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Fusion Reactors as Future Energy Sources

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The need is now apparent for a global energy policy which is compatible with environmental and economic factors and has large fuel resources, the recovery and exploitation of which do not introduce disturbing factors into the world political situation. In this article we discuss fusion power in this context, including assessments of its potential and of the problems that remain to be solved before it is realized. We propose that fusion should be considered as the ultimate source of energy, and that other sources of energy, including conventional nuclear power, should be considered as interim sources.

The Place of Fusion in Planning for the World's Energy Needs

Our use of energy has always been and will continue to be based on our exploitation of a heritage from the past. Whether it is energy derived from fossil fuels, laid in store millions of years ago, or even energy from the sun, kindled billions of years ago, we must project our needs for energy into the future on the basis of this heritage. Until the last relatively few years our fossil fuel supply seemed essentially limitless, and our use of energy based on that supply did not appear to threaten the environment or the stability of our political institutions in any substantial way. This situation has now changed irrevocably, and a new set of circumstances must be dealt with. It is becoming apparent that our use of energy in the future must not perpetuate the patterns of the past. Except for a necessary period of transition, the central issues for the future have become: What new energy sources will be able to meet our needs, and how can these be selected so as to reverse the trend of destructive impact of energy technology on the environment and on our political security?

We have had these questions thrust on us because of excesses of the past. We now have the obligation and the opportunity to find answers that will increase the likelihood that man's lot in the future will be happier and more secure. We submit that fusion power represents a practical and attractive solution to this new energy problem. In fact, it would be not only a permanent solution, but one that is almost ideally compatible with the crucial issue of achieving a stable physical and political environment.

As exemplified by the sun and the stars, fusion is a primordial energy source derived from a fundamental circumstance in nature—that the transmutation through combinatory nuclear reactions of light elements into heavier ones results in the release of energy, manifested in the form of kinetic energy imparted to the transmuted nuclei.

The significance of learning how to generate useful energy from nuclear fusion reactions is that fusion represents a virtually inexhaustible energy source, for which the fuels are of negligible cost (compared to fossil fuels), are universally available, and are obtainable with small environmental impact. Furthermore, although fusion energy is a form of nuclear energy, it bears almost no similarity to "conventional" nuclear energy, that is, energy from the fissile elements uranium, plutonium, and thorium. Compared to fission and its hazards—radioactive fission products, the potentially serious consequences of accidents due to loss of control or loss of coolant, and the problem of the proliferation of nuclear fission weapons—fusion can be made much safer. While conventional nuclear power will no doubt have an important role in electric power generation, we propose that it be considered as an interim source, in the same sense that oil (and eventually coal) are necessarily interim sources.

What is the credibility of arguments made today that fusion should be declared to be man's ultimate energy source? Fusion power does not exist yet, so we cannot deal with absolutes in advancing such a proposition, however firmly we may be convinced of it. Yet to say that fusion power does not yet exist and is therefore not worthy of consideration for such a role is itself not a credible argument. The search for fusion power has its roots in more than 40 years of nuclear physics (the discovery of the fusion reactions preceded by many years the discovery of fission) and more than 100 years of electromagnetic and kinetic theory—the basic science inputs needed for the development of practical fusion reactors. Furthermore, 20 years of research specifically aimed at achieving controlled fusion, coupled with concomitant technological developments in that field, in "conventional" nuclear reactors, and in space science, has given fusion power research a

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basis which we think is both sufficiently broad and sufficiently advanced to safely assume that within a relatively few years all the elements necessary for the successful solution of the fusion power problem will be in hand—given a level of support commensurate with its importance. It is true that fusion power represents one of the most difficult, if not the most difficult, technical challenges of this century. It is also true that this challenge is being met today. Fusion power research has not reached its scientific objective, but major progress is being made—progress such that we, along with many other fusion researchers, believe that in less than a decade sufficient scientific knowledge to ensure the practical achievement of fusion power will have been established. We also believe that world energy policy should take this likely possibility into account and begin to consider its consequences. Fusion cannot solve the energy problems of this decade, or even the next, but its undoubted impact on the future should be anticipated now.

Physical Conditions Required for the Fusion Process

While fusion reactions are among the most elementary and best understood nuclear processes, their achievement on a practical scale for the controlled release of energy presents formidable scientific and technological problems. The difficulty originates in the physical conditions that must be achieved to ignite and maintain energetically self-sustaining fusion reactions. Fusion is very unlike the nuclear fission process, in which heavy nuclei are broken up into fission-fragment nuclei by the absorption of neutrons derived from other fission-produced neutrons, in the familiar chain reaction. The neutrons which propagate and perpetuate the chain reaction are particles of zero electrical charge, and thus can freely enter the uranium nuclei, uninfluenced by their high positive electrical charge. By contrast, fusion reactions require the fusing together of energy-rich light nuclei to form heavier, less energy-rich fusion products. Here the nuclear charge plays a crucial role: Unless the colliding nuclei are moving toward each other with sufficiently high kinetic energy, they cannot overcome their mutual electrostatic repulsion in order to come close enough to fuse.

The discovery of nuclear fusion, in the early 1930's, followed the development of particle accelerators. These are devices in which beams of electrically accelerated light nuclei can be made to bombard solid or gaseous targets containing other fusible nuclei, so that nuclear fusion reactions take place. That this simple and straightforward technique is nevertheless not an answer to achieving power from nuclear fusion is an example of the subtlety and difficulty of the fusion power problem. To accelerate nuclei to fusion energies in such an accelerator requires an input of electrical energy. But when a gaseous or solid target is bombarded with accelerated nuclei only a tiny fraction will actually react. Most of the accelerated nuclei will miss the target nuclei and dissipate their energy uselessly (as heat) within the target. The power produced is thus minuscule compared to the power required. Although the use of high-current beams of energetic particles is important in fusion power research today, these beams are used in a very different way from that described above.

The failure of the simple beam-on-target approach for the generation of fusion power illustrates the two key scientific problems that must be solved to achieve fusion power. These are heating and containment. Fusion fuel must be "heated" to a sufficiently high kinetic temperature that the fuel nuclei can collide with each other with sufficient vigor to react. Since such heating requires an investment of energy, the heated fuel must be confined, without escape to or contact with material surroundings, for a time sufficient to allow nuclear reaction energy to be released in excess of this energy investment. How long the confinement time must be will depend on the particle density of the heated fuel. At high fuel density the reactions will occur quickly, and thus the confinement times needed can be short; at lower fuel density the time must be correspondingly longer. This dependence is most succinctly expressed by the Lawson criterion, which states that for a net positive release of fusion energy the product of particle density (in particles per cubic centimeter) and confinement time (in seconds) must exceed 10^{14} ($n\tau > 10^{14}$ cm^{-3} sec).

The twin requirements—high kinetic temperature and adequate confinement— define and circumscribe all of fusion research, the story of which is to be told in terms of the various approaches to these problems and the scientific difficulties these approaches have encountered. As discussed below, major progress has been made on many fronts toward reaching the formidable physical conditions required for net fusion power release, but in no case has this end actually been reached. Beyond the achievement of these conditions will lie special problems—some of them very difficult—of engineering and materials. Although these problems will affect the timetable for the achievement of fusion power, they are not as fundamental as the scientific issues.

Fuels for Fusion

In principle, most of the nuclear isotopes near the lower end of the periodic table could combine in nuclear fusion reactions with a net release of energy. Indeed such reactions in stellar interiors are thought to be the dominant processes in the evolution of stars. On the earth, however, we cannot hope to reproduce such conditions, and the list of fusion fuel candidates is much shorter, being confined to special isotopes of the elements at the bottom of the periodic table, such as hydrogen and helium. However, there is a richness of possibilities for fuel combinations for fusion power that is unmatched by any other energy source.

The primary fuel for fusion is deuterium—heavy hydrogen. This isotope alone represents an almost inconceivably large fuel reserve for fusion power, is of near-zero net cost (less than 1 percent of the cost of coal), and is available universally. Deuterium, a stable isotope of hydrogen, has the second simplest nucleus in the periodic table, consisting of one proton and one neutron bound together. Used as a fusion fuel, deuterium can react with itself or with other light isotopes. The four most important reactions involving deuterium are listed below, written in the same way as the formula for a chemical combustion reaction (such as the combination of hydrogen and oxygen to form water, with the release of chemical energy). The species involved are: *p*, protons (the nuclei of ordinary hydrogen); D, deuterons; T, tritons (tritium is an unstable, heavier isotope of hydrogen); ^{3}He, nuclei of helium-3 (a stable, light isotope of helium); and *n*, neutrons. The first two reactions listed are alternate possibilities for the D-D reaction and occur with roughly equal probability. The energy release from the reactions is given in two ways: (i) millions of electron volts (Mev), the electrical equivalent energy imparted to the product nuclei, and (ii) kilowatt-hours per gram mass of the reacting nuclei (kwh/g). As a comparison, the chemical combustion reaction between hydrogen and oxygen which leads to water is also listed, with the same energy units.

$$D + D \rightarrow p + T + 3.25 \text{ Mev} \quad (22{,}000 \text{ kwh/g})$$

$$D + D \rightarrow n + {}^3He + 4.0 \text{ Mev} \quad (27{,}000 \text{ kwh/g})$$

$$D + T \rightarrow n + {}^4He + 17.6 \text{ Mev} \quad (94{,}000 \text{ kwh/g})$$

$$D + {}^3He \rightarrow p + {}^4He + 18.3 \text{ Mev} \quad (98{,}000 \text{ kwh/g})$$

$$[2H_2 + O_2 \rightarrow H_2O + H_2O + 0.000006 \text{ Mev} \quad (0.0044 \text{ kwh/g})]$$

These reactions, plus additional ones involving lithium and boron isotopes, represent the elements of the fuel cycles for future fusion reactors. The D-T reaction is the one on which most present-day studies of fusion reactor possibilities are based. The last deuterium reaction listed, D-^{3}He, is of particular interest, since its energy release is large and its reaction products are charged. In such a case there exists the possibility of a fusion reactor cycle involving direct conversion of fusion energy to electricity, potentially at very high efficiency.

Note that deuterium as a fuel has the unusual property that its "ashes" are themselves combustible (via the D-T and D-^{3}He reactions), so that a fusion reactor fuel cycle can be visualized in which deuterium is burned to completion; the end products are ordinary hydrogen and helium plus the release of 7 Mev per deuteron burned, that is, about 100,000 kwh of energy per gram of deuterium fuel, or about four times the energy per gram released in the fission of uranium.

While there is every reason to believe that such D-D-T-^{3}He fuel cycles will in time be employed, the first achievement of fusion power will probably depend on the use of the D-T cycle. This is because the D-T reaction has the lowest "ignition temperature" (about 50 million degrees kinetic) of all the reactions and therefore is the least demanding in terms of heating and confinement. But since tritium exists only in trace quantities in nature (it is radioactive, with a half-life of 12 years), it must be "bred." Although there are several ways in which such breeding might be accomplished, the only one that has received serious study involves capture of the neutron reaction product of the D-T reaction in a "blanket" containing lithium surrounding the chamber. This capture process leads to tritium generation, with a potentially generous breeding ratio (1.1 to 2.0). Here the breeding ratio is the number of tritium nuclei produced per tritium nucleus consumed.

It is important to put the questions of fuel cost and availability in perspective. At levels of 100,000 kwh/g, the amount of primary fuel needed for future world electrical power generation is exceedingly small. As a present-day example, the U.S. electrical power demand averages about 350 million kilowatts. Including conversion efficiencies, this power could be supplied by an input of about 10 kilograms of deuterium per hour (the corresponding figure for coal is about 180,000 metric tons per hour). A deuterium input of 10 kg/hour could be produced by a small deuterium separation plant, the input to which was simply the amount of ordinary water that would flow through a pipe 5 cm in diameter at normal pressures. The need for lithium in the D-T breeding cycle would be correspondingly minuscule. Compared to the mining of coal, the drilling and recovery of oil, and even the mining of uranium, fusion's impact on the environment with respect to obtaining its fuels would be negligible. Correspondingly, fuel costs for fusion would also be so small as to be essentially ignorable. Primary fusion fuels are so abundant as to be virtually inexhaustible, even on time scales measured in millions of years. The solution of the fusion power problem would indeed represent a permanent solution to man's energy needs.

To put fusion in perspective with respect to other sources of energy we see that not only are fusion fuels virtually inexhaustible, but the spectrum of future possibilities and options is itself very broad. Whereas the fission process inevitably leads to radioactive fission products of high biological hazard potential and long life, the ashes of fusion are inert. Furthermore, with the unfolding of fusion technology in the future there will undoubtedly be opportunities to choose among different fusion cycles, including ones involving only charged reaction products. The adoption of such fuel cycles not only would eliminate or greatly reduce neutron activation, but also would permit direct conversion of fusion energy to electricity, potentially at very high efficiency.

Approaches to Fusion Power

Fusion power depends on the achievement of the physical conditions required for fusion reactions—high kinetic temperature to initiate the reaction, and sufficiently long confinement time to yield a net power output. Impossible though it seemed at first to achieve such conditions in any practical way, there now exist at least two viable approaches to this problem. These approaches are sufficiently well rooted in basic physics that it seems likely that both will succeed scientifically. Given scientific feasibility, economic factors will then dictate which approach will be preferred for practical power generation.

Confinement is the central scientific issue. At fusion plasma temperatures matter can exist only in the gaseous state known as plasma—a charged-particle gas composed of an equal mixture of positively charged nuclei and free electrons (stripped from the nuclei). To avoid quenching its high temperature, this gas cannot be allowed to contact any matter at ordinary temperatures. Thus, it must be contained in a hermetically sealed vacuum chamber (to keep out atmospheric air), and the fusible nuclei of the plasma must not be allowed to touch the chamber walls before they have had sufficient opportunity to collide and fuse. However, at fusion temperature the nuclei are moving so rapidly that they would fly to the walls of any chamber of practical size in less than a millionth of a second.

One of two basic choices must be made at the outset in any serious attempt to achieve fusion power. These are either (i) to introduce nonmaterial means to confine the fusion fuel gas, free from contact with the chamber walls, long enough for a net release of fusion power, or (ii) to carry out the processes of heating the fusion fuel so rapidly that the fuel nuclei will react with each other before they can escape to the walls—that is, to initiate a microexplosion. The latter approach is often called inertial confinement. These two approaches differ from each other profoundly and define two completely different operating regimes for a fusion reactor.

The first approach, and the one on which most of fusion research has been concentrated, is best exemplified by the idea of magnetic confinement. In magnetic confinement the charged particles of the plasma are constrained to remain within a defined region by the action of intense and specially shaped magnetic fields. In a sense the magnetic field acts as a nonmaterial furnace liner that insulates the hot plasma from the material chamber walls. In the second approach, of more recent origin, an attempt is made to take advantage of new technology—in particular the laser, or intense focused beams of ultrahigh-energy electrons—to heat a small frozen pellet of fusion fuel to its ignition point.

In magnetic confinement the fuel plasma pressures are limited by attainable values of magnetic field. Since at fusion reaction temperatures (100 million degrees kinetic or higher) the pressure exerted by a gas at atmospheric density could be enormous—hundreds of thousands of atmospheres—the fuel density in a fusion reactor utilizing magnetic confinement must be kept well below atmospheric density, in order to keep the pressure exerted on the confining magnetic field (and ultimately transmitted to the surrounding material structure) within practical limits. Typically, these densities range from about 1/100,000 of atmospheric density (or 3×10^{14} particles per cubic centimeter) to as high as 1/1000 of atmospheric density. The corresponding Lawson-criterion confinement times range from about 1 second to a few hundredths of a second. Even so, the fusion power released is large. At the lower density it is some 100,000 to 300,000 kw per cubic meter of reacting plasma. Varying as the square of the fuel density, the power density rises to values in excess of a thousand million kilowatts per cubic meter at the higher densities. The lower range of the two power releases can be handled in a steady manner, the power being generated at levels comparable to those in the furnace of an ordinary steam power plant. The higher values of power density could not be handled in steady state, so that an intermittent or "pulsed" mode, resembling an internal combustion engine cycle, must be contemplated.

Between the rather narrow range of fuel densities and long confinement times of the magnetic confinement method and the high densities (many thousands of times greater) of the microexplosion method lies a gap where a workable approach seems much more difficult to find. At pellet densities (solid densities or greater) the time scales for energy release are measured in thousandths of millionths of a second or less, and both the required rates of heating of the pellets and their instantaneous rates of power release are astronomical.

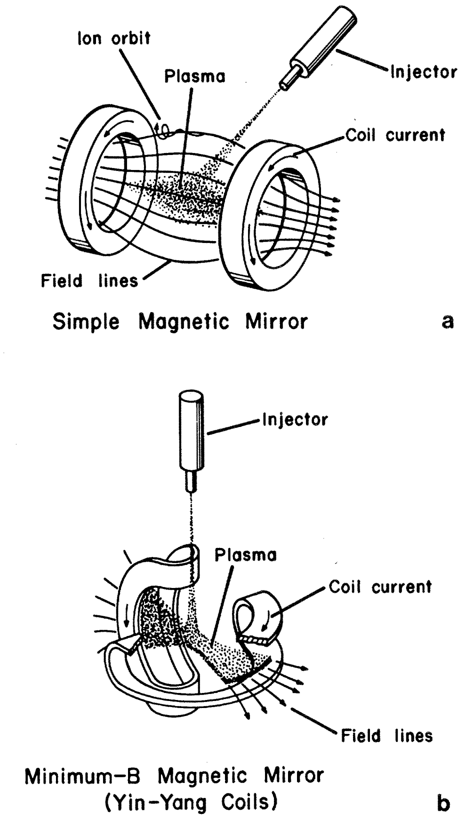


Fig. 1. Principles of a magnetic mirror experiment.

The radically different physical regimes envisaged for the two basic approaches to fusion—magnetic confinement of a low-density fuel gas or beam-pellet heating at solid densities—imply completely different sets of scientific and technological problems that must be solved in following the two lines of attack. These problems can be identified and stated succinctly. For magnetic confinement they are finding the combinations of magnetic field configuration, intensity, and size and the plasma conditions that result in stable confinement of the reacting plasma for a long enough time to yield a net energy release. For pellet-heating fusion the problems are primarily those of creating sufficiently intense and well-focused laser or electron beams that can heat and compress a pellet in such a way and in a short enough time that a microexplosion yielding net energy (more than used in the heating) is released.

Difficult though the problem for fusion may appear, many if not most of those listed above, particularly for the magnetic confinement approach, have now been solved. Critical scientific issues do remain, but they are at the quantitative level, not at the level of questioning the basic workability of the idea of magnetic confinement.

The basic idea of magnetic confinement is that a charged particle, when it moves within an intense magnetic field, is constrained to move in a helical orbit that lies along the direction of the lines of force of that field. The simplest embodiment of magnetic confinement would therefore have a chamber in the form of a long, straight tube around which would be wound a magnetic coil. The plasma particles in the tube would then be constrained to move, like beads on a string, in helical orbits lying inside and parallel to the tube walls. They would in this way be kept isolated from contact with the walls of the tube, as required for fusion. But such a simple system fails for a fundamental reason: This shape of field provides no confinement in directions parallel to the tube axis. Except at very high densities or with very long tubes (kilometers in length), the plasma would spill out the ends of the tube too rapidly to permit a net fusion energy release.

The response to this "problem of the ends" in fusion research has been to divide the research into two broad categories—"open-ended" confinement systems and "closed" or toroidal systems. Open systems rely on the so-called magnetic mirror effect, or the repelling effect of extra-strong magnetic field regions (the mirrors) on helically moving particles. By locating magnetic mirrors at both ends of a confinement region, charged particles can be trapped between these mirror regions and reflected back and forth for a long enough time to permit fusion reactions to occur, with a theoretically predicted net positive power balance.

Closed systems take the other topologically possible approach—to bend the open tube into a circular shape, forming a torus or doughnut-shaped figure within which the field lines close on themselves. In this geometry the only path of escape for particles trapped on the field lines is to cross the field lines. In theory this is a very slow process, the time for which is predicted to vary as the square of the tube diameter. Thus closed systems, if large enough in size, should be assured of being able to achieve even the longest of the required confinement times.

The central issue for magnetic confinement fusion research has been to adequately realize the theoretical ideals just described. Until relatively recently neither of the approaches, the mirror or the torus, yielded plasma confine-

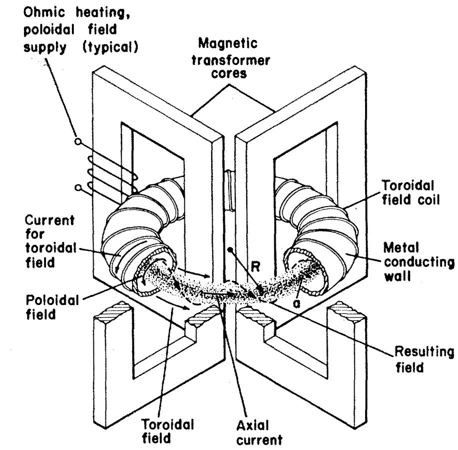


Fig. 2. Schematic drawing of a Tokamak device.

ment that did not fall far short of these ideals. The basic problem in both cases was the existence of plasma instabilities, that is, unstable gross motions or fine-scale turbulences in magnetically confined plasmas. These lead either to rapid expulsion from the field or to somewhat slower but still unacceptable rapid diffusion out of the field.

In the more than 20 years during which magnetic confinement research has been pursued, plasma instabilities have been studied, analyzed, and brought close to the point of complete control. This has been accomplished mainly through increasingly sophisticated understanding of the magnetic field shapes that are best suited for stable plasma confinement. Perhaps one of the best examples of this is the "magnetic well" idea now used in mirror systems. The first mirror systems used a simple "barrel-shaped" field (Fig. 1a) in which the mirrors were at the ends of a tube of circular cross section. This field shape has a fatal flaw: by moving sideways the plasma can move into a region of weaker field; that is, it flows downhill, magnetically speaking. This was in fact observed on a time scale of millionths of a second. However, by reshaping the field in the manner shown in Fig. 1b, the plasma is placed in effect at the bottom of a magnetic well. Gross motion in any direction is uphill, toward stronger fields, and thus cannot occur spontaneously. In such a field the only possible remaining unstable effects are residual high-frequency oscillations that might be stimulated by the detailed nature of the state of the confined plasma. These microinstabilities have by now been largely controlled in mirror systems, although the task is not yet complete.

Toroidal systems cannot use the magnetic well idea in unalloyed form, but field shapes have been devised which approach this desired property and have other stabilizing features as well. One of the most favored of these is the "Tokamak" idea, pioneered by Soviet scientists. In a Tokamak the simple toroidal field (see Fig. 2) is augmented by inducing a strong electrical current in the plasma itself. The combined fields, plus additional correction fields, produce a confinement structure that is the best yet in toroidal systems. As a result, the confinement comes far closer to the theoretical ideal than has heretofore been possible.

Means of heating plasma to fusion temperature are obviously necessary elements in the search for fusion by magnetic confinement. Here also major progress has been made: the problem has been essentially solved at the scientific level, and it is expected that these solutions can be carried to the reactor level. There are three main techniques by which plasmas can be heated at magnetic confinement densities. (i) In ohmic heating a plasma is heated by passing an electric current through it. This technique is used in present Tokamak experiments. (ii) In magnetic compression the plasma is either heated "adiabatically" (slowly) by compressing it through an increase in the strength of the confining field, or it is "shock heated" by a rapidly rising magnetic field, or a combination of these techniques may be used. Magnetic compression is used mainly in the mirror and theta-pinch approaches (Fig. 3), although it has recently also been applied to Tokamaks. (iii) In neutral beam heating intense beams of energetic neutral atoms are focused and directed at the plasma from neutral beam sources located outside the confinement region (Fig. 1). Being neutral, these beams freely cross the confining fields. Once inside the plasma they are ionized (broken up into electrons and positive nuclei), in this way depositing both new particles and heat in the form of the kinetic energy carried by these particles. Neutral beam injection is a central feature in open-ended systems, which must rely on a continuous input of new energizing particles to maintain the plasma temperature and density in competition with the particle leakage through the mirrors. The technique is also being applied to Tokamaks, where it provides an important means for augmenting ohmic heating. Other methods, less widely used, include heating by radio-frequency and microwave power and laser heating of dense magnetically confined plasma in long linear geometries.

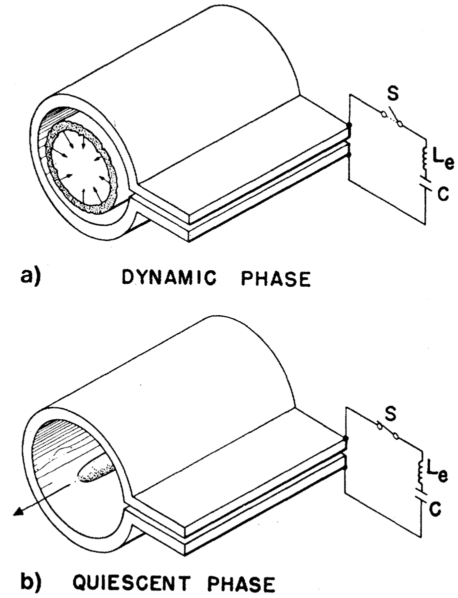


Fig. 3. Basic principles of the theta-pinch magnetic confinement system.

The remaining scientific and technical issues for magnetic confinement research are generating the magnetic field itself and utilizing it efficiently in terms of sustainable plasma pressure. Generally speaking, high magnetic fields are required for practical fusion. With the advent of the new superconducting materials (special alloys that lose all electrical resistance when refrigerated to liquid helium temperatures) it is now possible to generate extremely high magnetic fields—high enough to satisfy the requirements of all but the most demanding of the various fusion approaches—without the need for power to sustain resistance losses. As a consequence of these developments fusion reactor ideas involving such coils can be studied and progress toward fusion power will be hastened.

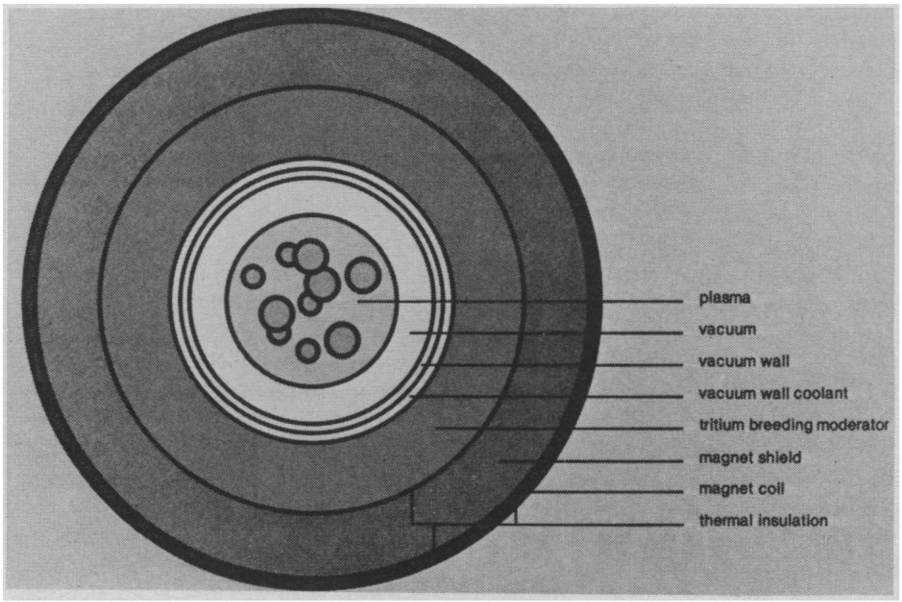
An important scientific issue (and one of eventual economic importance) related to magnetic fields is the question of plasma "beta." If a magnetic field is thought of as a kind of pressure vessel in which the plasma is confined, then the issue is how much pressure it can hold. The controlling limitation is the strength of the field itself. At superconductor fields (approximately 100 kilogauss) this pressure is high—400 atmospheres or more. The quantity beta measures how closely the plasma pressure can approach the limiting magnetic value, beta = 1. If beta is too small, the reaction power density, varying as beta squared, would be too small to pay back the capital investment in the magnet coil. Fortunately, in some of the approaches (theta-pinch and mirror) high beta values (0.5 to nearly 1.0) have been demonstrated. The beta issue has still not been resolved for the Tokamak, which so far has only been operated at low beta values.

In summary, far more of the critical issues of stability, heating, and plasma pressure have been solved for the magnetic confinement approach to fusion than remain to be solved. At the same time, critical technological needs related to vacuum, plasma heating, and magnetic field technology have been or are being met. While serious scientific issues remain, it is generally believed in the fusion community that they will be resolved within 10 years.

Fusion Reactor Systems

In the preceding section we discussed the basic principles of the three main magnetic confinement systems: (i) the Tokamak, low-beta toroidal system; (ii) the theta-pinch, high-beta toroidal system; and (iii) the open-ended, mirror system. For the past decade or so the principles embodied in these systems have been used to provide conceptual designs of fusion reactors, assuming that sufficient plasma confinement can be achieved. Ideal confinement is that which is limited only by the inevitable collisions of the plasma particles with each other. The conceptual reactor designs have allowed examination of the engineering environment necessary to heat the plasma and to extract its thermonuclear power and convert it to useful electrical output. Particular aspects of the power plant design which have been investigated are fuel processing, regeneration, and injection; cooling and heat transfer; the effects of neutrons on the reactor structure; superconducting magnets; and power conversion.

In this section we describe the main features of power plants based on the three confinement systems. In all cases we consider the D-T fuel cycle with an associated blanket containing some form of lithium. A generalized illustration of the cross section of a fusion reactor is shown in Fig. 4. The plasma, at a temperature of 100,000,000°K (10 kev) to 6,000,000,000°K (600 kev), depending on the confinement concept, is surrounded by a vacuum and a magnetic field which confines it and holds it away from the first wall. This wall is surrounded by the coolant (usually liquid lithium), which is usually part of the tritium breeding moderator. Besides cooling, this moderating blanket catches the 14-Mev neutrons from the fusion reactions in the plasma and converts their kinetic energy to heat,



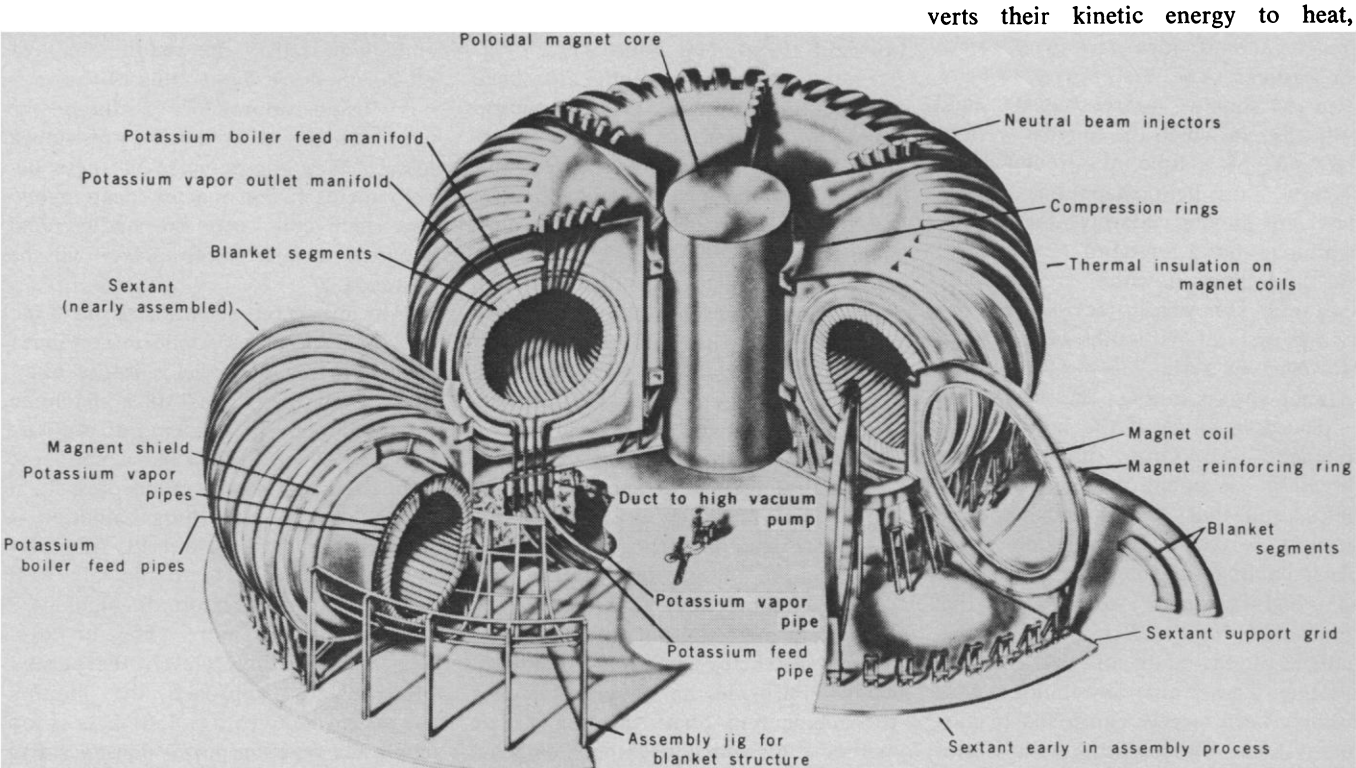


Fig. 4 (top). Generalized cross section of the core of a fusion reactor. Fig. 5 (bottom). General view of the ORNL conceptual Tokamak reactor.

which is used to power the energy conversion equipment (turbogenerators) to produce electricity. (There are other, more direct sources of electrical output in the theta-pinch and mirror systems.) In addition, the moderator breeds tritium for refueling the plasma both through capture of slow neutrons in the lithium and through disintegration of the lithium by fast neutrons. The moderator also serves to shield the magnet coil from the neutrons.

Tokamak reactors. The essential features of a Tokamak are shown in Fig. 2. The plasma, of major radius R and minor radius a, forms the secondary of a set of transformer cores whose primaries drive a pulse of current in the axial (or toroidal) direction in the plasma. This current serves two purposes: it heats the plasma, and it provides a "poloidal" field which encircles the plasma ring and contains the plasma pressure. It is generally recognized that the current heating can produce plasma temperatures no greater than about 4 kev, whereas temperatures greater than about 10 kev are required for reactor operation. Thus, supplemental heating is required. A method generally accepted is to inject beams of energetic neutral deuterium and tritium atoms into the plasma. To keep the plasma stable, an additional toroidal field in parallel to the plasma ring is added so that the resulting field lines are helical, surrounding the plasma as shown in Fig. 2.

The conceptual Tokamak reactor design at Oak Ridge National Laboratory (ORNL) (*1*) is illustrated in Fig. 5. It uses an iron magnet core for the poloidal-field flux. A gas of deuterium and tritium is introduced, ohmically heated, and further heated by neutral beam injection, as indicated in Fig. 5. As burnup proceeds, ^{4}He "ash" collects in the plasma during the burning pulse. The system is then purged with fresh gas and pulsed again about every 15 minutes.

The plasma has a major radius $R = 10.5$ meters and a minor radius $a = 2.8$ m. The toroidal magnetic field in the plasma is 60 kilogauss, and its toroidal current is 20 megamperes. The first wall is cooled by liquid lithium flowing in the blanket segments, which run parallel to the toroidal magnetic field and have a radial thickness of 1 m. The lithium emerging from the blanket at 1052°C exchanges heat with potassium to provide potassium vapor at 982°C, which drives the topping-cycle turbine of the thermal conversion system. Of the 1000 megawatts

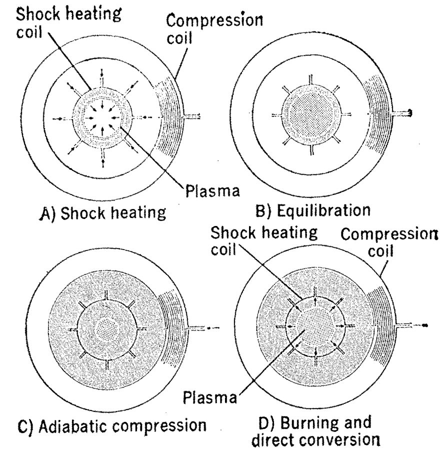


Fig. 6. Plasma heating and burning in a staged theta-pinch reactor. The shaded areas represent magnetic field perpendicular to the plane of the figure.

(thermal) from the blanket, 564 Mw of electrical power is produced at 56.4 percent efficiency, and the useful electrical power output is 518 Mw.

Other conceptual Tokamak reactors have been designed in the United States by groups at the Princeton Plasma Physics Laboratory (PPPL) (*2*) and the University of Wisconsin (*3*). In these designs, in order to maintain a low level of ^{4}He in the plasma and a constant plasma density, the plasma must be continually removed at its outer periphery as the burning proceeds. This is accomplished by means of "diverters." The magnetic lines have one (*2*) or two (*3*) cusps near the edge of the vacuum chamber, so that plasma diffusing across magnetic field lines encounters the cusps and is led out of the vacuum chamber to regions where spent plasma is collected. In all designs the reactor is enclosed in an evacuated vessel to prevent the escape of tritium to the atmosphere.

The theta-pinch reactor. The basic principles of the theta pinch are illustrated in Fig. 3. Ionized gas is placed inside a single-turn coil to which current is suddenly fed from a capacitor bank. This rapidly fills the coil with magnetic field parallel to its axis. During the dynamic (shock-heating) phase the surface of the plasma is driven rapidly inward by the axial field, heating the ions and electrons. Later there is a quiescent (adiabatic compression) phase after the magnetic field is built up to a steady value in the coil. The plasma is then held in a cigar shape by the steady magnetic field, gradually being lost out its ends along magnetic lines, as indicated by the arrow in Fig. 3b. Unlike the Tokamak, the theta pinch excludes all but a small fraction of the magnetic field from the plasma (the high-beta property).

In present experiments a single-turn coil furnishes both shock-heating and adiabatic compression fields. However, a theta-pinch reactor will be staged, with separate coils and energy sources for the shock heating and adiabatic compression. The shock-heating coil (first wall) is thin and cooled with a liquid metal. It is connected to a low-energy, high-voltage circuit. The magnetic compression field is furnished by a low-voltage, multi-turn coil which produces a slowly rising magnetic field (following the shock-heating field) appropriate to further adiabatic compression heating and confinement of the shock-heated plasma. The compression coil is of sufficient size to accommodate an inner neutron-moderating blanket.

Figure 6 shows the essential elements of a staged theta-pinch reactor. The shock-heating magnetic field drives the implosion of a fully ionized plasma (Fig. 6A). After the ions' energy associated with the radially directed motion of the plasma implosion has been randomized (thermalized), the plasma assumes a temperature characteristic of equilibration of ions and electrons (Fig. 6B). The adiabatic compression field is then applied by energizing the compression coil (Fig. 6C); the arrow in Fig. 6C indicates the direction of magnetic energy flow into the system. The plasma is compressed to a smaller radius, and its temperature is raised to 10 to 20 kev. As the D-T plasma burns, it produces 3.5-Mev alpha particles (helium nuclei) which further heat the D and T ions and the electrons. The plasma expands against the confining magnetic field, doing work which is about 8 percent of the thermonuclear energy produced by D-T fusion reactions. This work produces an electromotive force, which forces magnetic energy out of the compression coil (arrow in Fig. 6D) and back into the compression magnetic energy store. The high-beta heating by alpha particles and the resulting direct-conversion work are important factors in the overall reactor power balance.

The theta-pinch reactor is designed for repetitive pulsed operation. At the end of the burn approximately 5 percent of the plasma is helium ions. The magnetic field is then relaxed to some lower value, which allows expansion of the plasma column radially outward to the vicinity of the wall and extinguishes the burn. Neutral gas flows be-

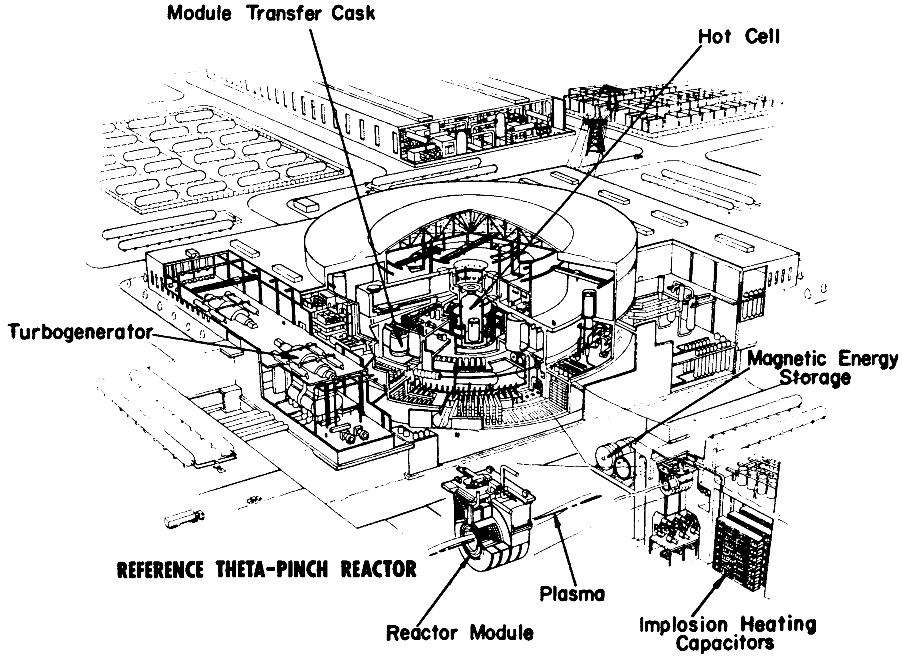


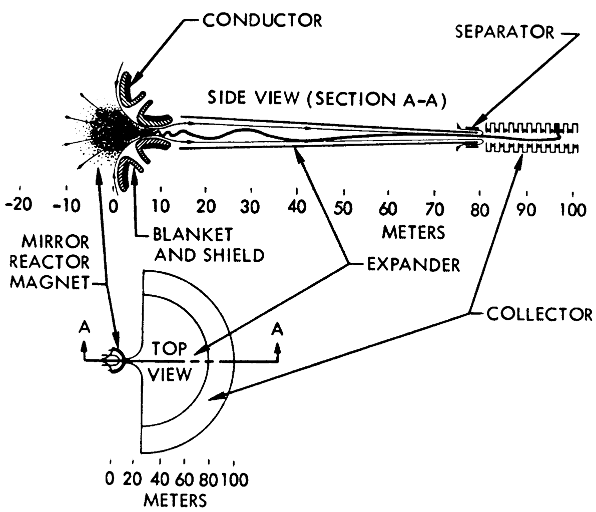
Fig. 7. General view of a 2000-Mw(e) theta-pinch reactor and power plant.

To sustain the plasma in a mirror device against end loss it must be injected with a neutral beam as shown in Fig. 1. The plasma is "opaque" to this beam and absorbs its energy, thereby becoming an energy amplifier because of the total thermonuclear power which it produces. The amplification factor Q is an important quantity and is defined as the ratio of thermonuclear power to the power which must be injected to sustain the plasma. In order to provide good plant efficiency at the low Q values which are allowed by collisional end losses, it is necessary to use the energy of plasma ions which escape out the mirrors to supply the injection power. The method (called direct conversion) by which end-loss plasma energy from a magnetic mirror is converted to useful electric power is illustrated in Fig. 8. This shows a vertical section of a magnetic-well mirror system (see below) like that in Fig. 1b and a typical escaping ion orbit. First the escaping plasma (and the ion orbits) are expanded in the horizontal fan-shaped magnetic field, which extends about 100 m from the mirror. In this process the plasma density is reduced, and the ion motion is converted into motion parallel to the field lines. After the expansion the plasma density is sufficiently low that the electrons can be diverted across the lines, and the ions continue horizontally to a collector. Here, depending on their energy, the ions are decelerated in a periodic set of charge-collecting electrodes, which collect them as they are brought to rest by retarding potentials. There results a distribution of high voltages on the collector electrodes, which store the energy of the slowed-down ions as

tween the wall and the plasma boundary, removing heat from the column and neutralizing the plasma. During the remainder of the cycle "off-time" of 3 to 10 seconds, the plasma and hot gas are flushed out of the system and replaced by fresh plasma with negligible helium content. The system is then ready for a new heating and burn pulse.

An overall view of the Los Alamos–Argonne reference theta-pinch reactor (RTPR) (*4*) is shown in Fig. 7. It has a maximum toroidal field of 110 kilogauss. The plasma chamber has a diameter of 1 m, and the overall diameter is 112 m. The compression and shock-heating coils, as well as the lithium blanket, make up reactor modules 2 m long which can be removed to the central hot cell for repair or replacement. The reactor modules are in an evacuated underground trench, which prevents leakage of tritium to the atmosphere. With a 10-second power cycle the reactor produces 3700 Mw of thermal power and 1830 Mw of electrical output. The direct-conversion power is 350 Mw electrical.

Magnetic mirror reactors. In a simple magnetic mirror (Fig. 1a), as in other containment devices, the plasma is confined transverse to the axis by its inability to diffuse at an appreciable rate across magnetic lines. However, containment along the axis results from the "mirroring" of individual ion orbits by the converging lines at the two ends, as discussed above.



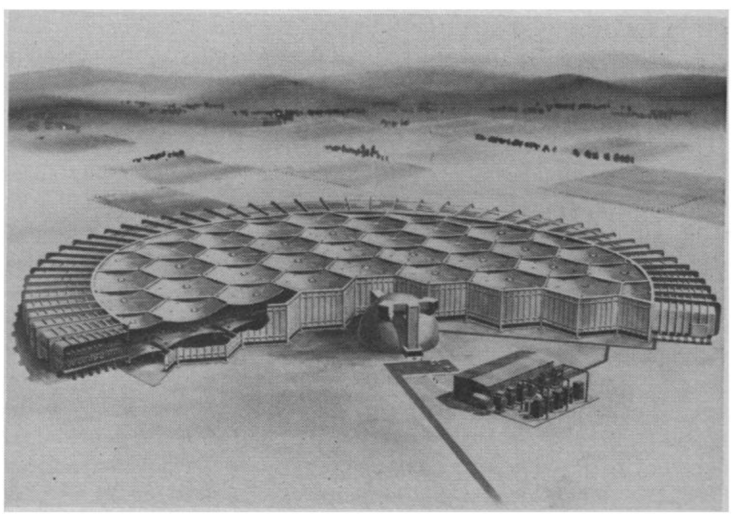


Fig. 8 (left). Method of direct conversion in a magnetic mirror reactor. Fig. 9 (right). An overall view of a magnetic mirror reactor and power plant.

electrostatic charge. The voltages of these charges are then brought to a common d-c potential, which represents the output of the direct-conversion system.

Plasma in the simple mirror geometry of Fig. 1a is unstable to gross motions across the magnetic lines, as discussed above. However, a system whose magnetic lines are everywhere convex toward the plasma (Fig. 1b) is stable. Such a system is a magnetic well in that it has minimum field strength (minimum B) on its axis at the center of the system, and B increases outward in all directions. The magnetic-well system of Fig. 1b has fan-shaped ends, one vertical and one horizontal, and the field is supplied by "yin-yang" coils, which are the most economical of the various possible coil systems for producing magnetic-well mirror fields. This coil system has been chosen by the Lawrence Livermore Laboratory (LLL) groups as the basis for their reactor design.

An overall view of the LLL conceptual mirror reactor is shown in Fig. 9 (*5*). The spherical dome covers a trap for neutrons emerging vertically from one mirror of the yin-yang coils, which are in an evacuated spherical cavity underground. The coils confine a roughly spherical plasma with a radius of 3.5 m whose vertically escaping ions are bent horizontally by a magnetic field to enter the direct-conversion structure, which is shown as the 240° "fan." In addition to the direct conversion there is a thermal conversion plant to provide electrical power from a neutron blanket which protects the superconducting yin-yang coils and breeds tritium. The plant shown has a fusion power of 520 Mw (thermal) and a net electrical output of 170 Mw. The collector structure of the direct converter is shown at the far right of the diagram. It produces 430 Mw of d-c electrical power; 580 Mw (electric) is recirculated.

Environmental Characteristics of Fusion Reactors

Radioactive effluents. The only radioactive substance that could be released during routine operation of a fusion power plant is tritium. An essential feature of all the conceptual fusion plant designs is to minimize the possibility of tritium leakage by making the tritium inventory as small as possible, enclosing the hot metal structures through which tritium can diffuse by vacuum and helium barriers, and finally surrounding tritium zones by cold metal walls. Attention is given to minimizing diffusion in the hot metal structure by the incorporation of diffusion barriers, such as copper or ceramic coatings. In a fairly straightforward design embodying these safeguards the amounts of tritium released to the condenser coolant system and ultimately discharged to the environment are orders of magnitude below permissible levels.

An important aspect of the tritium fusion fuel is that it has to be transported only once, for reactor start-up. Subsequently, it is handled locally in a closed cycle at the power plant. After start-up only the nonradioactive elements, deuterium and lithium, are required to fuel the plant.

Long-lived radioactive wastes. A D-T fusion reactor will produce nonvolatile radioactivity, primarily from the refractory-metal structural material of the blanket, which will become activated by neutrons. In the case of a fission plant the radioactive waste is almost entirely associated with fission products and not with the structure. In proceeding with a comparison of radioactivity between fusion and fission plants the following factors should be taken into account:

1) The total number of curies (c) of radioactivity generated for each watt of thermal power generated (c/watt).

2) The generated radioactivity expressed in terms of the gross biological hazard potential (BHP) (km^3/watt). This is the curies per watt divided by the maximum permissible concentration (MPC) of each radioactive nuclide expressed in curies per cubic kilometer. Here we use the MPC for air concentrations. The BHP measures the dilution in air necessary to reduce radioactivity to permissible levels.

Figure 10 presents a comparison of total activities of conceptual Tokamak (*3, 6–8*) and theta-pinch (RTPR) (*4, 9*) reactors with the activity of the fission products for a fission reactor (*10*). In the case of the fusion reactors the following alternative structural alloys are assumed: (i) niobium (99 percent Nb, 1 percent Zr) and (ii) vanadium (80 percent V, 20 percent Ti). The essential difference between the Tokamak and RTPR curves is that refractory metal is assumed to constitute approximately 1 percent of the structural material in the former case and 6 percent of the neutron blanket in the latter. The choice of a vanadium structure reduces the curies per watt by an order of magnitude, showing that the amount of induced radioactivity is to a considerable degree at the disposal of the plant designer in the fusion case, while it is an inherent property of the fuel in the fission case.

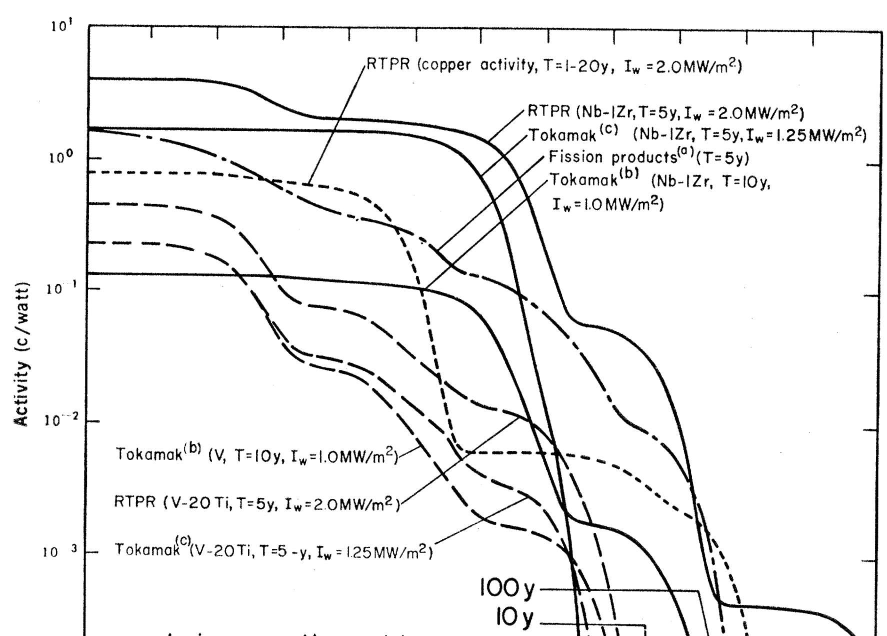


Fig. 10. Total induced activity for fusion and fission reactor plants as functions of time after shutdown. Abbreviations: T, operating time; I_w, 14-Mev neutron wall loading. References: curve a (*10*), curves b (*8*), curves c (*3*).

Figure 11 compares the relative biological hazard potentials of the radioactivities from fusion and fission reactors. For times after shutdown of less than 1 year the niobium fusion reactors have radioactive BHP's roughly equal to that of the fission products, but much less than that of the plutonium fuel of a reference liquid metal fast breeder reactor (LMFBR) (*11*). For the vanadium fusion reactors the BHP's are one to two orders of magnitude less than for the fission case. At times greater than 1 year (times of waste storage) the fusion BHP is one to two orders of magnitude less than that of the fission products in the niobium case, and is negligible in the vanadium case. Figure 11 shows that the plutonium BHP of an LMFBR exceeds that of the fission products by roughly an order of magnitude and that of the fusion structural activity by two or more orders of magnitude.

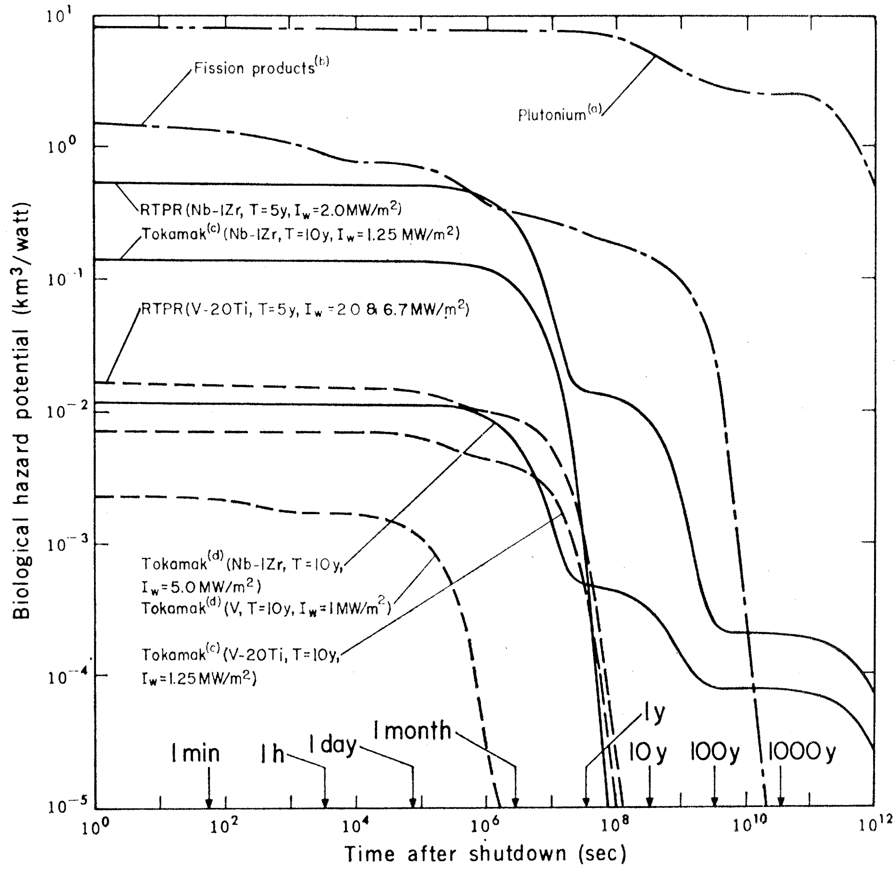


Fig. 11. Relative biological hazard potentials of induced activities in fusion and fission reactor plants after shutdown. The plutonium fuel is included in the fission case. Abbreviations are as given for Fig. 10. References: curve a (*11*), curve b (*10*), curve c (*3*), curve d (*8*).

Afterheat. In the event of a loss of cooling, the nuclear decay heat will result in an increased blanket or core temperature. It is conventional to express this afterheat power as a fraction of the operating power (P/P_0). Figure 12 compares P/P_0 values for niobium and vanadium Tokamaks (*3, 6–8*) and the RTPR (*4, 9*) with the values for fission plant. For short times after shutdown, particularly near 1 day, the values are comparable for the niobium fusion reactors and the fission reactor. However, the values are one to two orders of magnitude less for the vanadium fusion reactors.

In comparing afterheats it is important to consider not only the ratio P/P_0, but also the relative power densities of the afterheat. For example, the RTPR has an operating power density of about 5 Mw per cubic meter of blanket and an average afterheat power density in the niobium of about 0.8 Mw/m^3 shortly after shutdown. The corresponding power density in the active core volume of a reference LMFBR (*11*) is 360 Mw/m^3 or 1000 Mw/m^3 in the fuel. A few days after shutdown the afterheat power density is 48 Mw/m^3 in the LMFBR fuel. This is a factor of 62 greater than for the RTPR or for any of the Tokamaks. Although the relative heat-transfer effi-

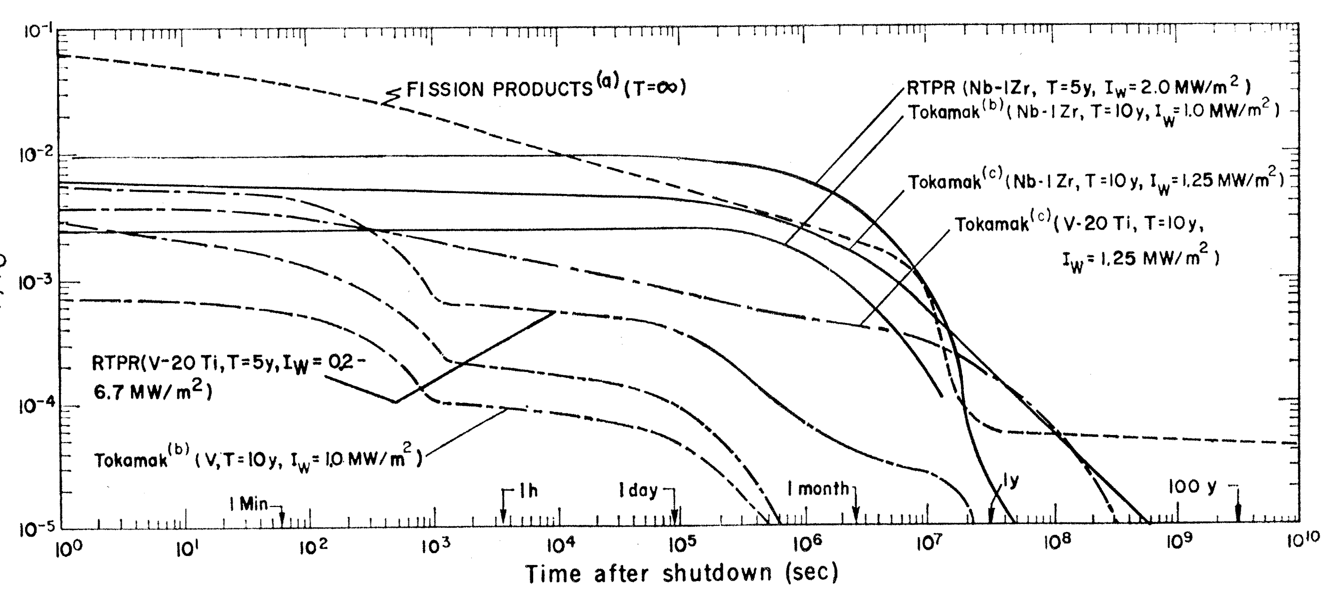


Fig. 12. Relative afterheat powers for fusion and fission power plants as functions of time after shutdown. Abbreviations are as given for Fig. 10. References: curve a (*12*), curve b (*8*), curve c (*3*).

ciencies have not yet been evaluated, they will probably not be greatly different for fusion and fission, and it can be stated that specific afterheat power densities will be considerably less significant for niobium fusion reactors and negligible for vanadium fusion reactors, compared to fission reactors.

Possible security aspects of fusion plants. With regard to possible diversion for weapons purposes, the fact that tritium would be generated, circulated, and burned within the fusion plant means that its availability outside the plant would be minimal. Furthermore, as far as is known, there is no way to construct a nuclear weapon without using fissionable material to initiate the explosion. A fission-free nuclear weapon may, in fact, never be achieved. In the foreseeable future, the issue is therefore the diversion of fissionable material, not of tritium.

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Structure of Wet Specimens in Electron Microscopy

Improved environmental chambers make it possible to examine wet specimens easily.

D. F. Parsons

Light microscopy has the advantage of permitting one to view objects in both liquid and vapor environments. However, its resolution is limited. So far, the only practical method of overcoming the wavelength resolution limit of the light microscope has been to build a microscope with magnetic or electrostatic lenses capable of focusing charged particles, for example, electrons (*1*), lithium ions (*2*), protons (*3*), various ions in the field ion microscope (*4*), or 14-megaelectron volt nitrogen ions (*5*). The use of charged particles, with their necessarily large scattering cross sections, requires that most of the beam path of the microscope be evacuated in order to prevent diffusion of the beam by gas scattering. In nearly all work with electron and ion microscopes it has been customary to place the specimen itself directly in the microscope vacuum, and only a few attempts have been made to isolate the specimen from the microscope vacuum.

One possible solution would be to build a short-wavelength microscope that uses neutral particles, for example, neutrons (*6*), or electromagnetic radiation such as x-rays (*7*). Various point projection and curved mirror lens systems (*7, 8*) for x-rays and neutrons have been devised, but the resolution achieved so far has been no better than that of the light microscope.

In this article I consider to what degree the electron microscope allows the viewing of structures immersed in gas and liquid. Past work and recent advances will be reviewed. The main point to be made is that the routine operation of differentially pumped electron microscope environmental chambers has now been achieved, and these chambers appear to have a wide range of application in medicine, biology, chemistry, physics, atmospheric science, and other areas.

Two types of environmental chambers have been used. In one, the specimen and its environment are isolated from the microscope vacuum by two windows which are thin enough to allow penetration by the electron beam. In the second type of chamber, two small apertures are substituted for windows and the escaping gas is removed by differential pumping of one or more outer chambers surrounding the apertures. The relative advantages and disadvantages of these two approaches will be discussed.

The visualization of structures immersed in gas and liquid environments raises new problems. The presence of the liquid and gas may cause excessive background scattering with associated loss of resolution resulting from chromatic aberration and loss of contrast. Overcoming these problems involves (i) optimizing the design of the environmental chamber to reduce extraneous scattering due to gas (and film windows if present), (ii) surrounding the structure with the minimum necessary thickness of liquid, and (iii) choosing the optimum imaging mode that gives the desired contrast and resolution in rela-

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