural sources. Most concepts of DT fusion reactors therefore visualize the use of a "breeding blanket" containing natural lithium that would surround the reacting plasma. Capture of 14 MeV neutrons from the DT reactions would yield tritium through the reactions

or

Typical breeding ratios calculated for practical-appearing blankets range between 1.2 and 2.0 with short regeneration times (days to weeks). Thus tritium production by this method should be readily possible. Furthermore, the lithium needed is both inexpensive and abundant, being obtainable either from substantial reserves of lithium-bearing ores or by recovery

ery from sea-water.

Reaction 3, the D-³He reaction, has a special appeal. It has the second highest cross-section (but peaking at higher energy than DT) and the highest energy release. More significantly, both of its reaction products are charged, thus can remain within the reacting plasma and contribute directly to its kinetic energy. This circumstance opens up a new possibility for fusion - the direct conversion, at potentially very high efficiency, of fusion plasma energy to electricity. Whether this possibility becomes actuality depends on whether it will be possible to achieve efficient confinement of a D-³He plasma at very high temperatures (greater than 100 keV). The ³He required for such a cycle could either be generated by accompanying DD reactions - DD_n giving ³He directly or DD giving ³He through $T + {}^3\text{He} + e$ (12 yr) - or possibly be derived from other sources such as the reaction

also a conceivable long-range fusion fuel cycle candidate for a reactor with direct conversion.

Reactor Concepts

Reaction cross sections and reaction energy releases define the required plasma conditions (composition, temperature, $n\tau$), for self-sustaining reactions. Theory and the results of relevant experiments on the plasma state can then be used as starting points for conceptual designs of fusion reactions. At the present time there are three distinct reactor "approaches" based on magnetic confinement that have been thought through far enough to establish some degree of credibility.

Theta-Pinch Reactors

Simplest in concept would be a reactor based on the pulsed θ -pinch approach. In the U.S. this work is mainly being pursued at the Los Alamos Scientific Laboratory. Starting with a chamber filled with a deuterium-tritium gas mixture at a density of about 10^{16} atoms/cm³ (3×10^{-4} atmosphere) a very rapidly rising (sub-microsecond) pulsed magnetic field would be applied to the gas to ionize and shock heat it. This shock pulse would be followed by a slower rising higher intensity magnetic field that would both moderately compress and further heat the plasma to temperatures of 10 keV and to somewhat higher densities (3×10^{16} ions/cm³). The magnetic field would be kept on during a burning time estimated at 50 to 100 milliseconds duration. Following the burn phase the reaction chamber would be purged, a new charge of fuel introduced, and the cycle repeated. Fusion energy released would be converted to electricity through a thermal cycle. A portion of the energy generated in each cycle would be stored and used to supply the energy needed for the next shock heating and magnetic compression cycle.

Although most theta-pinch experiments have been conducted with straight tubes, the theta-pinch reactor is usually visualized as a toroidal system. That is, it would consist of a low aspect ratio torus (skinny, large major diameter) utilizing stellarator-type helical stabilizing windings, possibly also coupled with feedback stabilization to keep the plasma column properly centered. Straight tube versions have also been considered, thus building more directly on past theta pinch experience. But in this case the problem of plasma flow out the ends poses problems that are not yet resolved, short of using an unattractively long reaction chamber.

A Mirror Reactor Concept

Most thinking about mirror reactors has centered on steady state operation, along the following lines: The reactor is visualized as a sort of "energy amplifier" in which a portion of the fusion energy generated is fed back into the system, in the form of preheated (energetic) fuel ions, thereby to maintain both the plasma density and its temperature.

Besides requiring reaching at least a minimal plasma confinement time, this sort of scheme requires an energetically efficient technique for accomplishing continuous refueling. In fact the basic problem with steady state operation of any fusion system would be how to inject new fuel. In the mirror system it is proposed to solve both problems - refueling and heating - through the use of energetic neutral atom beams, as follows: Focused, energetic (100 keV or greater) beams of molecular or atomic ions are created by an array of high current ion sources. These beams pass through "neutralizer" cells filled with gas or metal vapor at low pressure. In these cells charge exchanging and/or stripping processes convert a large fraction of the incident ion beam into neutral atoms with negligible change in kinetic energy or direction. The directed neutral atom beams thus formed pass into the main chamber, across the confining field, where they are broken up into their constituent ions and electrons thereby becoming trapped between the mirrors. Since the ions are trapped within the plasma with their full initial kinetic energy the maintenance of a high plasma temperature is assured; the ability of energetic neutral beams to penetrate deeply into even a dense plasma solves the sticky problem of how to refuel a steady-state reactor plasma.

The neutral injection technique is not merely an interesting idea. It has been employed for several years in mirror experiments at Livermore, ORNL, in the U.K. and in the USSR. Fig. 11 is a cutaway drawing of one of the most recent of these, the Baseball II experiment at Livermore, which utilizes a superconducting baseball magnet to produce its magnetic field and high intensity neutral beams to create the plasma. This, and the other experiments have proved out the neutral injection technique, albeit thus far only at relatively low plasma densities.

BASEBALL II

Fig. 11 Baseball II mirror experiment using neutral beam injection (Lawrence Livermore Laboratory)

Returning to the question of the confinement time in mirror systems it must be understood that, contrary to the situation in closed systems, it is not possible to insure adequate containment in a mirror system of the kind discussed here by a scaleup in plasma dimensions. Instead it is necessary to rely on high tem-

perature operation (reduces coulomb scattering rates relative to fusion reaction rates) and to attain a high degree of plasma quiescence.

Insight into the limitations of mirror confinement is provided by considering the quantity "Q", defined as the ratio per unit release of the plasma, of nuclear power released to power input by injection.

$$Q = \frac{P_{nuc}}{P_{injection}} = \frac{\frac{1}{4} n^2 \langle \sigma v \rangle W_{nuc}}{J \cdot W_{injection}}$$

Since J, the injected current per unit volume, is related to the confinement time through $J = \frac{n}{\tau}$, Q can also be written

$$Q = \frac{1}{4} (n\tau) \langle \sigma v \rangle \left(\frac{W_{nuc}}{W_{injection}} \right)$$

Here $\langle \sigma v \rangle$ represents the averaged value of the product of fusion reaction cross section and relative velocity of the plasma ions. For DT in mirror systems, the maximum value of $\langle \sigma v \rangle \approx 10^{-15} \text{ cm}^3 \text{ sec}^{-1}$, occurring at about 150 keV mean ion energy (about 100 keV kinetic temperature; see Fig. 10). $W_{nuc} = 22.4 \text{ MeV}$ for the DT cycle (17.6 MeV plus 4.8 MeV neutron capture energy in lithium), and $W_{injection} = 150 \text{ keV}$ in the example given. From these data one obtains a value for Q at the point of maximum $\langle \sigma v \rangle$ given approximately by

$$Q = 3.5 \times 10^{-14} (n\tau)$$

At the nominal $n\tau = 10^{14}$ Lawson criterion "break-even" point this gives $Q = 3.5$; in actuality Q for the DT reaction calculates to be about a factor of 2 lower (1.5 to 2.5) when evaluated specifically for the case of collisional, i.e. classical, mirror losses at maximum practical values of the mirror ratio (ratio of field at the mirrors to field at the minimum field point between the mirrors). Thus, in common with gas turbines, mirror reactors would be expected to be "low Q" devices, ones in which an appreciable fraction of the power generated must be recycled in order to keep the system going. To be successful mirror reactors would therefore require the achievement of high energetic efficiency in both the energy recovery and the refueling processes.

A means by which it is proposed to alleviate the Q problem in mirror systems is presently under investigation at the Lawrence Livermore Laboratory. An electrostatic direct conversion system would be used to recover energy directly from the charged particle streams emerging through the mirrors. A similar technique would also be applied to the neutral beam injector system to increase its energetic efficiency. Achievable conversion and injection efficiencies, η_{DC} and η_i , respectively, are predicted to be very high. Based on experiments and computations to date, 80 to 90 percent conversion efficiency from end losses and 85 to 95 percent injection efficiency seems attainable. The result would be to multiply the Q of a mirror system by a factor $(1 - \eta_i \eta_{DC})^{-1} \approx 3$ to 7, materially relieving the power balance problem. Stated another way, the effect of direct conversion is to reduce the Lawson $n\tau$ requirements for self-sustaining reactions in a mirror reactor by a substantial factor (from 10^{14} down to approximately 10^{13} sec^{-3} in typical cases).

As proposed, the direct converter system would operate as follows: (see Fig. 12)

Fig. 12 Schematic of mirror fusion reactor with direct conversion

Ions and electrons diffusing through the mirrors would enter a large fan-shaped region called the "expander". Within the expander the radially-directed magnetic field decreases from its peak value at the mirror, say 150 kilogauss, to a low value, of order 500 gauss, at the periphery. This results in conversion of the initially randomized velocities of the ions into radially directed motion. After expansion the particle density has fallen 8 powers of ten (for example from 10^{14} cm^{-3} to 10^6 cm^{-3}) relative to its value in the reactor chamber. Six of these powers stem from the difference between trapped and streaming particle densities: a drop of two more occurs in the expander. At such low densities plasma effects are essentially negligible and the particle behavior resembles that encountered in electron tubes or particle accelerators.

At the outer rim of the expander the field lines are abruptly folded back by the use of bucking coil windings. The result; electrons, which in the particle stream from a mirror system carry negligible kinetic energy, are diverted and collected at the "ground" or negative terminal of the direct converter. The ions, being both energetic and massive, emerge undeflected from the expander with their highly directed energy (~99% in the radially-outward direction). To convert this directed energy into useful electrical form the ions need only be decelerated and collected at potentials which correspond closely to their initial kinetic energy. If the ions were monoenergetic, then the use of a single properly biased collector electrode would do the trick. Such is not the case: ions emerging from a mirror reactor possess an inherent collisionally-induced spread of energies, ranging up to about a factor 3. The lower limit is set by the so-called ambipolar potential of the plasma, that positive electrostatic potential which arises naturally in achieving a balance between the rates of loss of the more mobile electrons and the slower ions. The upper "limit" is set by the exponential fall-off in ion energy associated with a competition between ion-ion and ion-electron effects, and mirror losses. Given the above requirements, the main trick in the direct converter system is therefore embodied in the "collector", a device that decelerates each incident ion, but collects it only after it has lost most of its initial kinetic energy (residual kinetic energy at collection only results in heating the collector electrode, thus results in reduced efficiency. One scheme being studied at Livermore uses spatially periodic electrostatic lenses, with an accompanying dc decelerating field (see Fig. 13).

Fig. 13 Electrode structure of collector for direct conversion experiments (Lawrence Livermore Laboratory)

As long as any ion has a substantial kinetic energy it is stably focussed and guided by the collector structure during deceleration. As soon as its energy falls below a critical value, however, it is defocussed, deflected sideways, and collected on an appropriate electrode. The end result is a multi-potential high voltage dc source. Subsequent conversion to ac or to a common dc potential would complete the process.

In the converter the expander losses should be low, and the theoretical efficiency of the collector can be high, being of order $(1-1/N)$, where N is the number of collection electrodes. With care in the system design it therefore should be possible to achieve high direct converter efficiencies using the methods outlined above. In fact in computer simulation and small-scale laboratory tests collector efficiencies between 83% and 88% have been achieved, with indications that higher values are possible. Overall conversion efficiencies would of course be lower than this.

At present it appears that there are no in-principle problems with the proposed direct conversion scheme. The main problems yet to be overcome are therefore now seen to be practical ones, such as space-charge effects, secondary electron emission, and high voltage insulation.

While electrostatic direct conversion is of primary interest in mirror systems as a means for enhancing Q , it should also be apparent that the use of direct conversion in connection with a $D-3\text{He}$ fuel cycle presents a real opportunity for fusion. In the usual mirror systems, the Q values calculated for this fuel cycle are so low as to be extremely marginal. But if it becomes possible to realize as little as a factor 2 to 3 improvement in confinement over these values $D-3\text{He}$ would become an attractive alternative to DT, with the possibility of overall system generation efficiencies of 60% or higher, and without some of the less desirable features of the DT cycle.

Tokamak Reactors

Following the tokamak successes thought has been given to the problems of incorporating this approach into a reactor concept. While the concept that has evolved is relatively straightforward, the tokamak approach introduces some special problems. Some of these arise from the transient nature of tokamak confinement and the problem of ignition. Note that, unlike the mirror reactor concept, a tokamak is visualized as a "high Q " (high n) device, one in which the fusion combustion process, once ignited, would maintain itself from internal self heating.

In a tokamak, equilibrium and stability requires the presence of both externally and internally generated magnetic fields, the latter being associated with the azimuthal current induced in the plasma by transformer action. This current also heats the plasma ohmically, and is thereby dissipated, leading in time to loss of confinement. In the context of a

reactor this circumstance presents two problems: First, on this picture tokamak confinement is necessarily transient, so that the reactor would operate in a cyclic mode - plasma heating followed by fusion reactions, followed by purging and the introduction of new fuel. While the cycle time might be long - many seconds - appropriate energy storage between cycles would still be needed.

The second problem in tokamaks has to do with the plasma ohmic heating process itself, as follows: The classical resistivity of a hot plasma has the approximate value

$$\rho \sim 3 \times 10^{-6} T_e^{-3/2} \text{ ohm-cm,}$$

(electron temperature in kilovolts). Thus at low plasma temperatures the classical resistivity is high, causing rapid ohmic heating. However, as plasma temperature increases classical ohmic heating rates fall, becoming too slow to be useful well before DT ignition temperatures (5 to 10 keV) are reached. Various methods have been proposed to overcome this problem. At present one of the most promising appears to be the use of neutral beams to add kinetic energy to the plasma during the ignition phase. By using beams with sufficiently high energies (perhaps several hundred keV) penetration of the plasma could be achieved and heating beyond temperatures where ohmic heating fails and up to the ignition point should be possible. Once ignition temperature is achieved plasma self-heating by trapped charged reaction products would maintain the temperature until the end of the cycle.

While neutral injection appears to be an attractive method for tokamak plasma heating, it is not the only one proposed. Heating by r.f. or microwave fields or by magnetic compression involving slowly rising magnetic fields has also been considered. Only experimental study will indicate which methods are suitable for reactors.

An additional problem that occurs in tokamaks is the problem of recycling plasma ions which diffuse to the chamber walls and there recombine to create a source of cold gas. Reflexing of this gas back into the plasma causes cooling and other deleterious effects. For this reason it is commonly assumed that tokamak reactors would be fitted with "diverters" to remove outwardly diffused ions from the chamber before they could reach the walls. Extra windings would be used to break the flux surfaces beyond a critical radius so that their contained flux tubes are directed out through a slit in the chamber wall. Ions which diffuse to this critical surface would then be guided out of the reaction chamber before they would diffuse further.

Except for the necessity for means to achieve ignition, for cyclic energy storage and for a diverter, a tokamak reactor would be otherwise a simple device. Apart from these auxiliaries its main elements would be: 1) a toroidal vacuum chamber, 2) a blanket to regenerate tritium (ordinarily only the DT cycle is considered for closed systems, owing to temperature and β limitations), 3) a large superconducting magnet coil to provide a toroidal field of 60 to 80 kilogauss intensity, and 4) a steam turbine-alternator to convert reaction thermal energy into electricity. Owing to the relatively low operating temperatures envisaged (10 - 20 keV) and to the use of the DT cycle, direct conversion of the type proposed for mirror systems does not at present appear to be applicable to tokamak reactors.

Depending on the degree of plasma quiescence the

overall size and therefore the electrical output power of a tokamak reactor is visualized as lying somewhere between about 500 megawatts (most quiescent) to several thousand MW (less quiescent). Lower limits on the power output of tokamaks are imposed by the circumstance that confinement time in closed systems depends on the plasma transverse dimensions, thus its volume. Too small a volume would prevent reaching the required Lawson breakeven $n\tau$ values, whence the lower limit on power.

To conclude the discussion of toroidal reactors mention should be made of the stellarator. While stellarator reactor concepts have been discussed in the past, such ideas are presently in limbo until more is known about the physics and the scaling of stellarator confinement. If the stellarator proved in fact to be a practical confinement geometry for a fusion reactor plasma it would have several advantages. Being a steady-state system many of the above discussed problems could be avoided, and the degree of control implicit in having purely externally generated fields could be a major advantage. However at present it is not known whether stellarators would be able to satisfy the equilibrium and stability requirements of reactor operation.

VII) Problems and Prognostications

As suggested above, though major progress has been made toward the solution of the scientific problems that have barred the way to fusion, the task is not yet completed. This is not to say that there remains any serious doubt among those doing research that magnetic confinement can solve the fusion problem. Rather it is that it is not yet known with adequate certainty what the scaling laws for magnetic confinement are for reactor-grade plasmas, and therefore how one would define with confidence the size, configuration and magnetic field intensity needed for confinement systems capable of meeting the $n\tau$ requirements for self-sustaining reactions.

In all cases the questions to be resolved relate to instabilities - existing or anticipated - and their possible influence on confinement. Taking the three reactor approaches in turn, the question areas are as follows:

1) Theta-pinch - Here the main problem has to do with keeping the compressed plasma column stably centered in the confinement tube, that is avoiding long-wavelength hydromagnetic kinking of the columns. Feedback stabilization has been proposed as a possible answer to this problem; the present approaches using magnetic shear are not found to be successful.

2) Mirror Machines - Here the use of magnetic wells has eliminated hydromagnetic instabilities. The tasks yet to be done have to do with finding plasma ion velocity distributions and plasma boundary conditions that will adequately suppress turbulence effects from residual high frequency modes. There is no positive assurance that this can be done, although the present experimental picture is encouraging.

3) Tokamaks - The primary virtue of closed systems such as the tokamak is that the confinement time in such systems should scale up with the square of the diameter of the plasma column, provided hydromagnetic instabilities do not dominate the behavior. Present enthusiasm for the tokamak stems from the fact that hydromagnetically stable regimes have been found which are sufficiently turbulence-free that good confinement is found, scaling indeed as the square of plasma column diameter. However, to date the plasma ion tempera-

tures in tokomaks have been limited to about 500 eV, substantially below the ion temperatures required for ignition (5000 to 10,000 eV). But under these conditions cross-sections for "coulomb" collisional interactions between the plasma particles are much larger than they would be at fusion temperatures. The concern is that at present collisions may be damping out some instabilities - called "trapped particle modes" - that are predicted to appear at fusion temperatures where collisional damping would be much less important. These modes might cause excessively rapid plasma losses, thus require tokomaks to be very large in size, or else require excessively high magnetic fields in order to obtain adequate confinement. The importance (or unimportance) of trapped particle instability modes cannot be adequately assessed until plasma conditions much closer to reactor conditions are obtained. This will require the performance of scaled-up experiments, such as the PLT experiment now under construction at Princeton.

Despite great progress it is apparent that it is still necessary to prove out some detailed aspects of magnetic confinement before the scientific feasibility ($n\tau$ and T) of fusion will have been demonstrated. Some estimates of the time it will take to prepare and to execute experiments of sufficient size and sophistication to settle these place this in the 1980-82 period. Conceivably the date could be moved up, given good luck with the present experiments.

Granted that proof of scientific feasibility will in time be obtained what then must be done to bring fusion to practical reality? Serious study of the engineering and technological problems that are anticipated in building a practical fusion reactor are now getting underway at several laboratories in this coun-

try and abroad, although this effort is still small compared to the total program effort. One circumstance, peculiar to fusion research, has given reactor studies a substantial headstart. This is the circumstance that in the process of studying the behavior of high temperature plasmas in the laboratory it has been necessary to solve many of the technological problems (vacuum, high magnetic fields, intense beams, etc.) that are expected to be encountered in full-scale fusion reactors. The problem areas for which this is not true are mainly those that arise from the nuclear power aspects of the problem, for example neutron bombardment of the inner wall of the reactor, and related problems. But even here, prior experience in the fission reactor program gives a base from which to start, though not providing all the answers. But it seems safe to say that no problems of a fundamental nature have turned up in any of the studies. Though much hard work will no doubt be required, practical solutions to fusion engineering and technological problems can be expected to emerge in time to be applied as soon as scientific feasibility is proved.

What of fusion as an energy source? The very breadth of the several approaches to fusion, and in many cases favorable differences and greater flexibility of fusion relative to other sources of energy suggest that it will indeed become the energy source of the future. Surely there seems to be no other conceivable energy source, with the possible exception of solar energy, that could come close to fusion on the basis of unlimited fuel reserves, minimum hazard and minimum adverse environmental impact and indeed, potential low cost for producing electrical energy. The search for fusion is not yet over, but the end seems in sight, and the achievement of fusion power will surely rank as one of the most far-reaching technological achievements of the century.