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AUTHOR(S): R. F. Post, Lawrence Livermore Laboratory

F. L. Ribe, Los Alamos Scientific Laboratory

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los alamos scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

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FUSION REACTORS AS FUTURE ENERGY SOURCES*

R. F. Post

Lawrence Livermore Laboratory, University of California
Livermore, California, U. S. A.

and

F. L. Ribe

Los Alamos Scientific Laboratory, University of California
Los Alamos, New Mexico, U. S. A.

ABSTRACT

The need is now apparent for a global energy policy with the following characteristics: Compatibility with environmental and economic factors; large fuel resources, the recovery and exploration of which have minimal environmental impact and which do not introduce disturbing factors into the world political situation. The paper discusses fusion power in this context, including assessments of its potential and of the problems yet to be solved in achieving its realization. We advance the proposition 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.

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I. THE PLACE OF FUSION IN PLANNING FOR THE WORLD'S ENERGY NEEDS

We propose here to discuss the topic of fusion power, its nature, the status of research aimed toward achieving it, and the implications we see for the world energy picture in its practical achievement.

It is self-evident that man's use of energy for whatever purpose has always been and will continue to be based on his 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, he must project his needs for energy into the future on the basis of this heritage. Through pre-history and until the last relatively few years his fossil fuel heritage has seemed essentially limitless, and his use of energy based on that heritage did not appear to threaten his environment or the stability of his political institutions in any substantial way. This situation has now changed irrevocably, and a new set of circumstances must be dealt with. This changed situation is being more and more widely recognized, and it is at the same time becoming apparent that man's use of energy in the future must not perpetuate the patterns of the past. Except for a necessary period of transition, the central issue has become the following one: What new energy source -- or sources -- can sustain man's needs in the future, and how can these be selected so as to reverse the trend of destructive impact of some of man's technology on his environment and on his individual security, as this security relates to the world political climate?

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

As exemplified by the sun and the stars, fusion energy is a primordial energy source, deriving from a fundamental circumstance in nature: That the transmutation through combinatory nuclear reactions of the nuclei of light elements (those located at the beginning of the periodic table of the elements) into heavier ones results in the release of energy, manifested in the form of kinetic energy imparted to the transmuted nuclei.

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The significance of learning how to generate useful energy from nuclear fusion reactions is that fusion represents not only a virtually inexhaustible energy source, but one, the fuels for which would be of near zero-cost (as compared to fossil fuels) and would be both universally available and obtainable with small environmental impact. Furthermore, although fusion energy is indeed a form of nuclear energy, it bears almost no similarity to "conventional" nuclear energy, i.e., energy from the fissile elements, uranium, plutonium, and thorium. Compared to the hazards of fission reactors -- radioactive fission products, the potentially serious consequences of loss-of-control or loss-of-coolant accidents and the problem of the proliferation of nuclear fission weapons -- fusion can be made much less hazardous. While conventional nuclear power will no doubt have an important role to play in electric power generation, we wish to advance the proposition 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 today exist, so that we cannot deal with absolutes in advancing such a proposition, no matter how firmly we may personally 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, now under active pursuit throughout the world, has its nuclear roots in over 40 years of nuclear physics (the discovery of the fusion reactions, which preceded by many years the discovery of fission) and has its physics roots in over 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 basis which we feel is both sufficiently broad and sufficiently advanced to assure the successful solution of the fusion power problem in a relatively few years -- 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 insure 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 implement its consequences. We are aware that fusion cannot solve the energy problems of this decade, or even the next. But its undoubted impact on the future should be anticipated now.

II. PHYSICAL CONDITIONS REQUIRED FOR THE FUSION PROCESS

While nuclear fusion reactions are among the most elementary and best understood of nuclear processes, their achievement on a practical scale for the controlled release of energy presents formidable scientific and technological problems. The origin of the difficulty lies in the physical conditions that must be achieved to ignite and to maintain energetically self-sustaining fusion reactions. Fusion is very unlike the nuclear fusion process, in which heavy nuclei are triggered into fission-fragment nuclei by the absorption of neutrons derived from other fission-produced neutrons, in the familiar chain reaction style. In fission the neutrons, which propagate and perpetuate the chain reaction, are particles of zero electrical charge. Thus they can freely enter the uranium nuclei, uninfluenced by its high positive electrical charge. By contrast fusion reactions, as the name implies, 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 a sufficiently high kinetic energy they cannot overcome their natural electrostatic repulsion in order to come close enough to each other to fuse.

The discovery of nuclear fusion -- accomplished in the early 1930's -- awaited the development of particle accelerators. These are devices in which beams of electrically-accelerated light nuclei were caused to bombard solid or gaseous targets containing other fusible nuclei, causing nuclear fusion reactions. 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. Yet in bombarding a gaseous or solid target with accelerated nuclei only a tiny fraction will actually react. Most will miss their nuclear targets and dissipate their energy uselessly (as heat) within the target. Power produced will thus be miniscule compared to power required. Though the use of high-current beams of energetic particles does in fact play an important role 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 technological problems that must be solved to achieve fusion power. These are heating and containment. To react, 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 this confinement time must be will depend on the particle density of the heated fuel. At high fuel density reactions will occur quickly; thus the confinement times needed can be correspondingly short; at low fuel density, the time must be correspondingly longer. This dependence is most succinctly expressed through 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 to the 14th power ($n\tau > 10^{14}$ 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 this problem and the scientific problems these approaches have encountered. As discussed below, major progress has been made on many fronts toward reaching the formidable physical conditions required for a net fusion power release, but in no case has this end actually been reached.

III. THE 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 processes, proceeding in stellar interiors, are thought to be the dominant processes in the evolution of stars. On 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 (hydrogen, helium, etc.). However there is a richness of possibilities in fuel combinations lying in the future for fusion power that may someday be of great importance.

The primary fuel for fusion is deuterium -- heavy hydrogen. As discussed below, this isotope alone represents an almost inconceivably large "fuel reserve" for fusion power, and one of near-zero net cost (less than 1% of the cost of coal), available universally. Deuterium, a stable isotope of hydrogen, is the next-to-the-simplest nucleus in the periodic table, consisting of a single proton and a 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 one would write 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 nuclei involved are: Protons (p; nuclei of ordinary hydrogen), deuterons (D); tritons (T; tritium is an unstable heavier isotope of hydrogen); helium-3 nuclei (He^3; a stable light isotope of helium). The first two reactions listed are alternate possibilities for the D-D reaction, occuring with roughly equal probability. The energy releases from the reactions are given in two ways; (1) millions of electron-volts, the electrical equivalent energy imparted to the reaction-product nuclei, and (2) kilowatt hours per gram mass of the reacting nuclei. As a comparison, the chemical combustion reaction between hydrogen and oxygen which leads to water is also listed, using the same units

$D + D \rightarrow p + T + 3.25$ MeV (22,000 kW hr/gm of fuel)

$D + D \rightarrow n + He^3 + 4.0$ MeV (27,000)

$D + T \rightarrow n + He^4 + 17.6$ MeV (94,000)

$D + He^3 \rightarrow p + He^4 + 18.3$ MeV (98,000)

($2H_2 + O_2 \rightarrow H_2O + H_2O + 0.000006$ MeV (0.0044))

These reactions, plus one or two additional ones involving lithium and boron isotopes, represent the elements of the fuel cycles for future fusion reactors. One of these (the D-T) is the reaction on which most present-day studies of fusion reactor probabilities are based. The last reaction listed, D - He_3, 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 the direct conversion of fusion energy to electricity, potentially at very high efficiency.

Note that deuterium as a fuel has the very unusual property that its "ashes" are themselves combustible (the D-T and D-He^3) so that a fusion reactor fuel cycle can be visualized in which deuterium is burned to completion -- the end products being ordinary hydrogen and helium, plus the release of 7 million electron volts per deuteron burned, i.e., about 100,000 kilowatt hours of energy per gram of deuterium fuel -- about 4 times the energy per gram released in the fission of uranium.

While there is every reason to believe that D-D-T-He^3 fuel cycles such as described above 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" of all the reactions (about 50 million degrees kinetic temperature). It is thus 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 that such breeding might be accomplished, the only one that has received serious study involves the 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).

It is important to put the questions of fuel cost and availability in proper perspective. At levels of 100,000 kilowatt hours per gram, the amount of primary fuel needed to sustain future world electrical power generation needs is exceedingly small. To take as a present-day example, the U. S. electrical power demand average is 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 kilograms per 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 5-cm diameter pipe at normal pressures! The needs for lithium in the D-T breeding cycle would be correspondingly miniscule. 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. The abundance of primary fusion fuels is so large as to be virtually inexhaustible, even on time scales measured in billions of years. The solution of the fusion power problem would indeed represent a permanent solution to man's energy needs.

IV. APPROACHES TO FUSION POWER

Fusion power depends on the achievement of the physical conditions required for fusion reactions -- high kinetic temperatures to initiate the reaction, and sufficiently long confinement time to yield a net power output. Impossible though it at first seemed 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 their 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 all matter can only exist in the gaseous state known as "plasma" -- a charged-particle gas composed of an equal mixture of positively-charged nuclei and free electrons (those 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 both be contained in a hermetically-sealed vacuum chamber (to keep out atmospheric air) but also 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 with other nuclei. However at fusion temperatures the nuclei are moving so rapidly that they would fly to the walls of any chamber of practical size in a few millionths 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: (1) to introduce non-material means to confine the fusion fuel gas, free from contact with the chamber walls, long enough for a net release of fusion power, or (2) to carry out the processes of heating the fusion fuel so rapidly that the fuel-charge nuclei will react with each other before they can escape to the walls -- i.e., to initiate a micro-explosion. The 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, 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 confinement region by the action of intense and specially-shaped magnetic fields. In a sense the magnetic field acts as a non-material 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 else intense focused beams of ultra-high-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 temperature or higher) the pressure exerted by a gas at atmospheric pressures 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 $1/100{,}000^{th}$ of an atmosphere (3×10^{14} particles per cubic centimeter) to as high as $1/1000^{th}$ 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 very large. At the lower density it is some 100,000 to 300,000 kilowatts per cubic meter of reacting plasma. Varying as the square of the fuel density, it 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. But the higher values 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 the rather long required confinement times of the magnetic confinement approach and the high densities -- many thousands of times greater than the micro-explosion approach -- lies a gap where a workable approach seems much more difficult. 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.

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 a completely different set of scientific and technological problems that must be solved in the following two lines of attack. These problems can be identified and stated succinctly. They are: For magnetic confinement, finding those combinations of magnetic field configuration, intensity and size, and those 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 particle beams that can heat and compress a pellet in such a way and in a short enough time that a micro-explosion yielding net energy (more than used in the heating) is released.

Difficult though the problems for fusion may appear, many if not most of the problems listed above, particularly for the magnetic confinement approach, have now been solved. Critical scientific issues do yet remain, but they are at the level of quantitative issues, 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, coil-spring-like, 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 helical magnetic coil winding. Inside the tube the plasma particles would then be constrained to move, like beads on a string, in helical orbits lying inside of 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 purposes. 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", the repelling effect of extra-strength magnetic field regions (the mirrors) on helically moving particles. By locating 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 logically 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 <u>square</u> 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 confinement that did not fall far short of these ideals. The basic problem in both cases was the existence of plasma instabilities, unstable gross motions or fine-scale turbulences in magnetically-confined plasmas that lead either to rapid expulsion from the field or to somewhat slower but still unacceptable rapid diffusion out of the field, caused by unstable oscillations within the body of the plasma.

In the 20-year-plus span of time during which magnetic confinement research has been pursued plasma instabilities have been studied, analyzed, and brought close to the point of complete control. The means by which this feat was accomplished were 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 as now used in mirror systems. The first mirror systems used a simple "barrel-shaped" field (upper diagram of Fig. 1) in which the mirrors were at either end 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 -- i.e., 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 the lower diagram of Fig. 1, the plasma is placed in effect at the bottom of a magnetic wall. 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, though 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 an obviously necessary element in the search for fusion by magnetic confinement. Here also major progress has been made, to the point that this problem is largely solved at the scientific level, with the expectation that these solutions can be carried to the reactor level. There are three main techniques through which heating of plasmas at magnetic confinement densities can be accomplished. These are: (1) "Ohmic heating" -- heating a plasma by passing an electric current through it. This technique is used in present Tokamak experiments. (2) Magnetic compression -- in this technique the plasma is heated, either "adiabatically" (slowly) by compressing it through an increase in the strength of the confining field or "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. (3) Neutral beam heating -- this technique involves the generation of intense beams of energetic neutral atoms 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 reason for augmenting ohmic heating.

Other heating methods, less widely used, include heating by radiofrequency and microwave power and laser heating of dense magnetically-confined plasma in long linear geometries.

The remaining scientific-technical issue for magnetic confinement fusion research is the generation of the magnetic field itself and the efficiency of its utilization 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, without the need for power to sustain resistance losses, extremely high magnetic fields, high enough to satisfy the requirements of all but the most demanding of the various fusion approaches. As a consequence of these developments serious study can be made of fusion reactor ideas embodying such coils, and progress toward the solution of fusion will be hastened.

An important scientific issue, and one of eventual economic importance which relates 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 this limiting magnetic value. Beta equals one is that limit point. 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 is however still not resolved for the Tokamak, which thus 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 the number remaining 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 yet remain to be resolved, our confidence level as to their resolution is very high. It is generally believed in the fusion community that these last remaining scientific issues will be settled within less than 10 years.

V. FUSION REACTOR SYSTEMS

In the preceding section the basic principles of the three main magnetic confinement systems were discussed: (1) the Tokamak, low-beta toroidal system; (2) the theta-pinch (or Scyllac) high-beta toroidal system; and (3) the open-ended, mirror system. For the past decade or so the principles embodied in the present experiments have been used to provide conceptual designs of fusion reactors under the assumption 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 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 plant 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 the following we shall indicate 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 from 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 cooled 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 which is used to power the energy conversion equipment (turbo generators) to produce electricity. (There are other, more direct, sources of electrical output in the case of the theta pinch and the mirror.) In addition the moderator breeds tritium for refueling the plasma both by capture of slow neutrons in the lithium and by disintegration of the lithium by fast neutrons. The moderator also serves to shield the magnet coil from the neutrons.

A. 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 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 D-T ions into the plasma. In order 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 Oak Ridge National Laboratory (ORNL) Tokamak-reactor design[1,2] is illustrated in Fig. 5. It uses an iron magnet core for the poloidal-field flux. D-T gas is introduced, ohmically heated and further heated by neutral beam injectors as indicated in the figure. As burn-up proceeds, He^4 "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 m and a minor radius a = 2.8 m. The toroidal magnetic field in the plasma is 60 kG, and its toroidal current is 20 MA. The first wall is cooled by liquid-lithium flow in the blanket segments which run parallel to the toroidal magnetic field and have a radial thickness of 1 meter. The lithium emerging from the blanket at 1052°C exchanges with potassium to provide vapor at 982°C which drives the topping-cycle turbine of the thermal conversion system. Of the 1000 MW (thermal) from the blanket, 564 MW of electrical power are produced at 56.4% efficiency, and the useful electrical power output is 518 MW.

There are also conceptual designs in the U. S. A. by groups at the Princeton Plasma Physics Laboratory (PPPL)[3] and the University of Wisconsin.[4] In these designs, in order to maintain a low level of He^4 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[3] or two[4] 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.

B. The Theta-Pinch (Scyllac) 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 (or "shock-heating") phase the surface of the plasma is driven rapidly inward by this 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, for a linear geometry. For a torus (circular geometry) the ends and the end loss are eliminated. Unlike the Tokamak, the theta pinch excludes all but a small fraction of the magnetic field B from the plasma (the high-beta property).

In present experiments a single-turn coil furnishes both the shock-heating and adiabatic-compression fields. However a theta-pinch reactor will be a "staged" theta pinch, with separate coils and energy sources for the shock heating and adiabatic compression. The shock-heating coil is thin and liquid-metal-cooled. It is connected to a low-energy, high-voltage circuit. The magnetic compression field is furnished by a low-voltage, multiturn 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 ion 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). In Fig. 6 the darkly shaded areas represent magnetic field perpendicular to the plane of the figure. 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 a value of 10-20 keV. As the D-T plasma burns, it produces 3.5-MeV alpha particles (helium nuclei) which further heat the D-T ions and the electrons. The plasma expands against the confining magnetic field, doing work which is about 8% 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 (cf. the arrow in Fig. 6D) and back into the compression magnetic-energy store. This high-beta alpha-particle heating 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 the plasma contains approximately 10% 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 between 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 which is then ready for a new heating and burn pulse.

An overall view of the Los Alamos-Argonne Theta-Pinch Reactor (RTPR)[5] is shown in Fig. 7. It has a maximum toroidal field of 110 kG. The plasma chamber has an inner diameter of one meter and a major diameter of 112 m. The compression and shock-heating coils, as well as the lithium blanket, make up 2-meter reactor modules 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.

C. Magnetic Mirror Reactors

In a simple magnetic mirror (Fig. 1, upper diagram), 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 field lines at the two ends as discussed in Sec. IV above.

To sustain the plasma in a mirror device against end loss it must be injected with a neutral beam as shown in Fig. IV. The plasma is "opaque" to this beam and absorbs its energy, and the plasma thereby becomes 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 classical collisional end losses, it is necessary to use the energy of plasma ions which escape out the mirrors in order 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 the lower part of Fig. 1 and a typical escaping ion orbit. First the escaping plasma (and ion orbits) are expanded in the horizontal fan-shaped magnetic field which extends about 100 meters 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 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 electrostatic charge. The voltages of these charges are then brought to a common DC potential which represents the output of the direct-conversion system.

Plasma in the simple mirror geometry of Fig. 1 is unstable to motions in which the plasma moves grossly across the magnetic lines (cf. Sec. IV). However a system whose magnetic lines are everywhere convex toward the plasma (lower part of Fig. 1) is stable. Such a system is a "magnetic well" in that it has minimum field strength B on its axis at the center of the system, and B increases outward in all directions. The magnetic well system of Fig. 1 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[6] in Fig. 9. The spherical dome covers a trap for neutrons emerging vertically from one mirror of the Yin-Yang coils which are in an evaluated spherical cavity underground. The coils confine a roughly spherical plasma of 3.5-meter radius whose vertically escaping ions are bent horizontally by a magnetic field to enter the direct-conversion structure which is shown as the 240-degree "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 has shown 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 direct current electrical power.

VI. ESTIMATED ENVIRONMENTAL CHARACTERISTICS OF FUSION REACTORS

A. Radioactive Effluents

The only possibility of radioactivity release during routine operation of a fusion power plant is tritium leakage. An essential feature of all of conceptual fusion plant designs is to minimize this leakage by minimizing the tritium inventory and enclosing the hot metal structures through which tritium can diffuse in vacuum and helium barriers, finally surrounded by cold metal walls. Attention is given to minimizing diffusion in the hot metal structure by the incorporation of non-diffusive elements, e.g., copper or ceramic coatings. Fairly straightforward design gives tritium releases to the condenser coolant system which, when discharged to a body of water, give negligible tritium concentrations. In the case of a dry cooling tower the diffusion barrier design is more stringent in order to achieve a similar relatively low level of tritium release.

An important aspect of the tritium fusion fuel is that it need 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 non-radioactive elements, deuterium and lithium, are transported in to fuel the plant.

B. Long-Lived Radioactive Wastes

A fusion reactor will produce non-volatile 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 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 (Ci) of radioactivity generated for each watt of thermal power generated (Ci/Wt).
2. The generated radioactivity expressed in terms of the gross biological hazard potential (BHP). This is the Ci/Wt divided by the maximum permissible concentration (MPC) of each radioactive nuclide expressed in Ci/km^3. Here we use the MPC for air concentrations.

Figure 10 presents a comparison of total activities of conceptual Tokamak[7,8,9] and theta-pinch (RTPR)[5,10] reactors with that of the fission products for a fission reactor.[11] In the case of the fusion reactors the following alternative structural materials are assumed: (1) niobium (Nb-1 Zr) and vanadium (V-20Ti). The essential difference in the Tokamak and RTPR curves is that the former case assumes 1% refractory-metal structural material, and the latter case 6% in the neutron blanket. It is seen that the choice of a vanadium structure reduces the Ci/Wt 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.

Figure 11 compares the relative biological hazard potentials (BHP) of the fusion- and fission-reactor radioactivities. For times after shutdown less than one year the Nb fusion reactors have radioactive BHP's roughly equal to that of the fission products. However, the fusion BHP is much less than that of the plutonium fuel of a reference LMFBR.[12] For the vanadium fusion reactors the BHP's are one to two orders of magnitude less than for the fission case. At later times (> 1 year -- the times of waste storage) the fusion BHP is one to two orders of magnitude less than for a fission reactor, in the niobium fusion case, and is negligible for the vanadium fusion case.

C. Afterheat

In the event of loss of coolant, the nuclear decay heat will result in an increased blanket or core temperature. It is conventional to express this afterheat power as fraction of the operating power (P/P_o). Figure 12 presents a comparison of niobium and vanadium Tokamaks[4,7,8,9] and the theta pinch RTPR[5,10] with a fission plant. For times after shutdown in the one-minute-to-one-year range, and particularly near one day, the relative powers are comparable for the niobium case and one to two orders of magnitude less for the vanadium fusion case.

In comparing afterheats it is important not only to consider the ratio P/P_o, but to consider it in relation to the relative power densities of the afterheat in the fusion and fission cases. For example the RTPR has an operating power density of about 10 W/cm^3 of blanket and an average afterheat power density in the niobium of about 4 W/cm^3 shortly after shutdown. The corresponding power density in the active core volume of a reference LMFBR[12] is 360 W/cm^3 or 1000 W/cm^3 in the fuel. A few days after shutdown the afterheat power density is 48 W/cm^3 in the fuel. This is a factor of 10 greater than for the RTPR fusion case, or for any of the Tokamaks. Although the relative heat-transfer efficiencies are not yet evaluated, they will probably not be greatly different for fusion and fission, and it can be stated that specific afterheat power densities are of considerably less significance in the niobium-fusion case than for fission and negligible in the vanadium-fusion case.

D. Possible Security Aspects of Fusion Plants

In 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 external to the power plant would be minimal. Furthermore, as far as is known, there does not exist any means for constructing a nuclear weapon that does not employ 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 that of tritium.

ACKNOWLEDGEMENT

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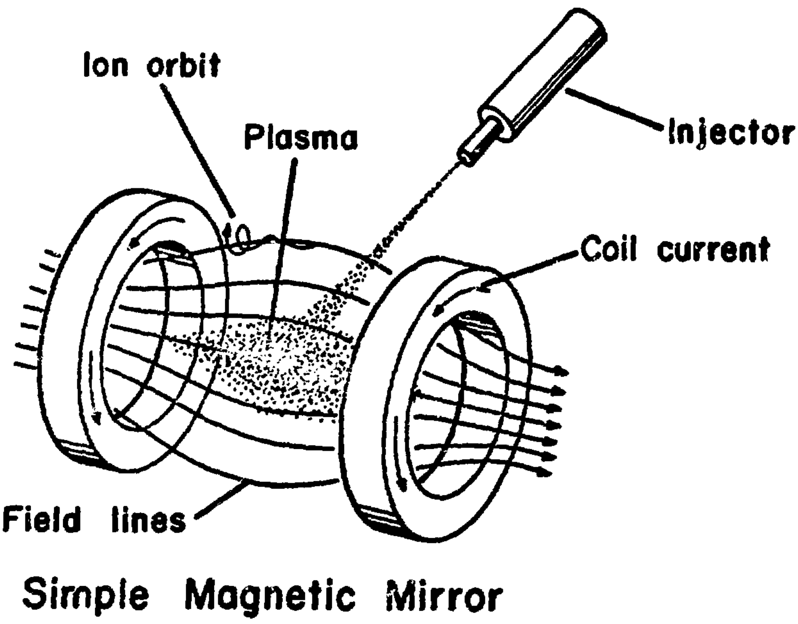

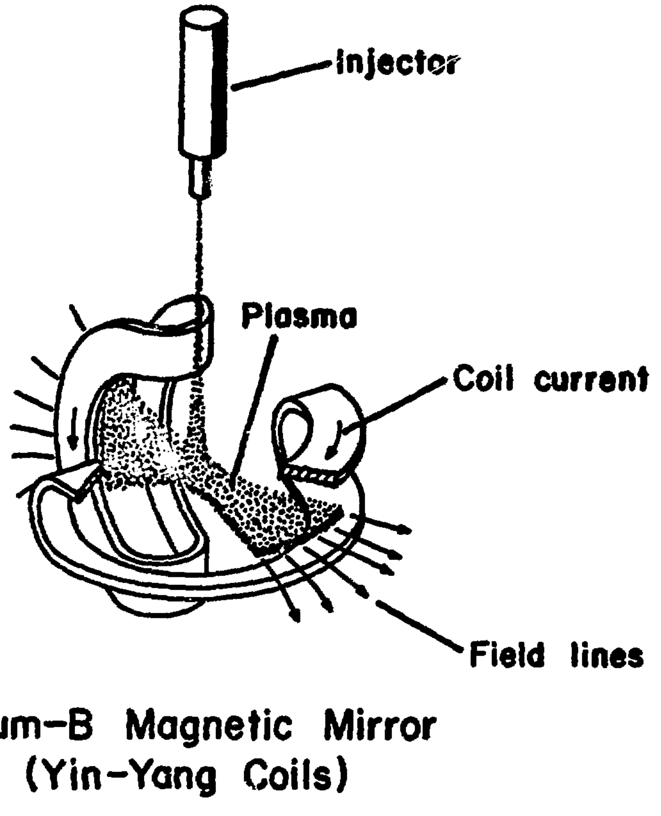

Fig. 1. Illustrating the principles of a magnetic mirror experiment.

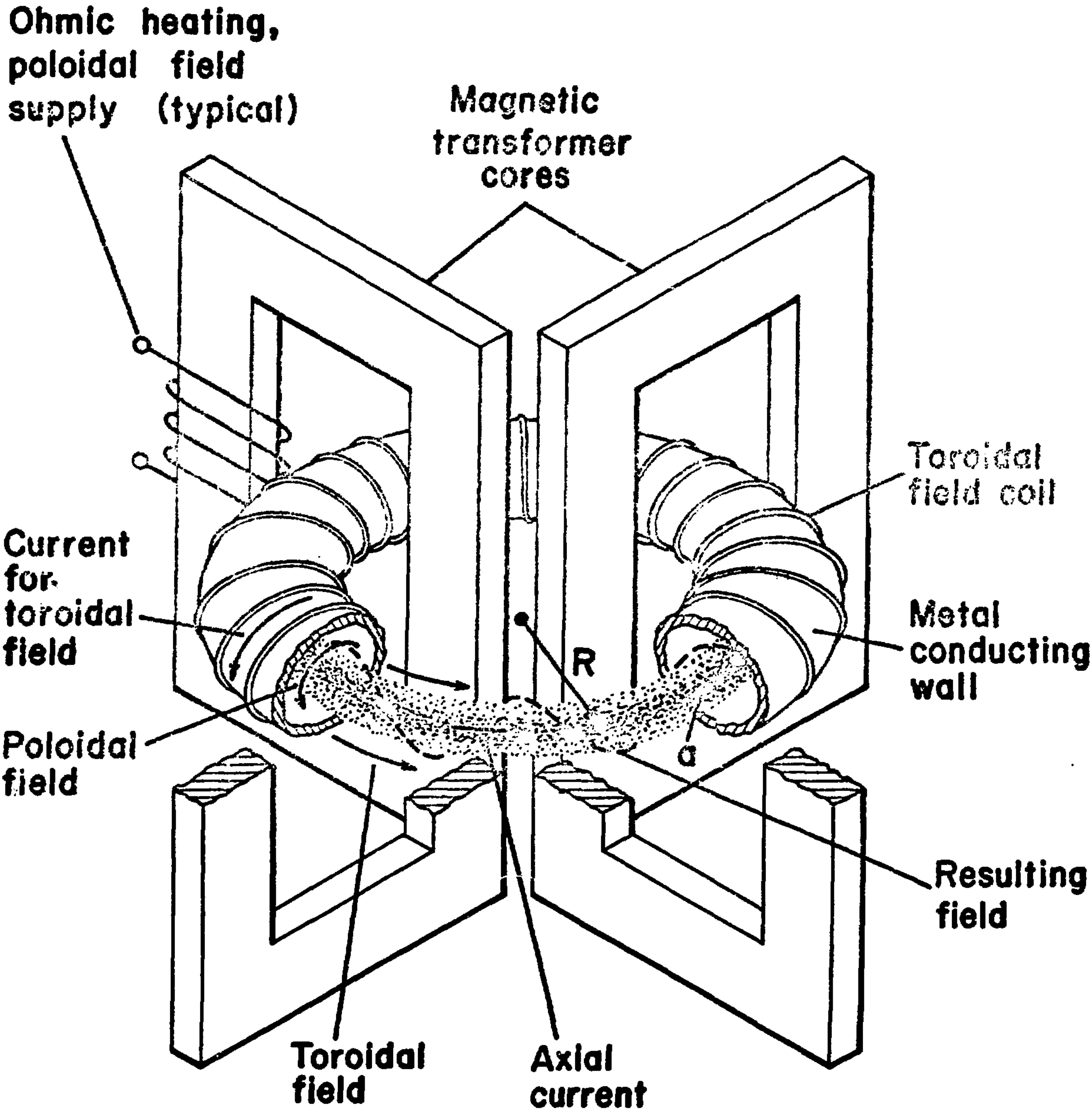

Fig. 2. Schematic drawing of a Tokamak device.

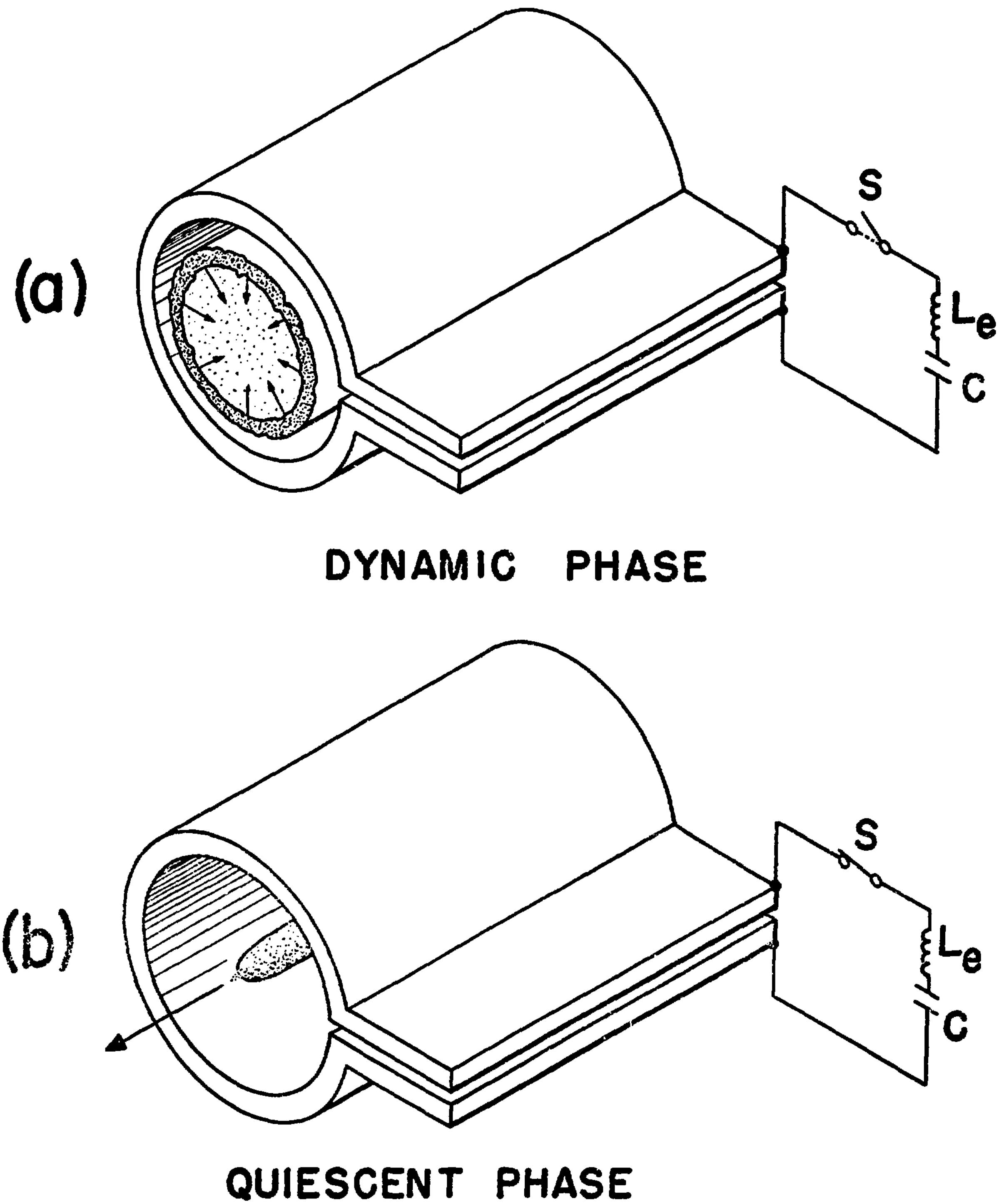

Fig. 3. Illustrating the basic principles of the Theta Pinch.

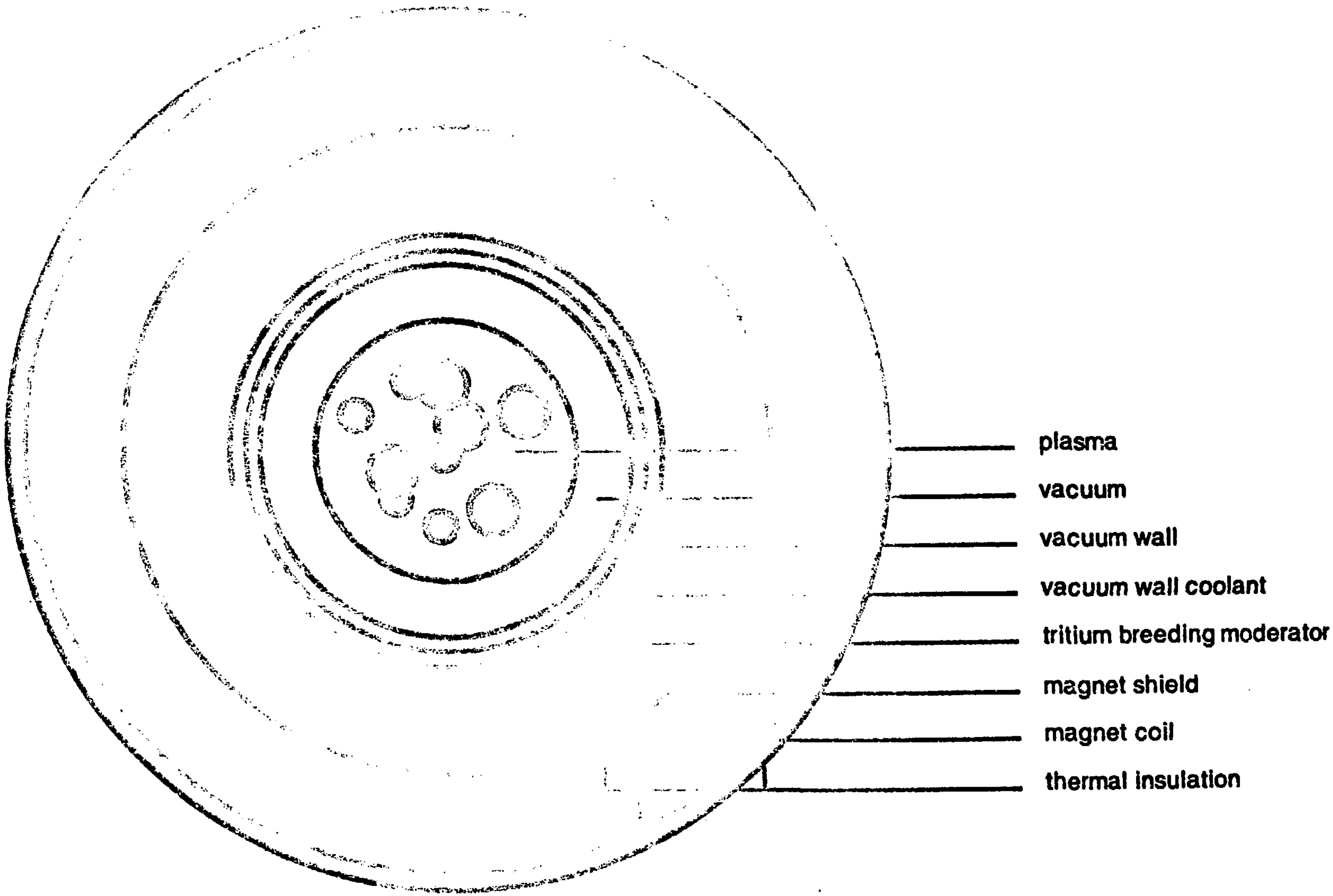

Fig. 4. Generalized cross section of the core of a fusion reactor.

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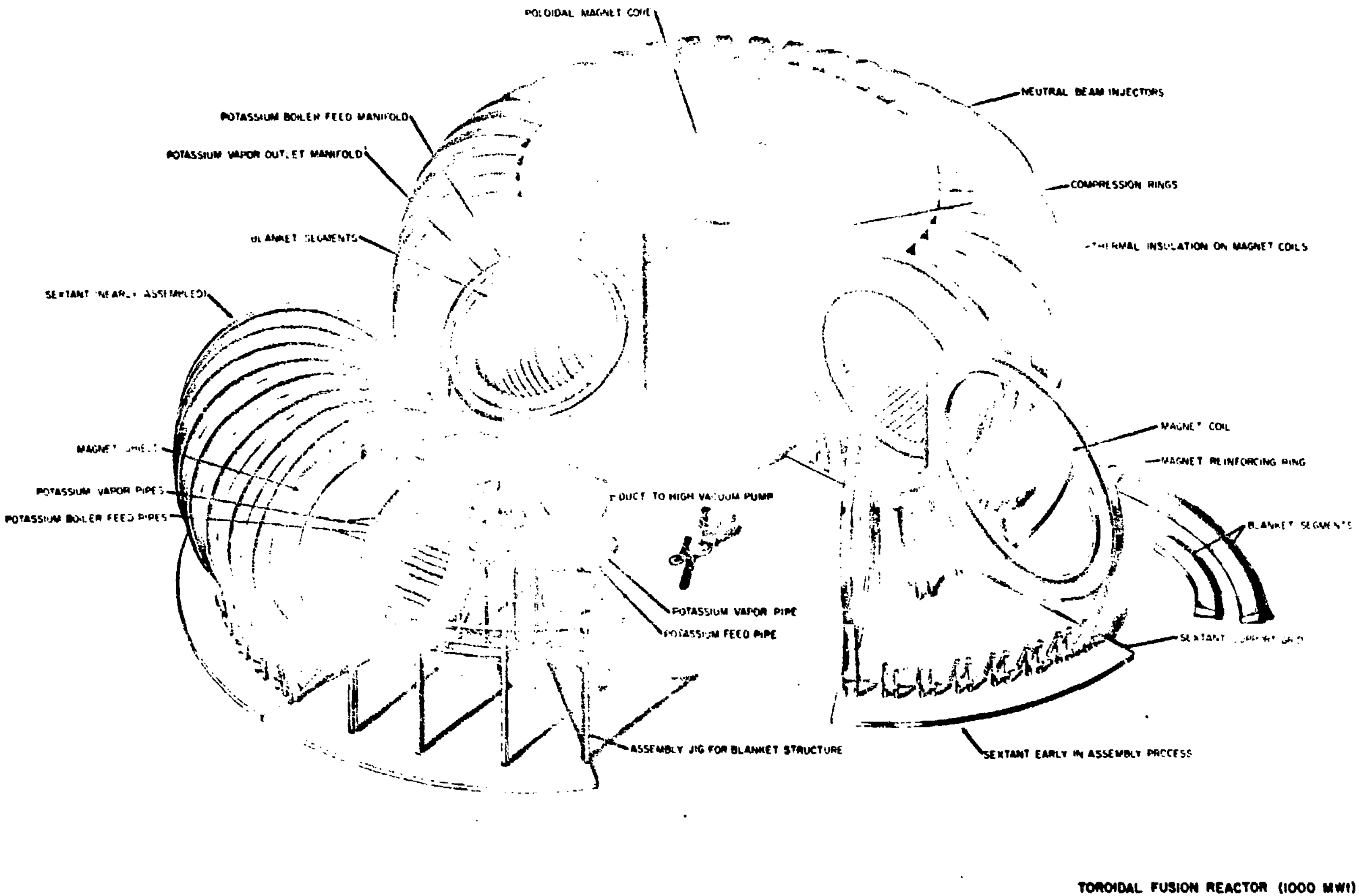

Fig. 5. Overall view of the ORNL conceptual Tokamak reactor.

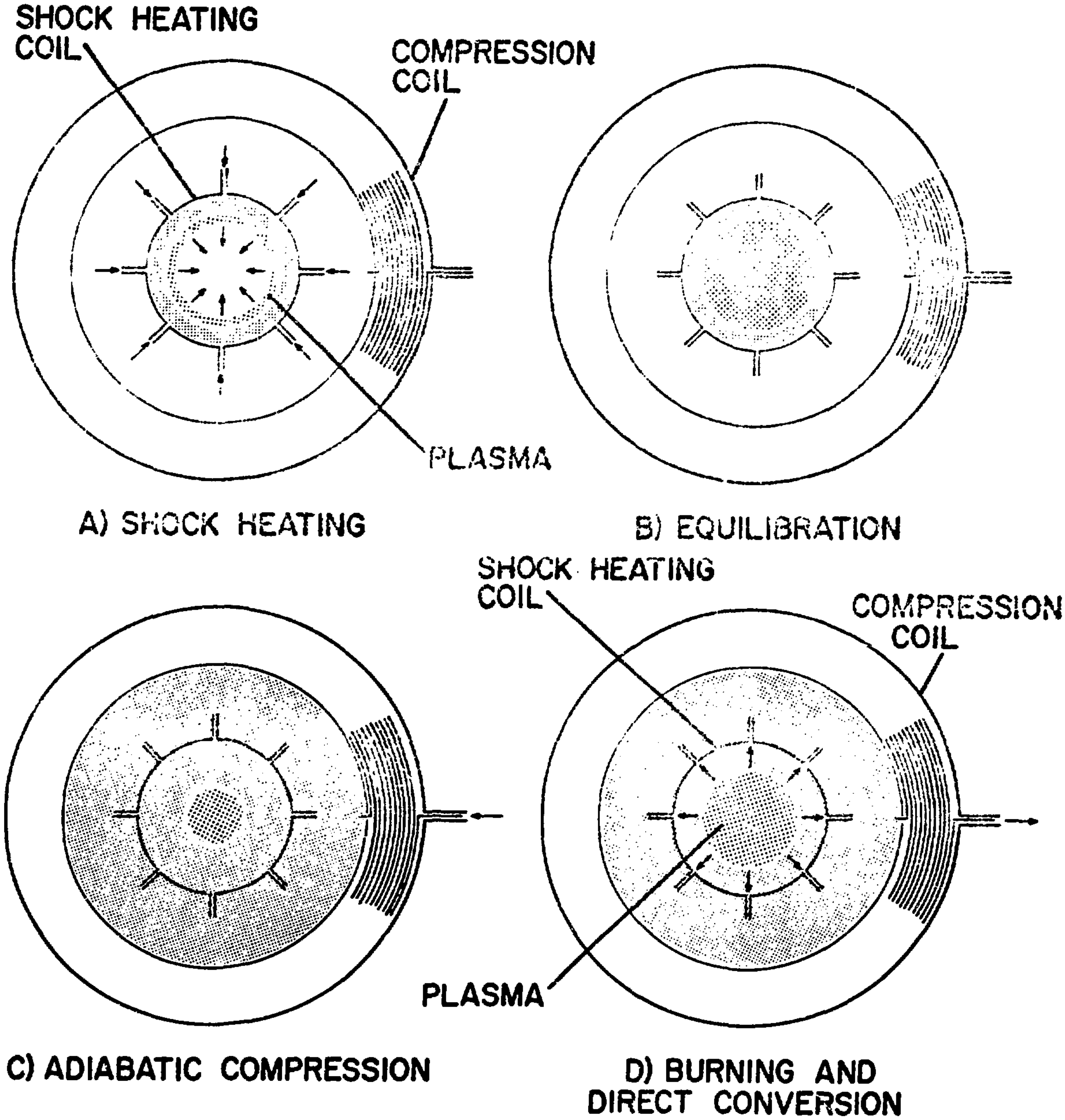

Fig. 6. Plasma heating and burning in a staged Theta-Pinch reactor.

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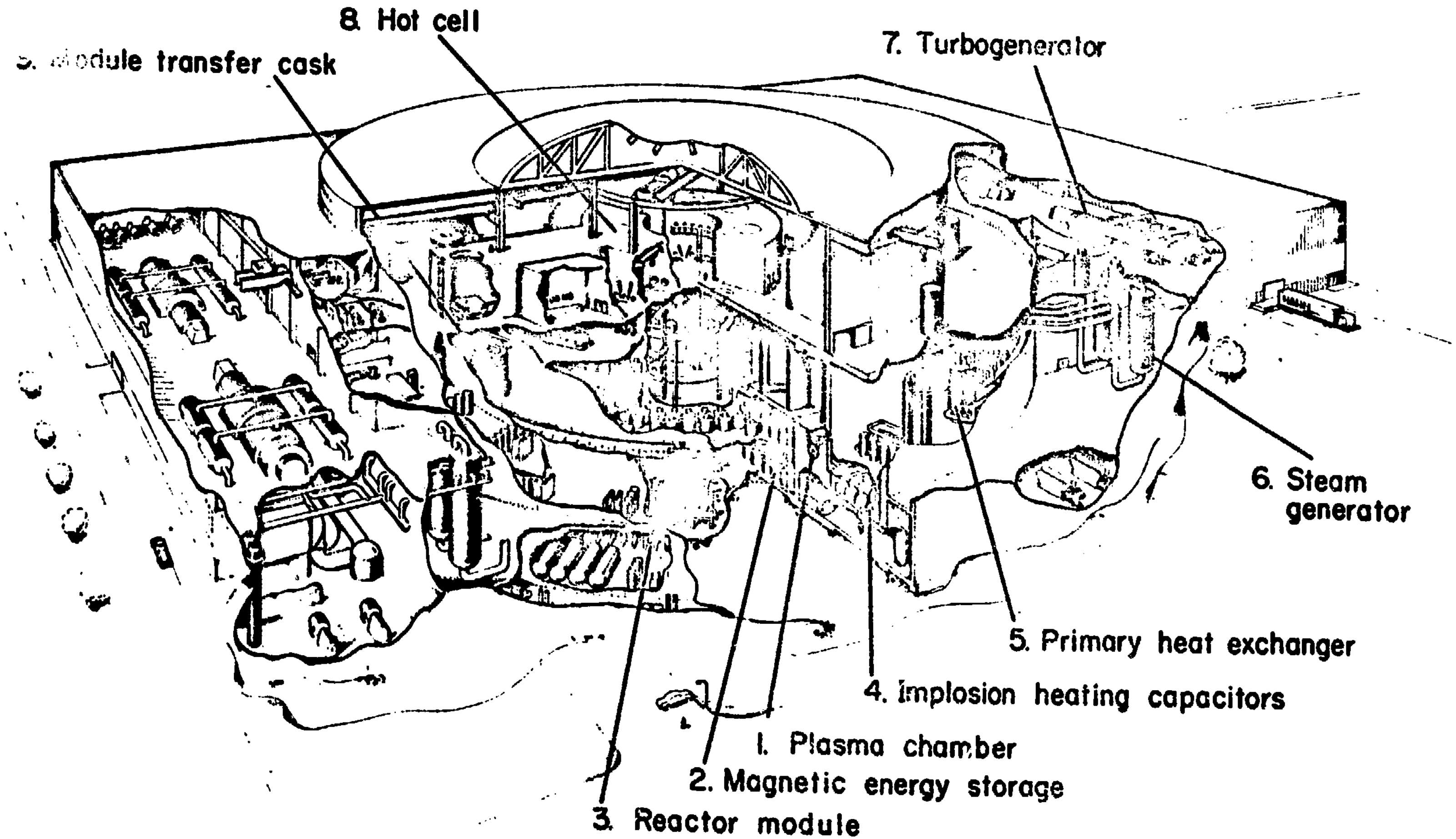

Fig. 7. General view of a 2000 MW(e) Theta-Pinch reactor and power plant.

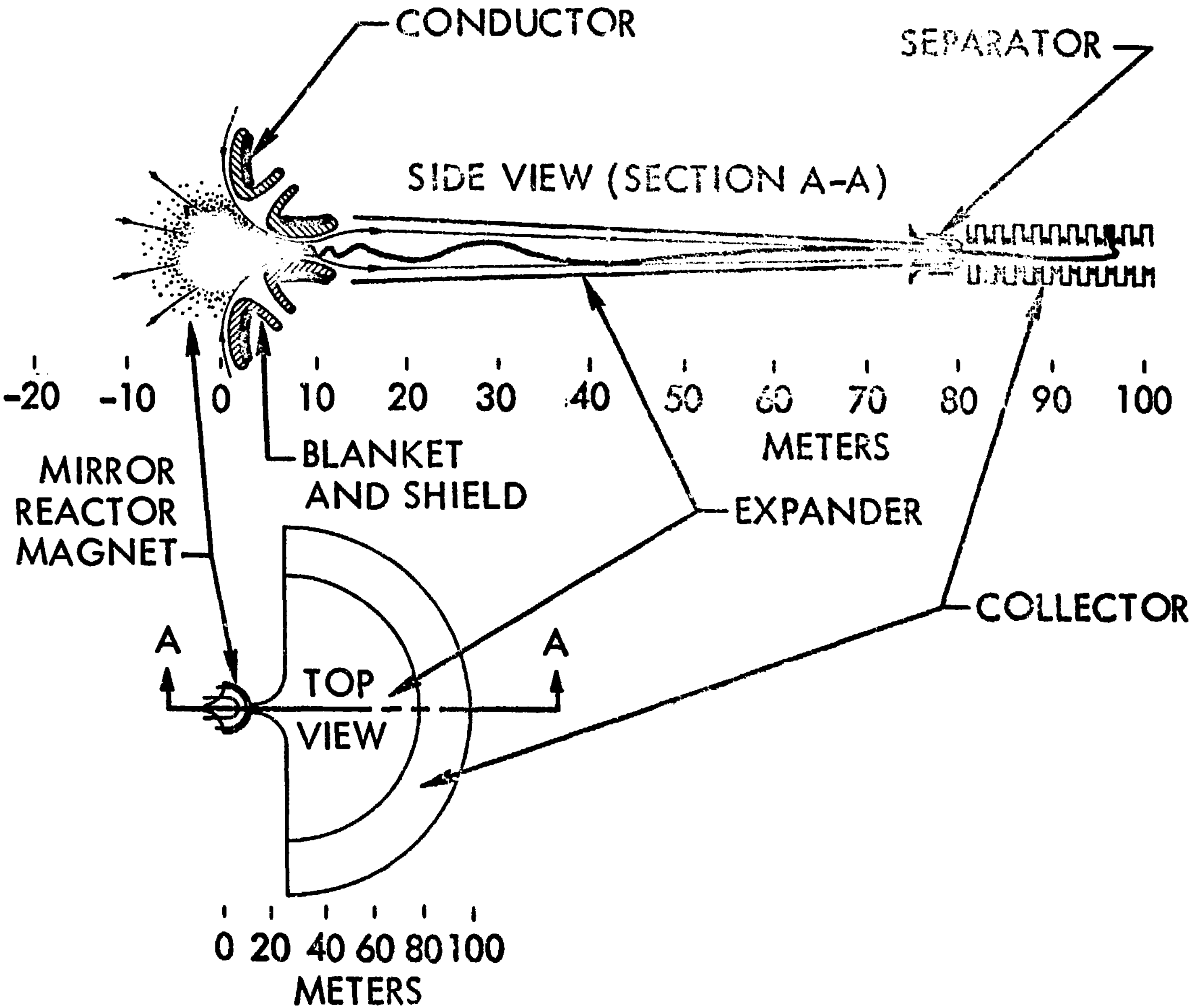

Fig. 8. Illustrating the method of direct conversion in a magnetic-mirror reactor.

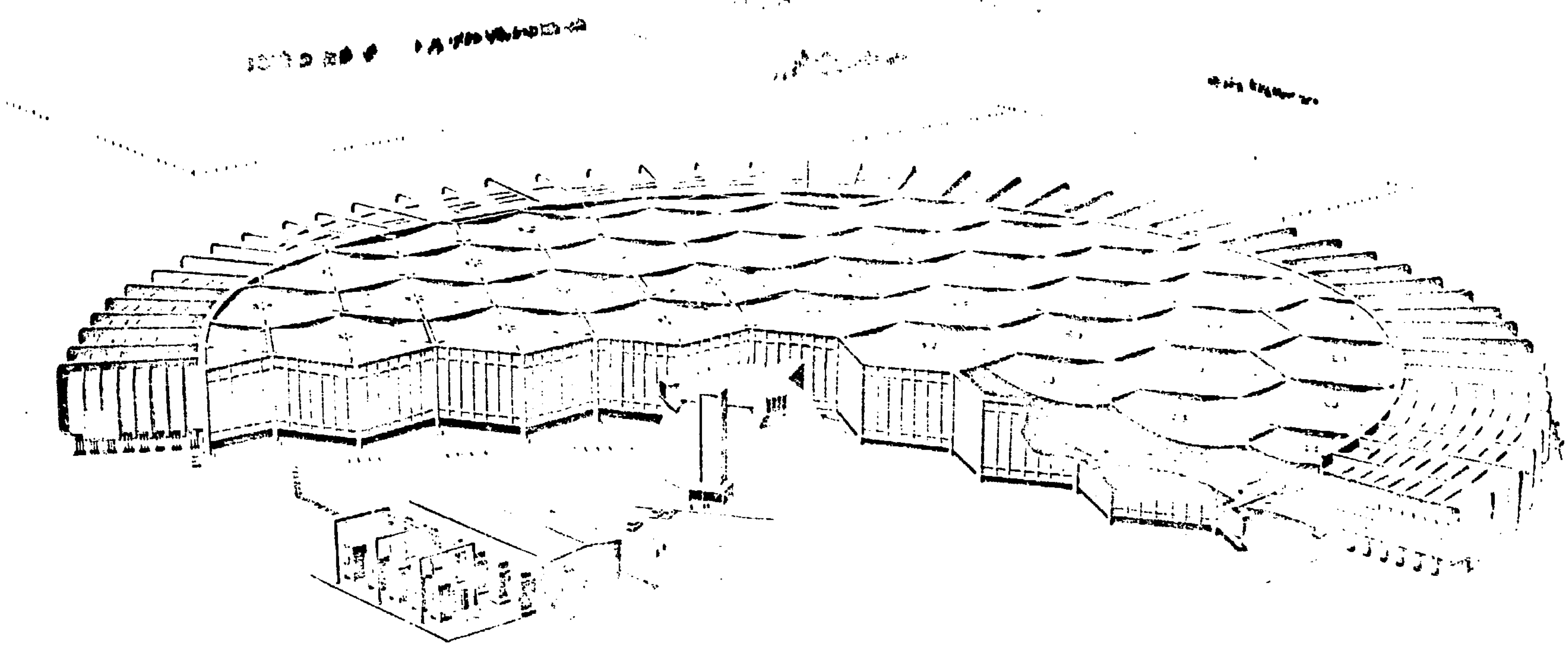

Fig. 9. An overall view of a magnetic-mirror reactor and power plant.

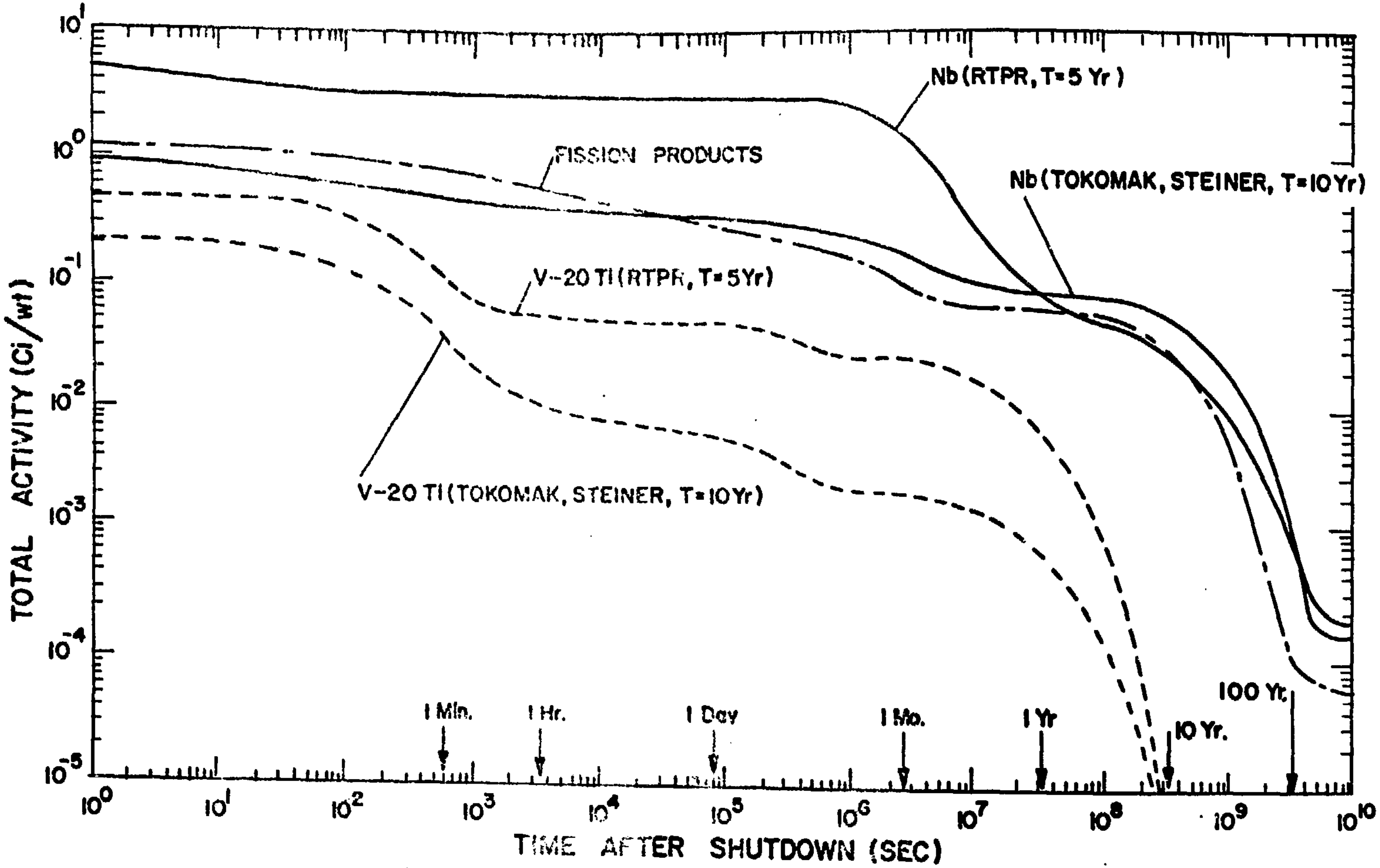

Fig. 10. Graphs of total induced activity for fusion and fission reactor plants as functions of time after shutdown.

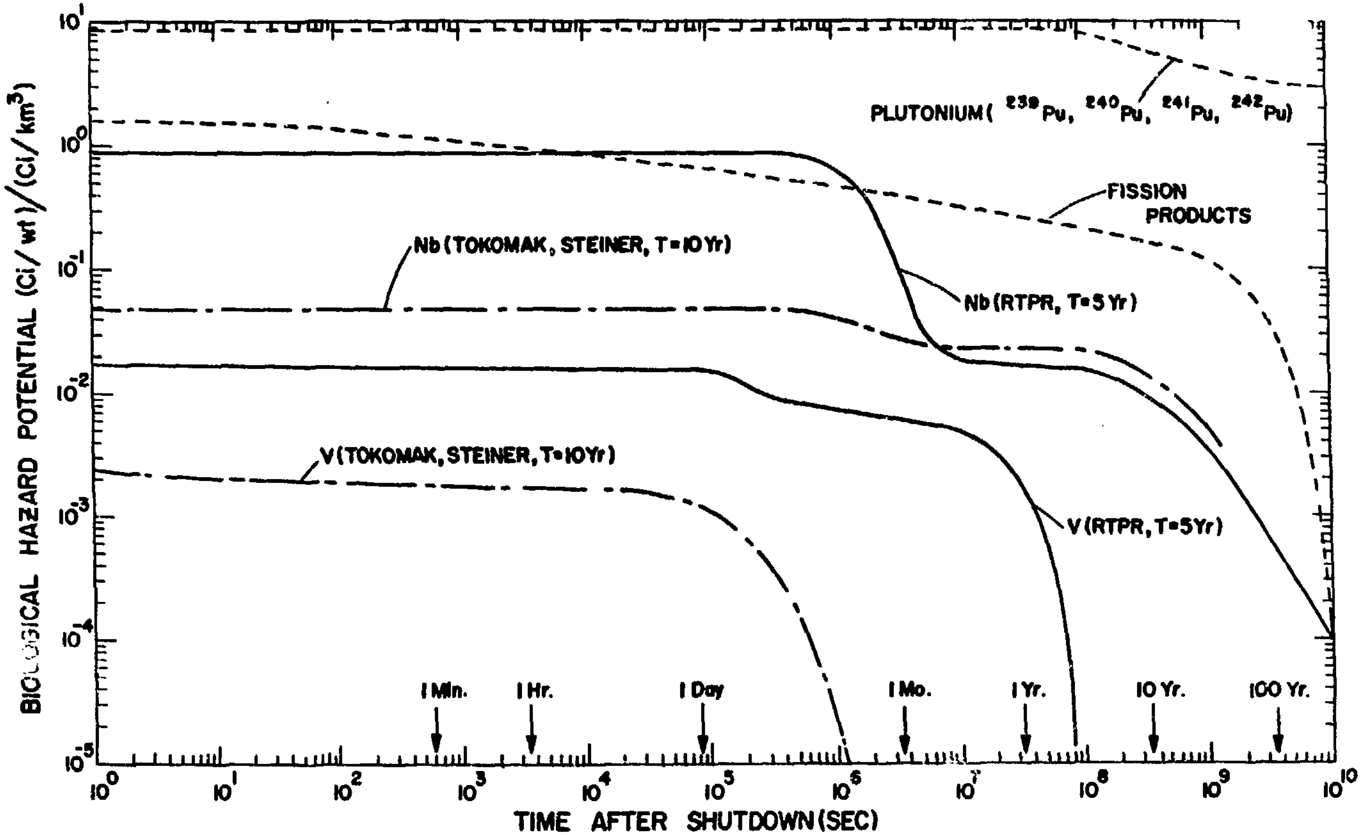

Fig. 11. Relative biological hazard potentials of induced activities in fusion and fission reactor plants after shutdown. The plutonium fuel is included in the fission case.

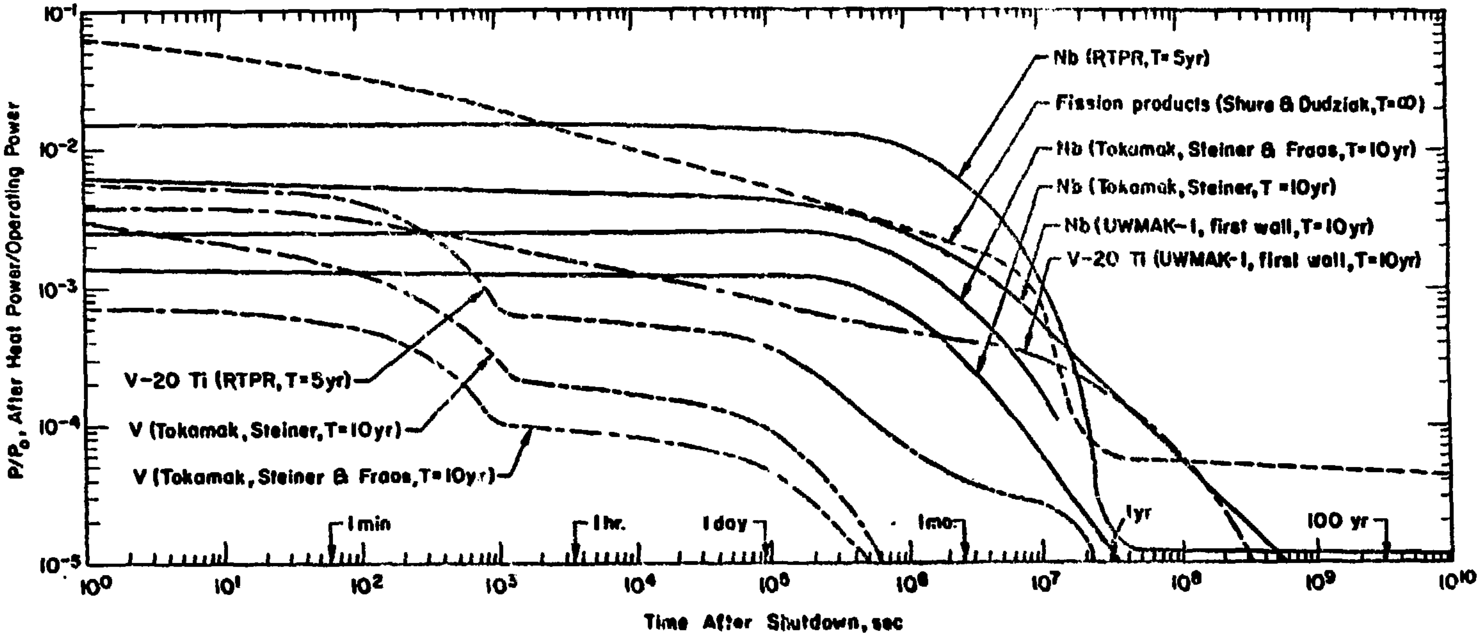

Fig. 12. Relative afterheat powers for fusion and fission power plants as functions of time after shutdown.