Controlled Fusion-- Clean, Unlimited Power Generation

by Roy W. Gould

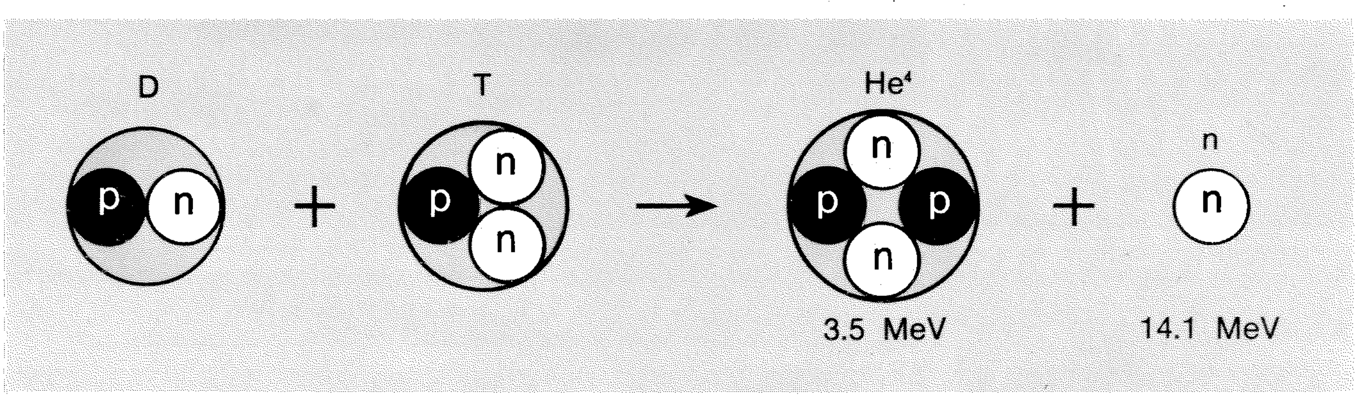
Our sun, like many other stars, produces its energy—the energy that sustains life on earth—from the thermonuclear fusion of nucleon isotopes of hydrogen into helium nuclei, with an accompanying release of energy. Hydrogen bombs, which man has modeled after the stars, derive their destructive force from similar thermonuclear processes. It now seems likely that by the end of this century fusion will play a third key role in our lives—the production of the electrical power that civilization so heavily relies on.

Electrical power consumption in the United States has been doubling and is expected to continue doubling every ten to twelve years. By the year 2000 we will duplicate our electrical generating capacity five times over. Only nuclear power can satisfy this voracious appetite. We must conserve our valuable and limited fossil fuels (coal, gas, and oil) for more important specialized uses in the chemical and steel industries. Increased air pollution from fossil fuel power plants would be intolerable.

Nuclear power from fission reactors already accounts for about 1 percent of the nation's electrical power. Power from fission reactors will certainly increase rapidly in the years ahead. But because fission fuel resources are also limited, development of a fission breeder reactor, which breeds fissionable fuel from more common nonfissionable elements, and the research toward the development of a fusion reactor are now being vigorously pursued in the United States as well as in Western Europe, Russia, and Japan. In the United States, research on controlled thermonuclear reactors is carried out in four major laboratories: the Lawrence Radiation Laboratory (Livermore, California), The Los Alamos Scientific Laboratory, the Oak Ridge National Laboratory, and the Princeton Plasma Physics Laboratory, with smaller but significant programs of varying size in many American universities and industrial laboratories.

Fusion reactors would "burn" deuterium, a heavy isotope of hydrogen which occurs about once in every 7,000 atoms of hydrogen. The energy available from fusion of the deuterium (about ⅛ of a gram) in one gallon of water is equivalent to that of 300 gallons of gasoline. The current cost of extracting this deuterium from the water is only four cents. Deuterium in the oceans would be sufficient to supply the world's energy needs for 10 billion years (at the current rate of consumption). This was the principal argument advanced for beginning work on fusion reactors in the early 1950's.

In a fusion reactor, deuterium (H^2) and tritium (H^3) nuclei come together and fuse into an unstable nucleus which then ejects a very energetic neutron—about 14 million electron volts (eV) of kinetic energy—leaving behind a helium nucleus which also has considerable kinetic energy—about 3½ million eV. The most difficult aspect of this kind of reaction is that it is very hard to get these two particles together in the first place. They are both charged and strongly repel one another. In order to come together and react, these particles must approach one another with kinetic energies of about 10,000 eV. But when they do react, they give back 17 million eV—a very handsome gain. The source of the most difficult problems in a fusion reactor is that the reacting deuterium-tritium (D-T) mixture must be heated to fantastic temperatures—as much as 100 million degrees Centigrade (180 million degrees Fahrenheit). These kinds of temperatures occur



In a fusion reactor, deuterium and tritium nuclei come together and fuse into an unstable nucleus, which then ejects a very energetic neutron—the power source. The problem is to get these two strongly repelling particles together in the first place.

A tamed hydrogen bomb running your electric toothbrush? It's beginning to look possible.

in the interior of the stars, and we provide them in the hydrogen bomb by exploding a fission bomb. At these temperatures, all the atoms have shed their electrons to form an ionized gas, or plasma.

The fusion reaction energy generation rate increases sharply with the temperature of the reacting mixture, and the D-T reaction rate is much more favorable than others for the same temperature. While we can get the necessary deuterium easily from sea water, we must manufacture, or "breed," the necessary tritium. Fortunately, tritium breeding can be carried out in the reactor itself. Eventually, it should be possible to dispense with tritium breeding and burn pure deuterium.

At the very least, the fusion reactions must make up for energy which is radiated away because of the high temperature. For the D-T mixture this happens at 45 million degrees (4,000 eV) and at 400 million degrees (40,000 eV) for the D-D mixture. These are said to be the ignition temperatures. For the reaction also to provide the energy to heat the fuel which is constantly being added as well as provide some useful energy to drive an electrical generator, the operating temperature must exceed the ignition temperature.

Furthermore, the particles must be kept around long enough to undergo fusion reactions. The more dense the mixture, the more likely is a fusion reaction and the shorter the time the particles need be contained.

In a typical fusion reactor the plasma density would be about 10^{15} ions/cubic centimeter, which is 25,000 times less dense than the air we breathe. High-vacuum techniques would be required in a reactor and in all experiments trying to achieve reactor conditions. We are limited to this very low density by the necessity to contain the tremendous pressure (about 10 atmospheres) of the very hot plasma on its container.

Thus we have to contain the plasma particles for a half second, during which time they can rattle back and forth (at a density corresponding to high-vacuum conditions) in their container, striking the walls about 10,000 times.

No ordinary container can hold the plasma. The reasons are somewhat unexpected. It's not so much what the plasma would do to the walls of the container, but rather what the walls would do to the plasma. The hot plasma would immediately be cooled by contact with the cold walls, with only slight damage to the walls. A few foreign atoms knocked out of the wall by the hot plasma particles (plasma impurities) increase the plasma radiation loss,

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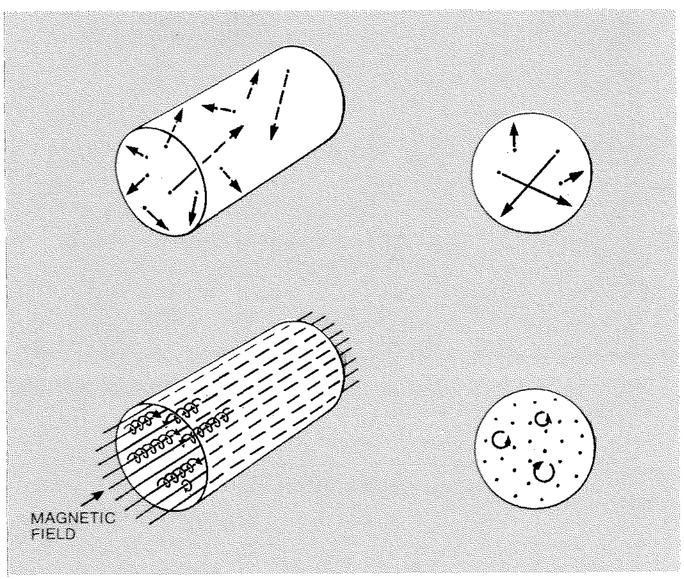
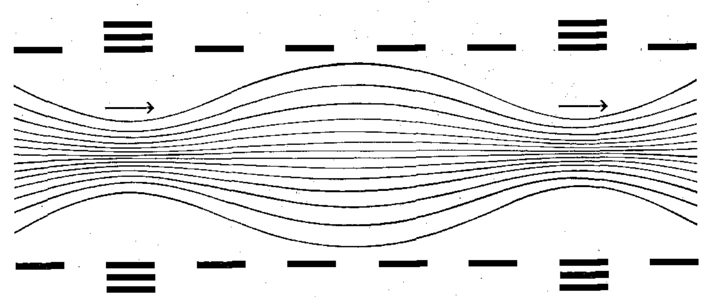
contributing to the cooling. In a practical reactor the impurity level in the plasma must be kept very, very low. However, the very high temperature is actually an advantage; as a result of it the particles which have to be contained are charged, and one can therefore contain them with magnetic fields (if you can't beat 'em, join 'em).

A magnetic field bends the otherwise straight orbits of charged particles into very tight helical orbits. The plasma particles may not move from one field line to another (unless they happen to collide with another particle, in which case they can take up a new helical orbit on a nearby field line). Such collisions are rare in such hot plasmas, but do give rise to a very slow leak, called classical diffusion. This sets a fundamental limit to the containment time of charged particles in any magnetic containment scheme. However, the leak due to classical diffusion is slow enough to be tolerable in a fusion reactor (which is good because we probably couldn't do much about it).



In the absence of a magnetic field, charged particles move in random directions, striking the walls and allowing cooling of the plasma. The introduction of a magnetic field contains the particles in tight helical orbits and restricts their movement across the magnetic field lines.

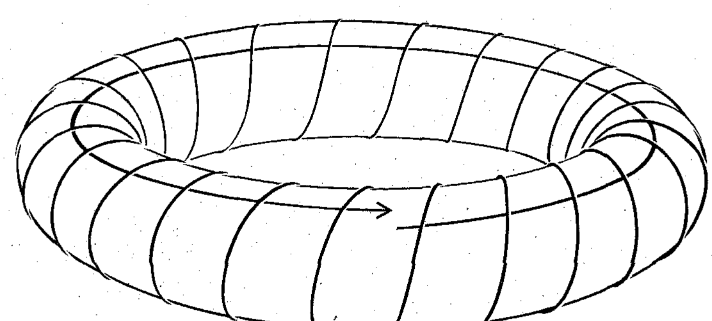
The particles, because they are free to move along the magnetic field lines, readily leak out the ends. One solution is to plug the ends. This can be done partially by "squeezing the ends," making the magnetic field much stronger at each end. When a particle moving along a field line encounters the region of increased field strength, it is reflected. But even in these mirror machines certain kinds of particles can still leak out the ends, and the residual end loss of particles from a mirror machine is potentially serious in the "reactor sweepstakes" race.



Because the particles are free to move along the magnetic field lines, they readily leak out the ends. One solution is to plug the ends. This can be done partially by making the magnetic field stronger at each end.

Another way to eliminate leakage at the ends is to actually eliminate the ends, wrapping the cylindrical container, and also the magnetic field lines, around on themselves in the form of a doughnut (or toroid).

Toroidal, or closed, confinement sounds like a much better solution to the end problem, but it is not as simple as it seems. Whenever magnetic field lines are curved, the magnetic field strength varies. When the magnetic field is not spatially uniform, the charged particles have the bad habit of drifting across the magnetic field and escaping. The loss of ions due to this drift can be eliminated by twisting the magnetic field. A particle trying to follow such a twisted field line drifts away from this field line during the first half-dozen revolutions, but then drifts back toward it during the second half-dozen revolutions. The net effect



Another way to eliminate leakage at the ends is to eliminate the ends, wrapping the cylindrical container and the magnetic field lines around on themselves in the form of a toroid.

If either of the two general approaches worked exactly as suggested, we would probably have a working reactor today.

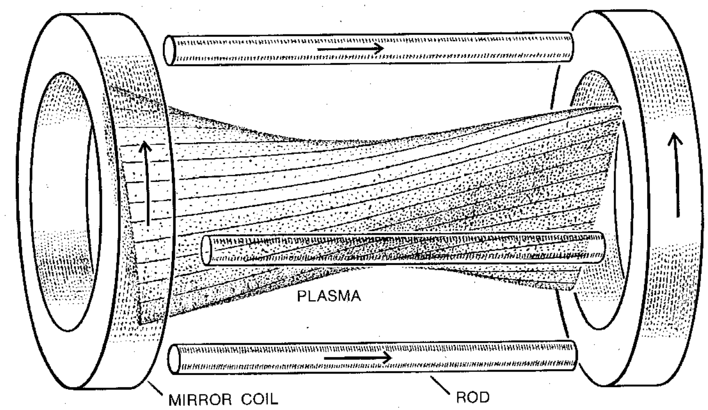
is that it comes back to where it started and doesn't escape. The twist, or rotational transform, is very important and can be provided by some additional coils located outside the plasma—as in the Stellarator type of machine, or by currents in the plasma itself as in the Russian Tokomak.

If either of these two general approaches—using open and closed magnetic field lines—worked exactly as suggested, we would probably have a working reactor today. What, then, is the problem?

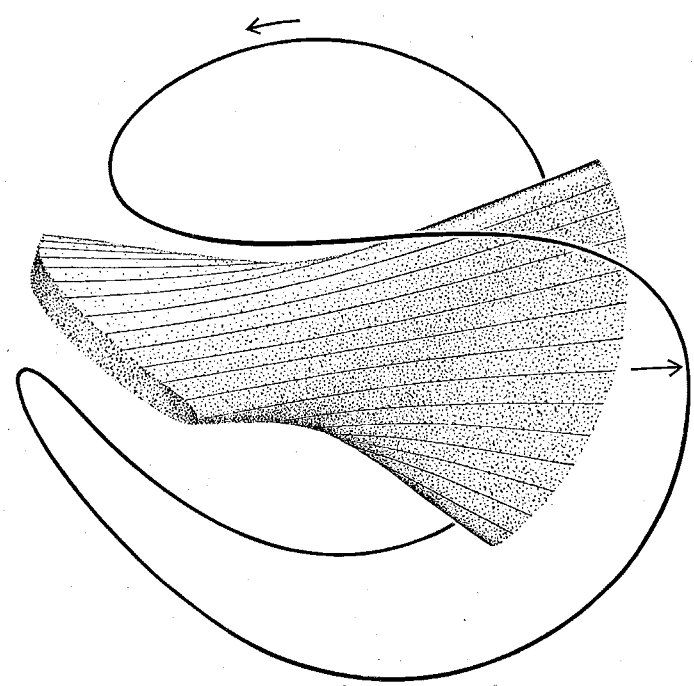
These approaches work beautifully for one or two, or even a few million ions—and this has been demonstrated very nicely by experiment. However, as we try to increase the density of ions, we find that the particles can cooperate with one another to produce substantial electrical currents; hence, they can make their own magnetic and electric fields. Some of these plasma currents and fields are innocuous enough—some are even necessary to the confinement of fusion reactor plasmas. But some are very detrimental.

If the field lines are curved toward the plasma, the magnetic field diminishes in strength away from the plasma, and creates an unstable situation. If a small ripple develops on the plasma boundary, allowing some of the plasma to move from a region of higher magnetic field into a region of lower magnetic field (away from the surface), the plasma finds a reduced containing force, thus allowing the ripple to grow even larger and allowing even more plasma to leave the confined region. If the field lines curve away from the plasma, the magnetic field increases away from the plasma, and a ripple meets an increasing pressure of the increasing field and is forced back. One refers to these situations as having bad curvature and good curvature, respectively. Clearly, one should only seek systems with good curvature.

The idea of good and bad curvature is basic to all containment systems, so let's see how it applies to the mirror machine. The mirror machine has bad curvature in the middle where most of the plasma is located, and has good curvature only at each end. According to this criterion, one would expect the mirror machine to be unstable and to lose its plasma by developing increasing ripples, or flutes, on the surface of the plasma which eventually come in contact with the solid walls of the machine. Indeed, this is exactly what happens, and this



A solution for the instability of the mirror machine was proposed in 1962 by the Russian physicist Ioffe. By adding four extra current-carrying bars, he reduced the instability and provided the necessary good curvature for the plasma.



Another method of achieving good curvature is called Baseball. The connection of the Ioffe bars to the mirror coils at either end results in a single continuous current path—in the form of the seam on a baseball.

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flute instability has been nicely documented in mirror machines.

In 1962 a Russian physicist, Ioffe, observed that by adding four extra current-carrying bars the flute instability could be stabilized and the plasma in the center could "see good curvature no matter which way it looked." (Ioffe was awarded the U.S. Atoms for Peace Award for his discovery.)

There is another way (topologically the same) to make this field. It is called Baseball, and there is a single continuous current path—in the form of the seam on a baseball.

The most striking confinement results in magnetic wells—also known as "minimum B" fields—have been obtained in the 2X machine at the Lawrence Radiation Laboratory. Here the ion temperature is already 80 million degrees, and the confinement appears to be limited only by classical scattering. These results are very encouraging.

Toroidal systems, with no "end problems" because they are closed, might be expected to be better than the open systems such as the mirror. The only leak in the simple toroidal system is expected to be from collisions which permit a particle to step from one field line to an adjacent field line—and after many such steps to make its way across the field to a metal surface—the vacuum chamber. These losses due to classical diffusion would be tolerable in a fusion reactor when using a strong magnetic field and large sizes—the containment time could be made many seconds.

However, most plasmas do not behave in this simple way. During World War II theoretical physicist David Bohm was working on the Manhattan Project with another form of plasma—gas discharges in a magnetic field—for the purpose of separating the various isotopes of uranium. It was observed that the ions of these plasmas escaped much faster than could be explained by classical diffusion—and Bohm "invented" a formula to describe this much shorter lifetime—now called the Bohm time. Perhaps Bohm understood where this formula came from—but he never bothered to write down his explanation. Nobody paid much attention to it until the fusion research program started, nearly ten years later. In an effort to understand Bohm's formula, some of the earlier experiments in gas discharges were repeated, and it was found that there was a different explanation for the high loss rates—and Bohm's formula didn't really apply to this situation after all. Nevertheless, there is a growing body of evidence that Bohm's formula really applies to many toroidal confinement experiments—even though the origin of the formula is unclear.

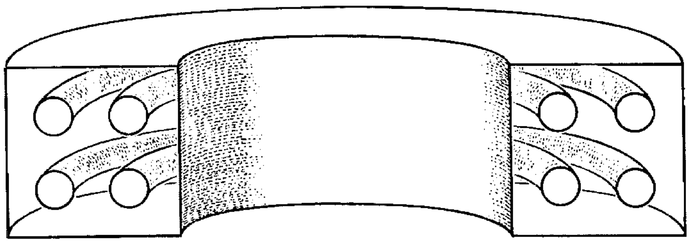
The Bohm containment time is typically a thousand to a million times shorter than the classical containment time; it also decreases with increasing temperature rather than increasing, which would be disastrous for a fusion reactor. The Bohm containment time also does not increase as fast with magnetic field as does the classical containment time.

In recent years it has become quite a challenge to young theorists to derive (and therefore to explain) the Bohm formula. This anomalous diffusion might result from turbulent fluctuations in the plasma. Indeed, with suitable assumptions about the nature of the turbulent fluctuations, one can actually obtain Bohm's formula. The fluctuating electrical fields associated with the plasma turbulence play a role very similar to that of collisions and allow the plasma particles to escape much faster.

The causes of plasma turbulence are only partially understood, but at the heart of the matter is the instability phenomenon. The interchange or flute instability is a relatively simple one—and can now be suppressed. But there are a lot more instabilities where that one came from. In the past ten years the plasma theorists have uncovered literally dozens of new instabilities. The Plasma Physics Division of the American Physical Society once discussed whether it should make an award for the "instability of the year." Fortunately, the rate at which new instabilities are being discovered is now falling off, and many of these new instabilities are variations of the old ones. They can probably be eliminated (or their effects minimized) through the use of the minimum B fields, or fields with good curvature.

It would certainly be desirable if one could find a way to have minimum B or favorable curvature everywhere in a toroidal system. This turns out to be topologically impossible in a closed system—the field lines cannot everywhere curve away from the plasma and still close on themselves.

However, it is possible to have favorable curvature—or minimum B properties—in most regions. It is also important for the favorable curvature regions to be connected by the field lines to the unfavorable regions with



Good curvature is essential to any containment system. In a closed system, it can most readily be achieved by using floating rings, each ring carrying a large current in the same direction.

a short connection length and for the effect of the favorable curvature regions to outweigh the effect of the unfavorable curvature regions. Systems employing this idea are called average minimum B systems. (One might say average favorable curvature.)

The average minimum B property can readily be achieved with closed field lines by using floating rings, which carry the currents that make the magnetic field. Each circular ring inside the toroidal chamber carries a large current in the same direction, and the good curvature regions do predominate.

Although it would probably be impractical to have big metal rings suspended in a reactor, this arrangement has nevertheless led to some very striking advances in containment principles. Floating ring devices do provide an average minimum B field, and turbulent fluctuations are either absent or exist at a low level.

Containment times in some toroidal systems are very considerably increased over the anomalous Bohm value, and some are even believed to exhibit classical containment times. In those devices still exhibiting anomalous losses, the remaining losses are also found to vary with magnetic field in the manner given by Bohm's formula, although the losses are not nearly as large. Depending on the particular machine, the remaining anomalous losses are thought to arise from the supports which must be used to hold the rings, or from electric fields associated with rings which are electromagnetically levitated, or with small deviations in the precise azimuthal symmetry of the magnetic field. The cause of these residual losses is now under careful investigation, and they can probably be reduced still further.

The evidence that containment times which greatly exceed the Bohm containment time could be achieved in toroidal, or closed, systems was first presented in 1968 at the third International Conference on Plasma Physics and Controlled Fusion Research in Novosibirsk, Russia. (The next International Conference will be in 1971 in Madison, Wisconsin.) At the Novosibirsk Conference very significant improvements were reported in several different toroidal devices. The model C Stellarator at the Princeton University Plasma Physics Laboratory and a British Stellarator yielded about 10 Bohm times. Stellarators are heated by inducing a current to flow around the torus, and this current heats the plasma to modest temperatures—about 1 million degrees (or 100 eV). This method ceases to work after the plasma gets hotter. The detailed reasons for the still relatively poor containment in Stellarators are still not well understood, but their twisted magnetic field has only a weak shear and is not average minimum B.

Multipole devices, where the desired minimum average B property is easily achieved by the floating rings, yielded —both in the United States and in England—20 Bohm times.

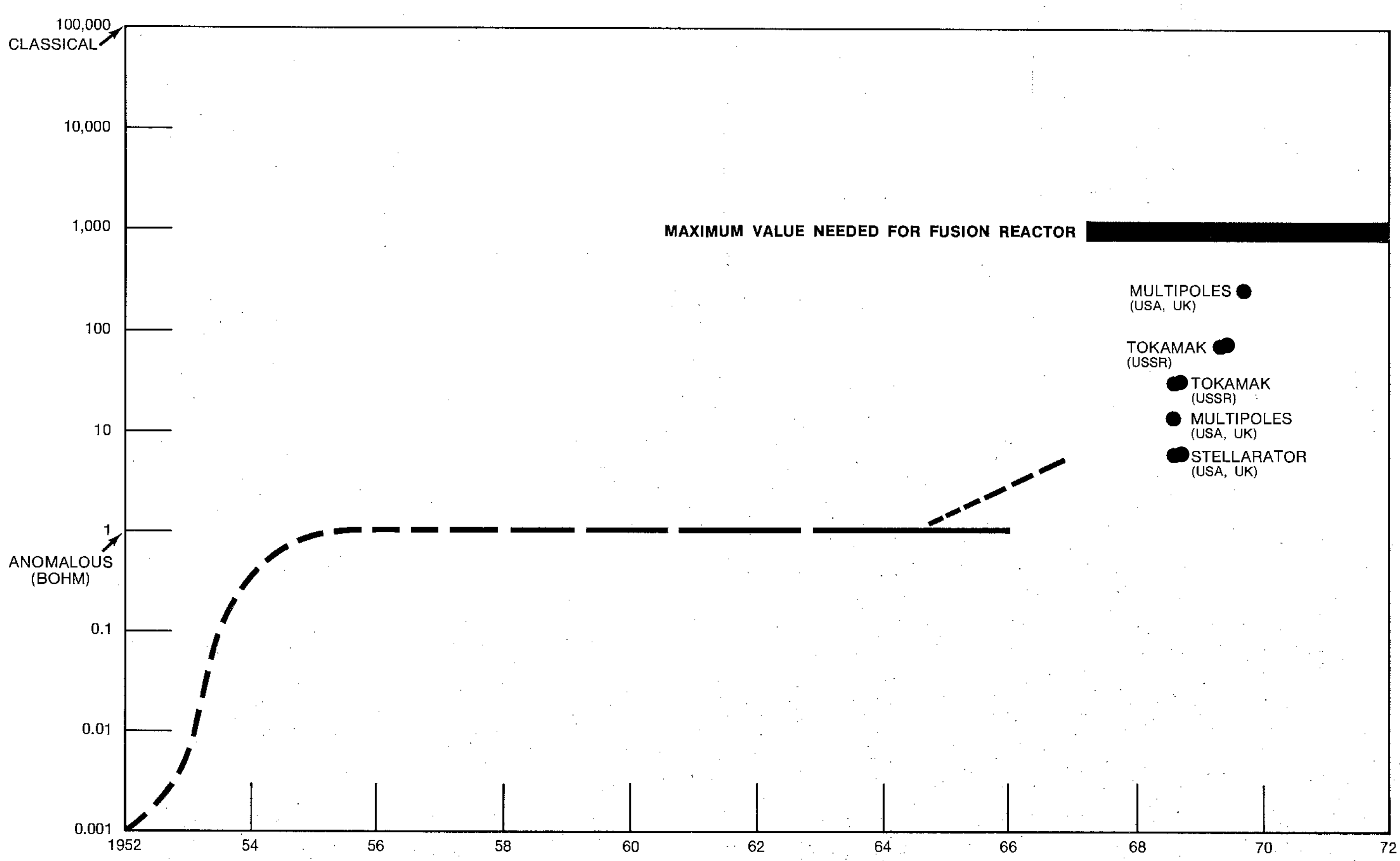
Still better performance was reported (30 Bohm times) from the Russion Tokomak. The Tokomak magnetic field is very similar to that of a Stellarator, except that the twist, or rational transform, is provided by the same current that is used to heat the plasma. In the Stellarator, the rotational transform is provided by currents flowing in coils external to the plasma. Since these currents could be controlled independently of the heating current and the two devices were otherwise quite similar, U.S. scientists felt that it was preferable to carry out their research on containment in Stellarators. They were more flexible. The reasons for the superior performance of the Tokomak are still not understood, and the 1968 results were put forth as tentative. The manner in which some of the experimental measurements were interpreted depends on a careful understanding of exactly what's going on, and the Russians weren't sure. To resolve the major questions in their interpretation of the Tokomak experiments, they needed to know whether there were an excessive number of high-energy electrons associated with the plasma current. They didn't think there were, but confirmation required sophisticated and difficult laser scattering techniques developed only in the past five years. Apparently the

Russians have not developed this measurement technique well enough, because they invited a team of British scientists who were skilled in these measurements and had the necessary giant-pulse laser to do the job. This unique and fruitful cooperative venture, which took about six months, confirmed the original optimistic interpretation—the energetic electrons were not found.

Since that time refinements have led to 100 Bohm times in the Tokomak, and the United States scientists have decided that, because of these striking results, the Tokomak configuration must now be taken very seriously—even though the reasons for its success are not yet understood, and despite the fact that the rotational transform can be changed only when changing the heating current.

Meantime, multipoles have gotten better. The Gulf General Atomic d.c. octopole has yielded containment times of nearly a quarter of a second or 300 Bohm times. During the high-density phases the losses appear to be mainly due to classical diffusion. I must hasten to add that this device is strictly a research device—it is not in the reactor sweepstakes. The plasma temperature is only 50,000 degrees (5 eV) rather than 5,000 eV, and it also has a low plasma density.

Nevertheless, it has provided a most significant advance, and the specter of Bohm is rapidly disappearing. Furthermore, it is now known that it is not even necessary to reach the classical diffusion limit to make a practical toroidal reactor—1,000 Bohm times will easily suffice. That prospect is now in sight.



Evidence that containment times which greatly exceed the Bohm containment time could be achieved in toroidal, or closed, systems was first presented in 1968. Although there have been significant improvements in performance since then, none of the three major testing devices (the Stellarator, Multipole, or Russian Tokomak) have achieved the maximum value needed for a fusion reactor, 1,000 Bohm times. But that prospect is now in sight.

Fusion power plants avoid the possibility of a potential nuclear accident since they are inherently safe against runaway reactions.

Progress on the basic plasma problems has been so substantial in the past few years that people have begun looking toward the other problems which must be faced in building an actual power-producing fusion reactor. Last September the first International Conference on Fusion Reactor Engineering Feasibility was held in England. To the plasma physicist, for whom the plasma problems have been (and still are) a truly uphill battle, the remaining problems appear more straightforward—and maybe they are.

The heat from fusion reactors will probably be used in a conventional thermal cycle—to make steam for turbines which drive electrical generators. This aspect of the fusion reactor design need not concern us too much, since it is common to most power plants and that technology is available. But there are technological problems which would be unique to a fusion reactor—particularly how to get the energy out of the fusion reactor. Since most of the energy of the fusion reaction is in the kinetic energy of the neutrons and the neutrons are not contained by the magnetic field which contains the ions, the plasma will have to be surrounded by a blanket which absorbs neutrons. Of course this blanket must not be in direct contact with the extremely hot plasma.

The neutron blanket serves several very important purposes. It must slow down, or moderate, the fast neutrons—turning their energy to heat which can be carried away to the turbines with a liquid coolant. The blanket also must breed the tritium needed for the plasma from some other plentiful material, until we learn to reach the more demanding conditions for a pure deuterium reactor. Tritium does not occur naturally, but is produced by neutron bombardment of lithium. We not only have the necessary neutrons, but lithium in chemical combination with other substances is also a suitable moderator to slow down the neutrons. Finally, the blanket must reduce the flux of the escaping neutrons to a safe level. On the inside of the blanket is the vacuum wall which faces the extremely hot plasma. It is subject to extremely high thermal stress and the extremely high neutron flux from the plasma. It must be cooled effectively with a coolant that doesn't absorb neutrons and is under high pressure. The neutron flux problem is similar to that encountered in breeder fission reactors, and the materials problems are severe. Since the coolant has to flow through regions of high magnetic field, it cannot be an electrical conductor—the power required to circulate it would be too great. The engineering problems associated with the vacuum wall are probably the most formidable of all and may be the ones which limit ultimate reactor performance.

Outside the blanket are the coils which produce the magnetic field—as high as 100,000 gauss may be required. Originally it was thought that as much as one-third of the fusion reactor's electrical power would be required to make this field by conventional current-carrying coils. The breakthrough in high-field superconducting magnets has completely revolutionized this picture. Superconducting coils are even now being used in several containment experiments.

This gives an idea of some of the great engineering challenges that lie ahead. In addition to technological problems of full-scale fusion reactors, consideration is also being given to environmental and sociological factors expected to affect the competitive position of such energy sources. In the case of fossil-fueled plants, the need to reduce objectionable combustion products to levels acceptable to society could be reflected in increased costs of power from such plants. This problem does not present itself in the case of fusion (or fission) power plants. Fusion power plants will not produce large quantities of radioactive wastes. While the internal structure of a fusion power reactor will become radioactive, the waste products from fusion reactions are nonradioactive. Hence, restrictions imposed by the environmental hazards of radioactive wastes will have little effect on fusion power costs.

Fusion power plants avoid the possibility of a potential nuclear accident since they are inherently safe against "runaway reactions." They contain only as much fuel as they can burn. Thus, they may not suffer from public safety restrictions that could cause increased capital and operating costs, insurance costs, and transmission costs due to limitations on plant locations.

Studies show that, with fusion reactors using D-T as a fuel, the thermal pollution to the environment could be reduced substantially below the values for existing power plants. (Comparable reductions are also projected for fission-reactor plants of the future.) The possibility of other fission fuel cycles and/or of direct conversion of fusion energy to chemical and electromagnetic energy could reduce the thermal pollution problem still further.