FUSION

SCIENCE • TECHNOLOGY • ECONOMICS • POLITICS

September 1982

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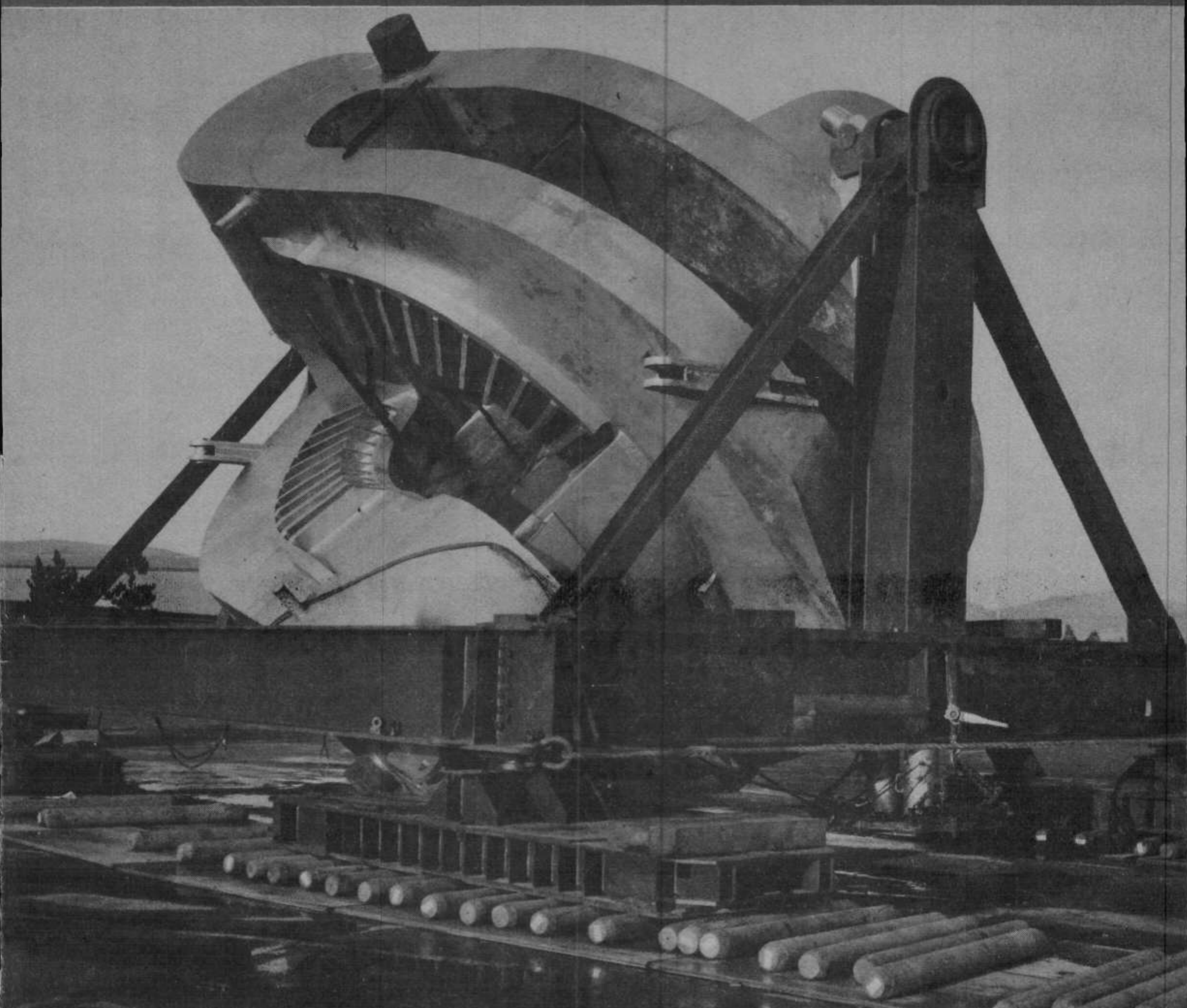
A Fusion Exclusive! Special Report On Polarized Fuel



New Fuel Promises Fusion by 1995

An Open Letter to Readers

At a time when "nuclear freeze" advocates are using antiwar rhetoric to promote a freeze on nuclear power plants, *Fusion* is not just a good magazine. It is the *only* science magazine fighting to continue the American tradition of progress.

The printing and mailing of our 1982 issues have been delayed because of our financial difficulties—difficulties that have been fostered by the same forces who bankroll the nuclear freeze and environmentalist movements.

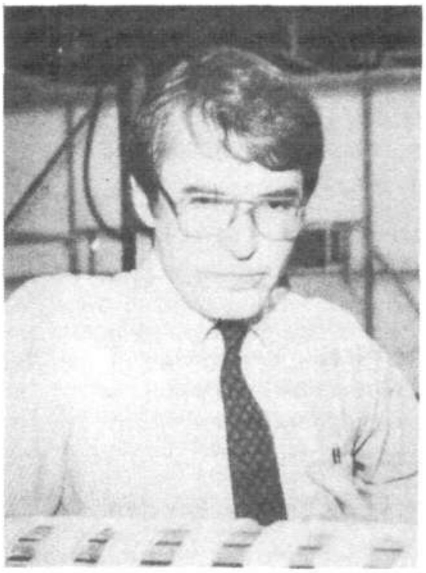
With this special format September issue, we resume regular publication. We also plan to publish more than one issue a month in order to send readers all the back issues we have prepared, dated January through August 1982, in this special shortened format. How fast we can catch up to our regular schedule depends on you.

With your financial help, we can win this fight for America, and get *Fusion* out regularly to its 200,000 readers.

- Join the Fusion Energy Foundation today. Memberships are $75 (individual), $250 (sustainer), and $1,000 (corporate).
- Send us a contribution to further our research and educational work and public lectures. Contributions to the FEF are tax-deductible.
- Donate subscriptions to your local schools, libraries, and legislators.

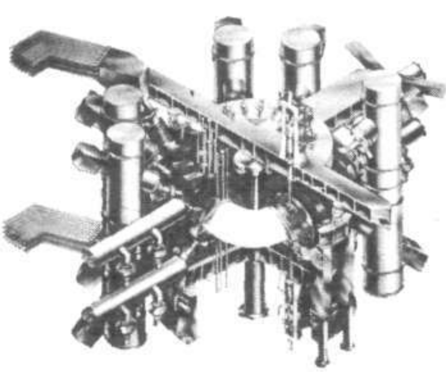
Paul B. Gallagher

Paul Gallagher, *Executive Director, Fusion Energy Foundation*



Prototype tokamaks could be operational in the United States before the 21st century, with the development of polarized fuel and with the kind of aggressive fusion development program that Japan has adopted. Presidential science adviser Dr. George Keyworth, however, would prefer to drag out fusion development for 70 years. Keyworth recently informed the Princeton Plasma Physics Laboratory that the lab must test polarized fuel within the resources of its existing budget (page 28).

Below, a model of Japan's JT-60 tokamak; above, Keyworth.



Front cover: One of the huge magnets for the tandem mirror experiment being moved from its fabrication site to the experimental building at Lawrence Livermore National Laboratory. The magnet, shaped like a baseball seam, acts as an end plug to confine the fusion plasma. Photo courtesy of LLNL.

New Fuel Promises Fusion by 1985

A special issue written by Dr. Steven Bardwell, Uwe Parpart, and Charles B. Stevens

From the Editor's Desk

This September 1982 issue of *Fusion* is doubly special. First, after a long absence caused by financial difficulties, this leading science magazine is able to reach its 200,000 readers. Second, this issue continues the *Fusion* tradition of bringing readers the most exciting news on the frontiers of science. As explained in these pages, polarized fuel could speed the arrival of the "plasma age" and make commercial fusion achievable five years earlier than is now possible. The significance of this accelerated schedule is momentous. For as *Fusion* and its publisher, the Fusion Energy Foundation, have argued for the past several years, it is only such advances or leaps in science and technology that can propel industry and the economy to more advanced levels. And, in turn, this increased capability allows an economy to support population growth at increasing standards of living—a process we call "progress."

It is precisely the possibility of such advances as polarized fuel—the opening up of an entire new era and a new, virtually unlimited resource base—that our zero-growth, Malthusian opposition is anxious to prevent.

We hope that this issue will mobilize our readership to support full funding for advanced science in the United States—and to support us. We have scheduled the printing and mailing of *Fusion* magazine more than once a month in this new format in order to provide subscribers with both current issues and the six back issues for January through August 1982. How fast we are able to do this and keep up our aggressive organizing campaign for advanced science is up to you.

Marjorie Mazel Hecht

Marjorie Mazel Hecht
Managing Editor

Abstract

Polarized Fuel—Threshold of a Second Industrial Revolution

This special issue of *Fusion* brings readers the first public report on a breakthrough in fusion research that could move up to 1995 the timetable for unlocking the cheap, clean, and unlimited energy of nuclear fusion. Scientists in research groups at the Princeton Plasma Physics Laboratory and Brookhaven National Laboratory have reported the theoretical demonstration of a new type of fusion fuel, called polarized fuel, which dramatically lowers the temperature and density requirements for fusion ignition. This new type of fuel takes advantage of the enhanced rate of fusion reactions that occur when the reacting fuel is magnetically aligned (polarized) to speed up desirable fusion reaction cycles and suppress undesirable cycles.

Our special report explains the scientific implications of the polarized fuel breakthrough and elaborates the major advantages and applications. The highlights of these are:

Enhanced reaction rates. The use of polarized fuel relaxes the temperature and density-confinement time conditions for fusion by a factor of approximately 1.5. The plasma conditions required for ignition of polarized fuel were, thus, already achieved in the Princeton Large Torus in 1978. The relaxed conditions mean that commercial fusion reactors can be smaller and simpler. The materials, magnetics, and control demands will be less strict. And the technological transition from fission to fusion will be correspondingly less difficult.

Control of reaction products. The advent of polarized fuel will permit first-generation fusion reactors to burn neutron-free fuels, such as deuterium-helium-3, which were previously considered for only second or even third generation reactors, because of their higher temperature and density requirements. The major technological difficulties facing fusion power development, which arise from neutron bombardment of the reactor wall and induced radioactivity, can thus be circumvented, and engineering requirements and materials development for reactors will be greatly simplified.

Advanced reactor designs. With early accessibility to neutron-free fuel cycles, the more advanced and efficient reactor designs become near-term candidates for development. These designs, such as the spheromak and reversed-field mirror machines, offer very advantageous plasma confinement possibilities.

The greatest promise of this new breakthrough is to accelerate the beginning of the plasma age. The energy created with polarized fuel is in the form of directed beams or particles, not a randomly moving exhaust. These beam forms of energy lend themselves very naturally to direct conversion energy technologies such as magnetohydrodynamics, which are twice as efficient as the conventional thermal cycle; to the generation of a fusion torch, which can economically process low grade ores and even ordinary garbage; and to propulsion technologies for space exploration and development. The full exploitation of the polarized fuel breakthrough will take us to the threshold of a second industrial revolution, transforming not only energy production but the entire sweep of materials processing and propulsion technologies.

FUSION
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The views of the FEF are stated in the editorials. Opinions expressed in articles are not necessarily those of the FEF directors or advisory board.

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Note to Libraries and Subscribers

To comply with postal regulations, the issues of FUSION in Vol. 5 are numbered in the order in which they were printed and mailed, not chronologically. Thus, September 1982, Vol. 5, No. 3, follows December 1981, Vol. 5, No. 2.

Subscribers who purchased a 10-issue subscription will receive all 10 issues. The FEF expects to publish 10 issues of FUSION in 1983; the six remaining 1982 issues—January through August—will be mailed to subscribers as soon as possible, but not necessarily in chronological order.

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The Economic Necessity of Developing Fusion Now

Since the oil crisis of 1973, the United States has chosen an energy policy based on permanent shortages, conservation, and resource control. At several critical junctures, strategic policy decisions have been made that rejected the technological and industrial potentials for producing more energy. Nuclear fission development has been slowed to almost zero; the congressional mandate for a massive nuclear fusion research program has been ignored by the Office of Management and Budget; the progress of the next generation of nuclear reactors has been almost completely stopped because of the cuts in funding for the high temperature reactor and the Clinch River Breeder Reactor; and fossil fuel development continues to lag behind the strategic requirements.

Instead, policies have been enacted that have enforced a situation of high energy prices, scarce domestic resources, and lagging technological innovation. Federal intervention has encouraged investment in economically and technically unsound energy technologies like large-scale solar energy and oil shale; government regulations have resulted in rising oil imports since the 1973 crisis; and malign neglect by the government has left the nation's nuclear industry crippled domestically and unable to compete internationally.

A Second Chance

The United States now has a second chance.

The latest theoretical development in thermonuclear fusion research, discussed at the international plasma physics conference in Stockholm in June, promises to bring commercial fusion power closer than ever before. It also makes it clear that the motivation behind the so-called science experts who want to push fusion development farther into the 21st century has nothing to do with science and everything to do with the politics of austerity. The question for the United States is why its President, Congress, and informed citizens have not chosen an energy policy based on adequate energy and advanced technology.

The man under the greatest heat of outrage should be the President's gloomy and pompous young science adviser, Dr. George Keyworth. Since taking office, Keyworth has everyone in the Department of Energy dutifully repeating that commercial fusion is "70 years away." Keyworth, it seems, plans to spend his whole life holding fusion at bay and protecting U.S. scientists from what he considers the evil influence of having funding to do research. At the same time, he wants to relegate the fusion program to "research only" on an indefinite basis.

This issue of *Fusion* is the first public announcement of a major scientific development that makes the promise of fusion even closer to technological realization.

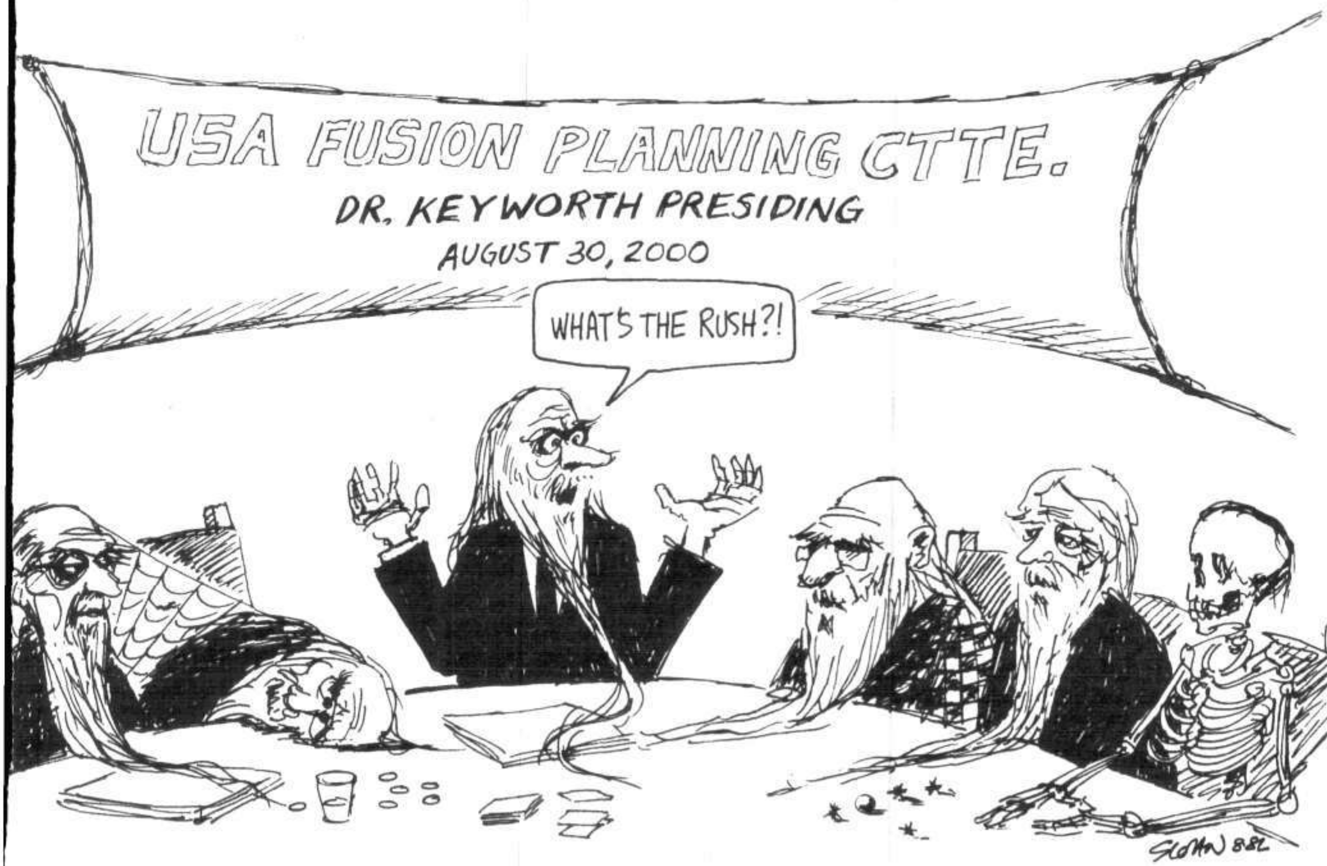
The proposed feasibility of "polarized fuels," discussed at Stockholm and now being tested in several countries, is an advance that would use the nuclear properties of the plasma fuel itself to enhance and "tailor" the desired qualities of reactions, reduce the temperatures needed to achieve them, and reduce the stresses they produce on reactor and other materials.

Yet, this announcement contrasted starkly with the overwhelming evidence at the Stockholm conference that the world's major civilian fusion research programs have been shrunk in real terms, except in Japan and India. In the United States, the Department of Energy, assured by Keyworth that it makes no difference anyway, has just instructed its fusion office to prepare for five years of the current, depressed budget.

Fusion Is Ready for Engineering

There is no shred of economic necessity to this chiseling. Fusion development in the United States, Europe, the Soviet Union, Japan, and elsewhere is now ready, by all unbiased assessments, to enter the stage of hands-on engineering: reactors, materials, special fuels, methods of conversion to electricity, process heat, and isotope separation.

With the breakthrough of polarized fuels, advanced second generation reactor design can become simpler and the entire process of learning to "engineer" fusion looks much easier and faster than



before. The implications of these continuing advances probably mean that Japan's fusion planners are right to set 1993—not 2000—as the earliest feasible date for putting operating fusion reactor prototypes on line; and uses of fusion processes to breed fission fuel and separate valuable isotopes can come even sooner. It means that virtually everyone living today, and certainly all of their children, *could* live to see the beginning of the fusion, or plasma, age.

That is economic necessity.

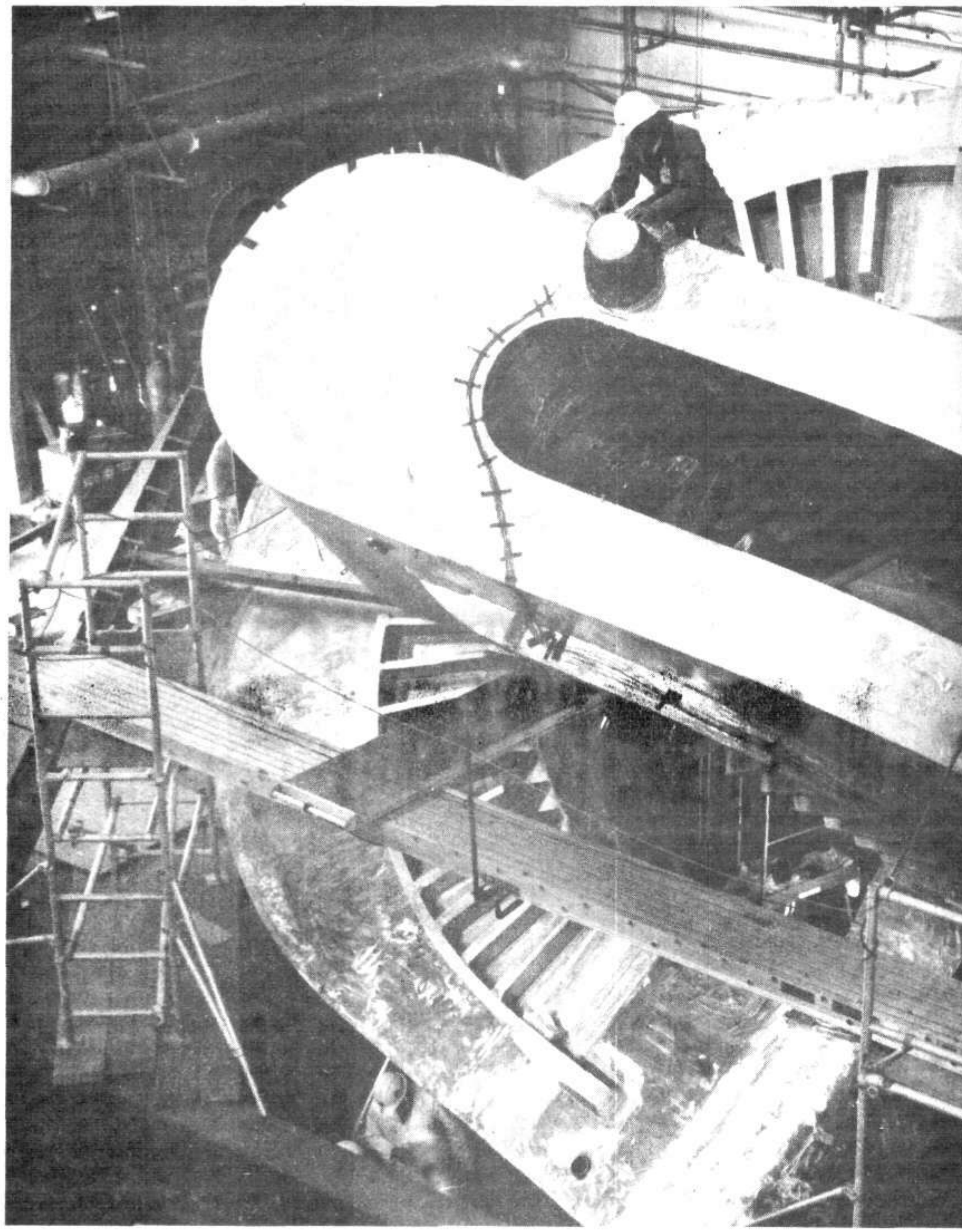
The vast energy deficit of the underdeveloped nations, rapidly worsening since 1965 because of the failure of the United States and other industrial countries to spread the benefits of nuclear fission power, has already cost the lives of 115 million people, by the most conservative methods of estimation, due to the resulting economic collapse in those nations. For failure to develop those nations or even to save them from collapse, the industrial countries have suffered stagnation and then economic decline, none worse than the United States.

The underdeveloped countries of the world currently suffer a total electrical energy deficit, relative to moderate current industrial standards, on the order of 3,000 gigawatts of capacity, a deficit larger than total world electricity capacity now.

This deficit and the lack of productive infrastructure associated with it are the intractable causes of worsening economic and social chaos, genocidal wars, and financial defaults spreading through Latin America, Africa, and Asia today. Closing that vast energy and related infrastructural deficit would revive the prostrate economies of the United States and Europe: It will take a net growth rate in electrical energy production of 7 to 10 percent per year for the rest of this century.

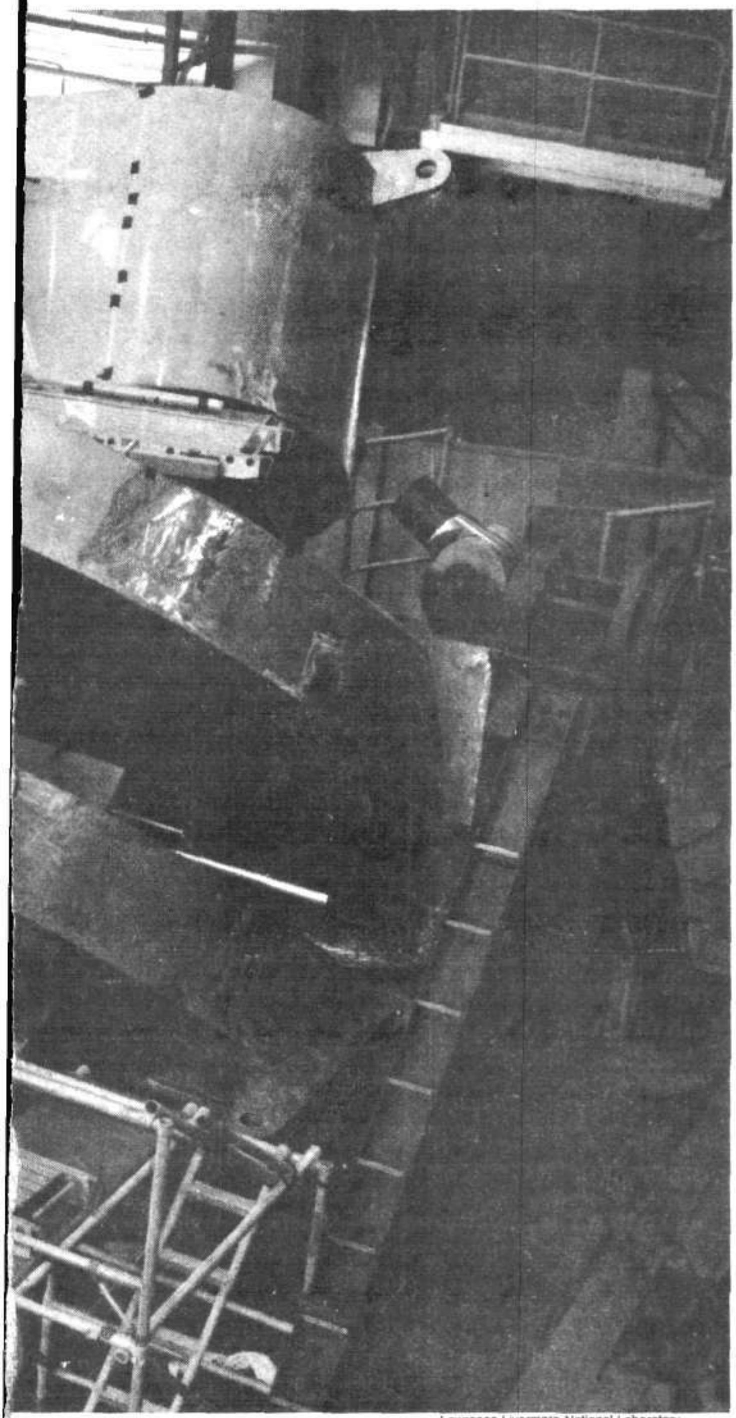
Only nuclear energy, which we promised the world in 1946 and never delivered, can launch this necessary rate of growth; only nuclear fusion energy can carry it past the 1990s.

New Fuel Promises Fusion



A technician works on the giant baseball magnet for the Tandem Mirror Fusion Test Reactor under construction at Lawrence Livermore. The tandem mirror design is one that should benefit greatly from polarized fuels.

by 1995


Lawrence Livermore National Laboratory

Introduction

As early as the 1930s, it was noted that the rate at which the nuclei of hydrogen or other substances undergo nuclear fusion reactions depends in significant part on an attribute of the nuclei (as well as of the surrounding electrons) called *spin*. The terminology, first developed by G. Uhlenbeck and S. Goudsmit in the early days of quantum mechanics (1925) in an attempt to account for the structure of complex spectra, is intended to suggest a self-rotation of the particles much like that of a spinning top. Since the particles are assumed to be electrically charged, their spin confers on them a certain magnetic moment, proper spin alignment yielding magnetic polarization (*spin polarization*), and enhanced particle attraction or repulsion. This picture is admittedly oversimplified and—as we shall argue below—at least partially misleading; however, it should succeed in conveying the basic idea: that spin polarization affects nuclear reactions.

This, as we said, is not new. However, it was generally assumed that the depolarizing mechanisms in a magnetic fusion reactor would be so strong and come into play so rapidly that the reaction-enhancing effects of spin polarization could not make themselves felt.

Now, a recent, unpublished Princeton Plasma Physics Laboratory report titled "Fusion Reactor Plasma with Polarized Nuclei," coauthored by R.H. Kulsrud, H.P. Furth, and E.J. Valeo of Princeton and M. Goldhaber of Brookhaven National Laboratory, argues that the conventional wisdom of fusion researchers regarding polarization is mistaken, that "the mechanisms for depolarization of nuclei in a magnetic fusion reactor are surprisingly weak," and that reaction enhancement factors of 1.5 for the deuterium-tritium (D-T) reaction and of 2.5 for the deuterium-deuterium (D-D) reaction can be expected from the use of polarized fusion fuel.

If experimentally verified, these new theoretical results will have the most far-reaching consequences for the U.S. and worldwide fusion programs. The two most immediately foreseeable ones are:

(1) Since the rate at which nuclear fusion reactions occur in a fusion plasma is roughly proportional to the plasma temperature, enhanced reactivity resulting from polarization means that a satisfactory number of reactions can be achieved at considerably lower temperatures than assumed so far. To put it more dramatically, the temperature already achieved in existing experiments is sufficient for scientific breakeven—the condition of producing enough fusion energy output to at least balance the energy input into the fusion plasma.

(2) The ultimate goal of fusion researchers has always been to produce a preponderance of charged particles rather than high-energy neutrons among the fusion reaction products. This would make possible *direct conversion* of the reactor output into electricity by simply collecting the charged particles at opposing electrodes. The entire "first wall" problem, of stopping the high-energy neutrons

in a steel-alloy wall, and then of removing the generated heat by means of coolants that drive a turbine, and so on, could be dispensed with. Reactor engineering problems would be greatly reduced, and there would be dramatic gains in reactor economy resulting from a large jump in conversion efficiency. However, the D-D or other advanced fuel reactions necessary for direct conversion were not assumed to be attainable in the first or even second-generation reactors, because of the extremely high temperatures required. Polarization could change all that. The reaction enhancement factor of 2.5 for the polarized D-D reaction would bring temperatures down into the range now thought necessary for D-T reactions and thus make advanced fuel direct-conversion schemes potentially realizable with first-generation reactors.

Moving to Advanced Fusion Fuels

The most important and far-reaching consequences of the utilization of polarized fuel are, in fact, virtually all derivable from the promise of moving to advanced fuels at an early point.

Since polarization allows not only for the enhancement but also for the selective suppression of certain reactions, the combination of polarization and advanced fuels will allow the precise "tailoring" of the fusion reactor output for purposes of electricity production on a broad spectrum of high temperature industrial applications.

Only this possibility of being able to access at will the full spectrum of electromagnetic radiation in an enormous range truly unlocks and defines the full potential of controlled thermonuclear fusion: Fusion will not just be a more advanced nuclear energy source; comparable to the role of the steam engine at the beginning of the 19th century, fusion defines the scientific and technological basis for a second industrial revolution.

The relevant point in economic theory, as developed quantitatively in the recently completed LaRouche-Riemann model of the "physical economy" (charting the trajectory of economic development in energy and population terms), is this: Long waves or epochs of economic development are defined as potential surfaces representing maximum average population densities. The density potentials, in turn, are defined as relationships between the major prevailing technologies and the total resource base accessible by means of these technologies. To quantify the productivity impact of given technologies on the economy, the new LaRouche-Riemann model employs as its principal parameters the energy flux density of the production technology in use—be that in energy, industrial, or agricultural production. It is in this context that the revolutionary significance of fusion, and specifically polarized, advanced fuel-based fusion, is best understood. Compared to present circumstances, it will give us relatively cheap access, both for energy and industrial production, to energy flux densities and temperatures many orders of magnitude greater than what is in use in our present mechanical-thermodynamical age, a jump similar to the one occurring at the beginning of the previous century.

Or, to put it differently, in terms of the type of forces of nature exploited, we are entering into an epoch in which energy and industrial production will be increasingly determined by the exploitation of nuclear forces rather than by the six-orders-of-magnitude-weaker molecular binding forces. Note, however, that deuterium-tritium fusion alone, with its energy output almost exclusively in the form of neutrons instead of charged particles, will not permit us this enlarged new technological epoch. Neutrons are extracted at relatively low temperatures, and still would mainly be used to boil water, much as we have done with the output of other energy sources for several centuries.

The Theoretical Challenge

Polarized fusion not only promises considerable speed-up in the timetable for fusion power development; it also poses the kind of challenge to theoreticians that neither plasma nor nuclear physicists are usually likely or eager to confront. In the first instance, the Kulsrud-Furth-Valeo-Goldhaber paper demonstrates the extent to which even rather modest theoretical contributions from the realm of nuclear physics can yield unexpectedly large dividends when combined with and considered in the context of a well-defined plasma physics problem. Clearly this is a most persuasive argument for greater collaboration between the two disciplines. And much as plasma physics will benefit from the intrusion of nuclear physics, the extent to which a beneficial effect in the opposite direction is possible is potentially much larger, if nuclear and particle physicists could be persuaded to consider more prominently the *collective effects* and *global modes* (that is, topological characteristics) that plasma physicists—however reluctantly—have found it necessary to confront.

Second, the great practical significance of spin-polarization for fusion puts the limelight on a host of theoretical problems, which most nuclear and particle physicists would prefer to have nothing to do with and thought they had safely put to rest at least 25 years ago. Since the death of that nasty nag Wolfgang Pauli, hardly anyone has been willing to raise the necessary penetrating questions concerning the foundations of quantum electrodynamics intimately connected to the problems of spin and the infinite energy of the electron, problems that today seem to bother no one except perhaps the ancient P.A.M. Dirac.

We will have more to say about that below. For now it will suffice to say that the broadest theoretical significance of spin-polarization in the fusion process lies in its potential analogy to phenomena such as superconductivity, where a phase change imparts a vastly higher degree of organization to the physical substance in question, which defines new macro-characteristics not derivable from simple summing up of local interactions. We expect a fully polarized fusion fuel to exhibit qualities that reflect a global (or topological) nonlinear change in comparison to a partially polarized plasma, qualities not immediately predictable from a linear increase in the probability of two-particle reactions proportional to the "number" of polarized nuclei.

Prospects for Fusion by 1995

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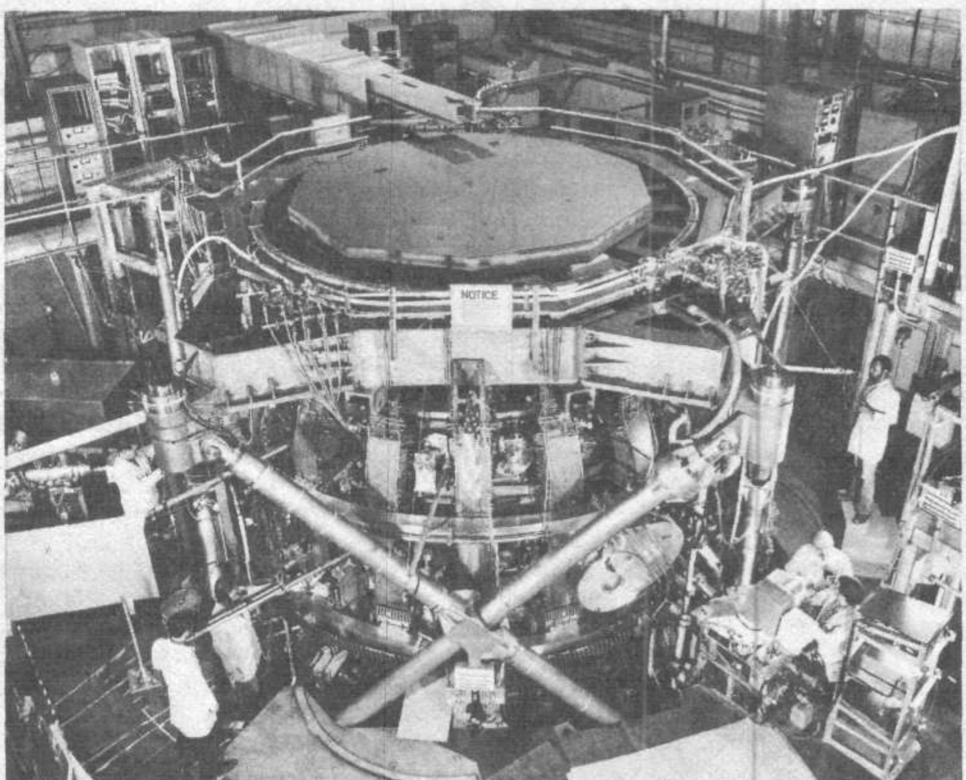


Princeton Plasma Physics Laboratory

The Poloidal Divertor Experiment (PDX) at Princeton Plasma Physics Laboratory, shown with its auxiliary neutral beam heating equipment.

Nuclear fusion has been called the ultimate energy source. Using the same energy generation mechanism as the stars, nuclear fusion produces energy more intensely, at higher temperatures, and in more different forms than any other form of energy known. The fuel for fusion is the various light elements, hydrogen and helium being the most important. The three fuel cycles most attractive for fusion energy generation are:

deuterium + tritium → helium-4 + neutron
deuterium + tritium → helium-3 + neutron
deuterium + deuterium → tritium + hydrogen
deuterium + helium-3 → helium-4 + hydrogen

The common ingredient in all these fuel cycles is deuterium, a doubly heavy form of hydrogen that occurs naturally; approximately 1 out of every 6,000 hydrogen atoms has a deuterium nucleus. This isotope of hydrogen shares all the chemical properties of normal hydrogen but has different nuclear properties. The energy attainable through the deuterium-deuterium cycle from a quart of water is equivalent to that produced by 300 gallons of gasoline. It is estimated that there is enough deuterium in the ocean to last 100,000,000 years at 100 times the present rate of energy consumption!

The rate at which a given mixture of fusion fuels will "burn," or fuse, is determined by the temperature of the reactants, the density of the fuel mixture, and, scientists have only recently stressed, the magnetic alignment, or polarization state, of the fuel. The accompanying table summarizes the conditions that must be achieved in a standard design of a fusion reactor using each of these fuel cycles. The temperature conditions listed combined with density conditions would result in what is called a breakeven plasma; that is, a fuel mixture (at these temperatures in an electrically charged, gaseous state called a plasma) that returns as much energy from the ignited fusion reactions as was required to create ignition conditions.

Figure 1 shows the historical progress made by the United States toward the breakeven point, for both polarized and unpolarized D-T cycles. Note that exponential progress has been maintained for almost 30 years in this research project and that, for the polarized D-T cycle, breakeven conditions were reached by the Princeton Large Torus in 1978.

A New Degree of Freedom

The primary approach to achieving the required temperature and density conditions uses the electrical properties of the plasma fuel itself to contain and heat the fuel with magnetic fields. Since the electrically charged fuel nuclei are deflected by a magnetic field, a *force field* can be created that insulates the fuel from the cold (that is, room temperature) containment vessel. A toroidal magnetic field configuration, the tokamak, is by far the most advanced design for such a fusion device, and the points shown on the graphs are all taken from recent tokamak experiments.

The use of polarized fuel adds a new dimension, a new degree of freedom, to the quest for fusion energy. Previously, only the temperature, density, and closely related quantities could be varied in tokamak experiments to achieve fusion ignition. It was known that the actual fusion reactions that occurred were overwhelmingly those between particles with the appropriate magnetic alignment, or spins. In the case of a conventional, unpolarized fuel, as many as half the collisions took place under unfavorable alignment conditions, and so only rarely resulted in fusion. The use of polarized fuel, on the other hand, creates a situation in which almost all the collisions between fuel nuclei occur under favorable conditions of magnetic alignment and, depending on the fuel cycle, increasing the *net* reaction rate by a factor between 1.5 and 2.5.

Using technologies described in part 2 of this report, the spins of the fuel can be aligned, and the auxiliary heating of the plasma (accomplished with beams of fuel particles) can also be polarized. The resulting mixture of polarized fuel provides the optimal conditions for ignition. However, there is one serious problem—a problem that seemed so overwhelming that scientists had not considered the possibilities of polarized fuel for many years: In the extreme temperatures and external magnetic fields of a fusion plasma, would not the polarized fuel quickly lose its state of higher organization as each particle underwent millions of collisions?

TEMPERATURE REQUIREMENTS FOR FUSION BREAKEVEN*
in degrees Kelvin

Fuel Cycle	Unpolarized	Polarized
D-T	100,000,000	80,000,000
D-D	350,000,000	220,000,000-300,000,000
D-He^3	700,000,000-1,000,000,000	400,000,000-500,000,000

*Assuming standard tokamak conditions for density-confinement time.

At first sight, the answer to this question seems to be an emphatic yes. But the more recent analysis done by a group at the Princeton Plasma Physics Laboratory (J. Kulsrud, H. Furth, and E. Valeo) and one at Brookhaven National Laboratory (Maurice Goldhaber) demonstrated that neither of the two mechanisms thought to depolarize the fuel would in actuality do so. First, it had seemed obvious initially that the collisions that result in the fusion of nuclei would also, when fusion did not occur, result in the disruption of the magnetic alignment of the colliding nuclei. However, a simple calculation done by these scientists showed that by far the predominant kind of collision, a collision governed by the electrostatic repulsion between the particles (called a Coulomb collision), cannot disturb the magnetic alignment of the nuclei. That is, this physical interaction does not affect the magnetic spin properties during the collision.

Second, it had also seemed obvious that the strong and rapidly changing magnetic fields that occur in a plasma would themselves act as random polarizers and rearrange the polarization of the fuel in a very short time. But detailed calculations of the effect of these magnetic fields on the magnetic alignment of the nuclei showed that they, too, were incapable of affecting the direction of spin of the fuel. The scientists summed up their results in stating that the depolarization time of a fusion plasma is much greater than the ignition time; that is, a fusion plasma at ignition conditions will burn a long time before it depolarizes.

These theoretical arguments are currently being tested in laboratories in the United States and other countries and the experiments should be completed by early 1983. There is almost complete confidence in scientific circles that these experiments will confirm the following hypotheses.

(1) Polarized fuel enhances reaction rates of all fuel cycles, in bulk plasma as well as in individual collisions (an already demonstrated fact). These enhancement factors are:

D-T increases by a factor of 1.5
D-D increases by a factor of 2.5
D-^{3}He increases by a factor of 1.5

(2) The depolarizing mechanisms in a fusion plasma, specifically Coulomb collisions and magnetic field fluctuations, are too weak to depolarize the fuel on time scales less than the ignition time.

An Historical Comparison

Scientists have compared the current situation in fusion research to that which prevailed in the development of nuclear fission in the late 1930s and early 1940s. At that time, the phenomenal energy potential of the nuclear fission of uranium had been proven in the laboratory, but the question remained as to whether such a fissioning process could be made self-sustaining. Specifically, the problem was: A neutron would cause a uranium nucleus to split and release both energy and additional neutrons,

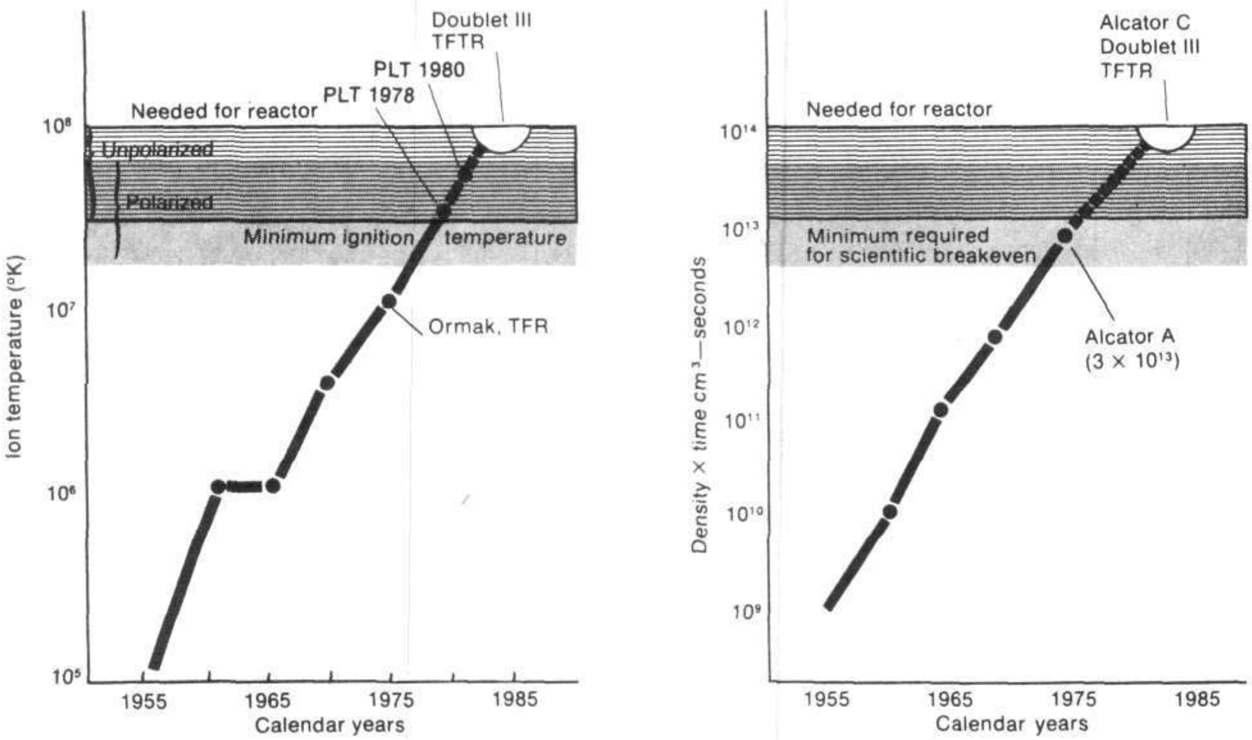


Figure 1
PROGRESS IN U.S. MAGNETIC CONFINEMENT EXPERIMENTS

In the past two decades, the U.S. magnetic confinement fusion research program has made dramatic progress toward achieving the plasma conditions necessary for ignition. This progress has been exponential, as shown in the graphs of the two key parameters for measuring progress toward plasma ignition. These parameters are temperature and density-confinement time.

The development of polarized fuels lowers both conditions as shown. For polarized fuels, breakeven conditions have already been achieved in tokamaks in the United States.

but were enough additional neutrons released in the fission process to keep the reaction going? That is, was a chain reaction possible? This question was studied simultaneously by scientists in the United States, Germany, and France. In the early 1940s, the scientists all reached the same conclusion—namely, that individual uranium fissionings would release three more neutrons, probably enough to create a chain reaction.

This theoretical prediction was to be tested two years later in Enrico Fermi's famous "Chicago Pile," in which the first chain reaction of bulk uranium was created and controlled.

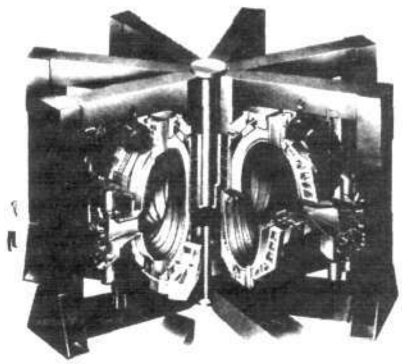
Today we stand at the same point in the development of fusion. The theoretical possibility of a much simpler, and more easily achievable, self-sustaining fusion reaction has been demonstrated; the data from individual fusion reaction experiments are absolutely clear in showing the importance of nuclei polarization. The remaining experimental question is: Can a bulk plasma be created that retains this polarization-enhanced reaction rate, the rough equivalent of the chain reaction for a fission reaction?

Applications of Polarized Fuel

The advantages of polarized fusion fuel fall into three different areas: (1) the enhancement of reaction rates and relaxation of ignition requirements; (2) the ability to control reaction products and tailor energy forms; and (3) the possibility of using advanced reactor designs and energy extraction techniques.

(1) *Enhanced reaction rates.* The enhancement of the reaction rates for all fusion fuel cycles dramatically changes the timetable for realization of fusion energy for commercial production of electricity. The most aggressive projection for the large-scale application of fusion for electricity production is that of the Japanese. Their fusion research project is planned to operate a commercial prototype fusion reactor, producing 150 megawatts of electrical energy, by 1993. This prototype reactor would then be

Joint European Torus (JET)



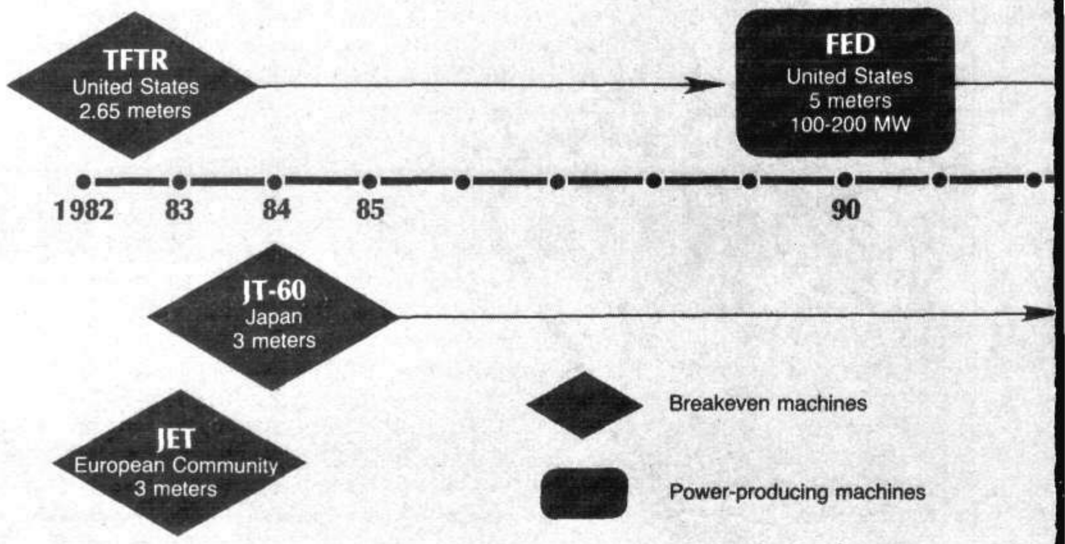


Figure 2
FUSION TIMETABLE
WITH UNPOLARIZED FUEL CYCLE

This timeline shows the scheduled date of operation and some major parameters for the next generation of fusion experiments and the planned engineering/test reactors and commercial prototypes. In the United States, the Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory, a breakeven machine that is expected to burn conventional D-T fuel after several years, is now expected to be succeeded by the Fusion Energy Engineering Device (FED) in 1990. The Magnetic Fusion Energy Engineering Act of 1980 mandates a commercial prototype fusion reactor by the year 2000.

Japan's JT-60 is designed to achieve breakeven using all deuterium fuel. It will be succeeded by an Engineering Power Reactor, which will, in effect, skip over the previously planned Engineering Test Facility. The JET is the Joint European Torus of the European Community. The machines are compared in terms of the size of their major radius (the long way around the torus).

scaled up to a reactor for export by the year 2000. This aggressive schedule has been confirmed by numerous U.S. government and private studies, which have stated unequivocally that the world's fusion effort (with the exception today of the Japanese project) is limited by funding, not by technology.

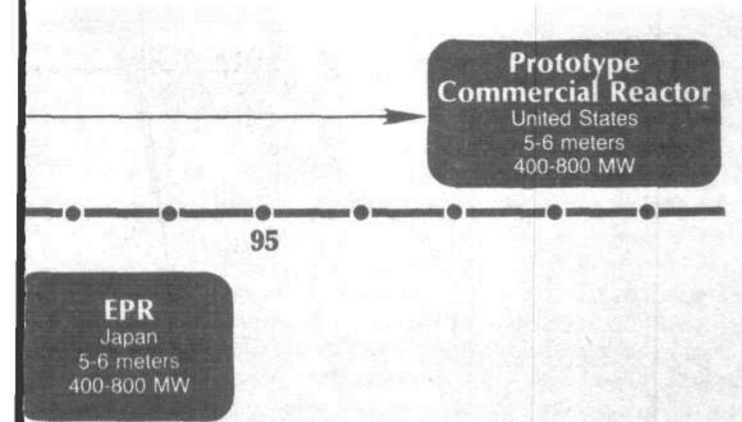
This fact was recognized by the U.S. Congress in October 1980 when it passed by an overwhelming margin the Magnetic Fusion Energy Engineering Act of 1980 (the "McCormack Bill"), mandating an accelerated U.S. program with the goal of achieving a commercial prototype reactor by the year 2000. This act has not been enforced, and the funding for the U.S. fusion program has actually been cut since the passage of the bill.

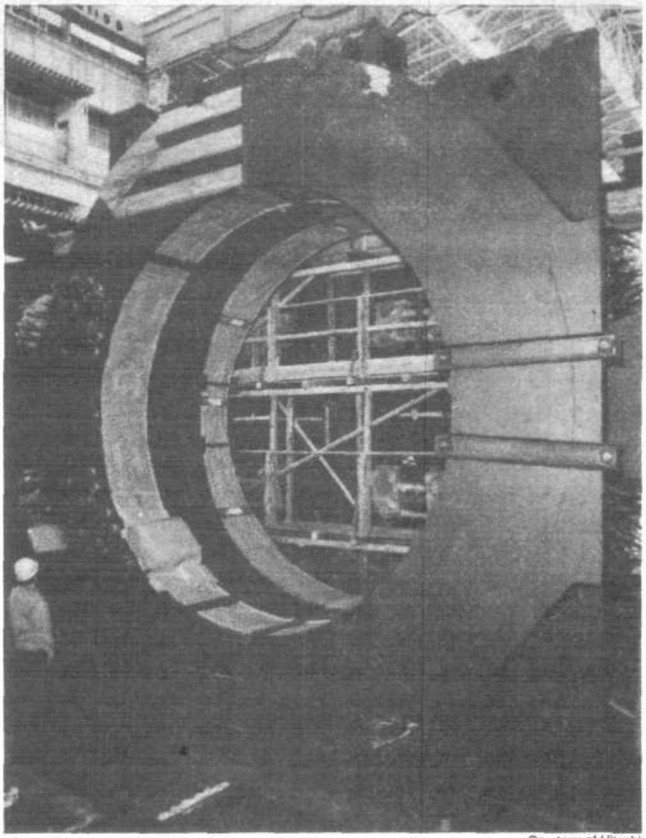
With the advent of polarized fuel, this already medium-term projection for the realization of fusion is significantly speeded up. Estimates are that the relaxation of plasma conditions made possible by the increased reaction rate of polarized fuel would enable a prototype reactor to be built before the end of this decade, and a commercial reactor to be built seven to eight years after that.

The plasma conditions in the next generation of fusion experiments would be very close to those required for a fusion reactor. These machines (the TFTR at Princeton, and the JT-60 in Japan, both scheduled for completion during 1983) were designed to be breakeven machines for the conventional D-T fuel cycle. In addition to achieving the plasma conditions necessary for ignition of D-T, they were to be modified after several years of operation, to actually burn this fuel.

With the development of polarized fuel cycles, however, this experimental program could be modified to shorten considerably the initial plasma demonstration period, and to proceed much more quickly to the actual ignition testing. Since the machine would now be operating not merely in the ignition range, but actually with plasma conditions similar to those in a reactor, the engineering schedule could essentially skip over one stage of experimentation.

Based on previous considerations, fusion scientists expected that TFTR would be followed by an engineering device (the Fusion Engineering Device, or FED) and, only after that step, a prototype commercial reactor would be built by the year 2000. However, by using polarized fuel and modifying the next generation of experiments—TFTR and the JT-60—it may be possible to move directly into a





Courtesy of Hitachi

With polarized fuels, plasma conditions in the next generation of fusion experiments would be close to those required for a commercial reactor. Shown here, the toroidal field coil for Japan's JT-60 tokamak.

commercial prototype by 1995, conservatively speaking (see Figure 2).

This speed-up in the possible experimental program leading to fusion would obviously be possible in all branches of magnetic fusion, not only in the tokamak schedule described above. The magnetic mirror machines, which have shown remarkable progress in the past several years, would also be accelerated, as would be the whole family of more speculative devices. With the plasma conditions so much easier to achieve, it is quite possible that the engineering advantages of some of the alternative approaches to fusion would compensate for their present inability to achieve the ignition conditions for conventional fuels. Thus, the Elmo Bumpy Torus, the reversed field pinches, and the stellarators—all of which have significant engineering advantages over tokamak designs, but have not as yet demonstrated a comparable ability to control a heated fusion plasma—might leapfrog the tokamak for a second-generation polarized fuel burner.

In any case, there seems little doubt that the use of polarized fuel in a fusion reactor allows the schedule for development of fusion to be accelerated by at least five years.

(2) *Control of reaction products*. The most significant engineering challenge posed by fusion devlopment is that of perfecting materials capable of withstanding the intense bombardment by neutrons from the fusion reaction. These neutrons cannot be controlled by the magnetic field (because they are not charged) and so are absorbed in the containment vessel and shielding blankets of the reactor. Indeed, the main factor limiting the technologically achievable energy density in a fusion reactor is the inability of conventional materials to withstand bombardment by energetic neutrons. The main advantage of the so-called advanced fuel cycles, especially the D-^{3}He cycle, is that they should theoretically produce fewer neutrons and, correspondingly, more charged particles.

However, conventional advanced fuel cycles are able to deal with the neutron problem in only a partial way because of the systematic inability to control the fusion process itself. Present-day fusion energy is frequently referred to as *thermonuclear* fusion since it is usually assumed that the fusion reactions take place in a random way in a randomized plasma—a condition that is called *thermal*. Polarized fuel changes this condition in two essential ways. First, the products of the fusion reaction (the ^{4}He particles and the neutrons of the fuel cycle reaction products) are produced in a *preferential direction* out of the fusion reaction. In conventional fuels, the reaction products come out uniformly in all directions because there is no preferred direction to the reacting nuclei and no imposed directionality in the reaction itself. This situation is changed in the case of polarized fuels, with the result that the reaction products are produced with a preferential direction, in the form of a loosely bunched beam of particles. The implications of this important fact we turn to below (see page 16).

Second, the kind of fusion reactions that occurs can be controlled by the polarization. Consider the case of the D-^{3}He fuel cycle. In a plasma consisting of this fuel mixture, it is clear not only that the D-^{3}He reaction will occur, but also that the D-D reaction will occur. With conventional fuels there is no way to control the additional reactions. With polarized fuel, on the other hand, a whole new degree of freedom is introduced into the fusion process that enables us to control to a large extent not merely *when* the fusion reaction happens, but *what* reactions happen.

Since the basic nuclear physics interaction involved in the fusion process is enhanced when the spins of the species to fuse are oppositely directed, consider the result of igniting a D-^{3}He plasma in which the deuterium nuclei are polarized in one direction and the helium-3 nuclei in the other direction. The D-^{3}He reaction will be enhanced. This is desirable because the D-^{3}He reaction produces no neutrons. On the other hand, the D-D reaction will be suppressed (since all the deuterium nuclei have the same polarization). Thus, we can separate the two cycles using the polarization of the nuclei and eliminate almost entirely the neutron production of this cycle.

The suppression of neutron production in a fusion reactor simplifies the engineering of a commercial reactor in a number of interconnected ways.

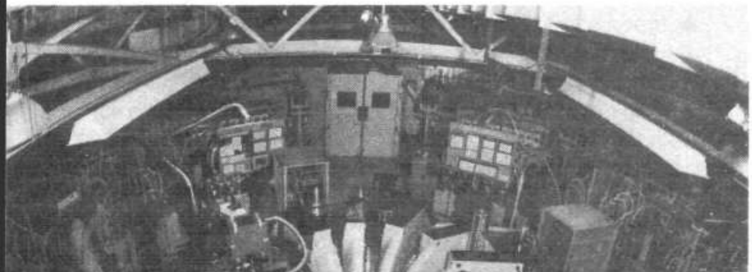
(a) The neutron activation and induced radioactivity of the reactor vessel is reduced to almost zero. First-generation tokamaks were projected to require remote maintenance (because of the large, but short-lived, radioactivity produced in the immediate vicinity of the plasma) and related radioactivity-control technologies. This radioactivity is solely a result of the neutron production, since the fusion reaction itself produces very little radioactivity in the biologically relevant sense. Without the neutrons, essentially all radioactivity concerns are eliminated.

(b) The shielding for both biological and machine protection is eliminated. Since the immediate flux of neutrons is itself dangerous, large amounts of shielding must be provided to protect people, magnets, computer equipment, and the like associated with a fusion reactor. Without the neutrons these problems are vastly simplified.

(c) The extraction of energy from the plasma, which requires a complex lithium or sodium blanket with conventional fuels, is eliminated. The neutrality of the neutrons makes it difficult to extract their energy of motion, but the charged particles produced in the advanced fuel cycles can be converted to electricity in a variety of very efficient ways.

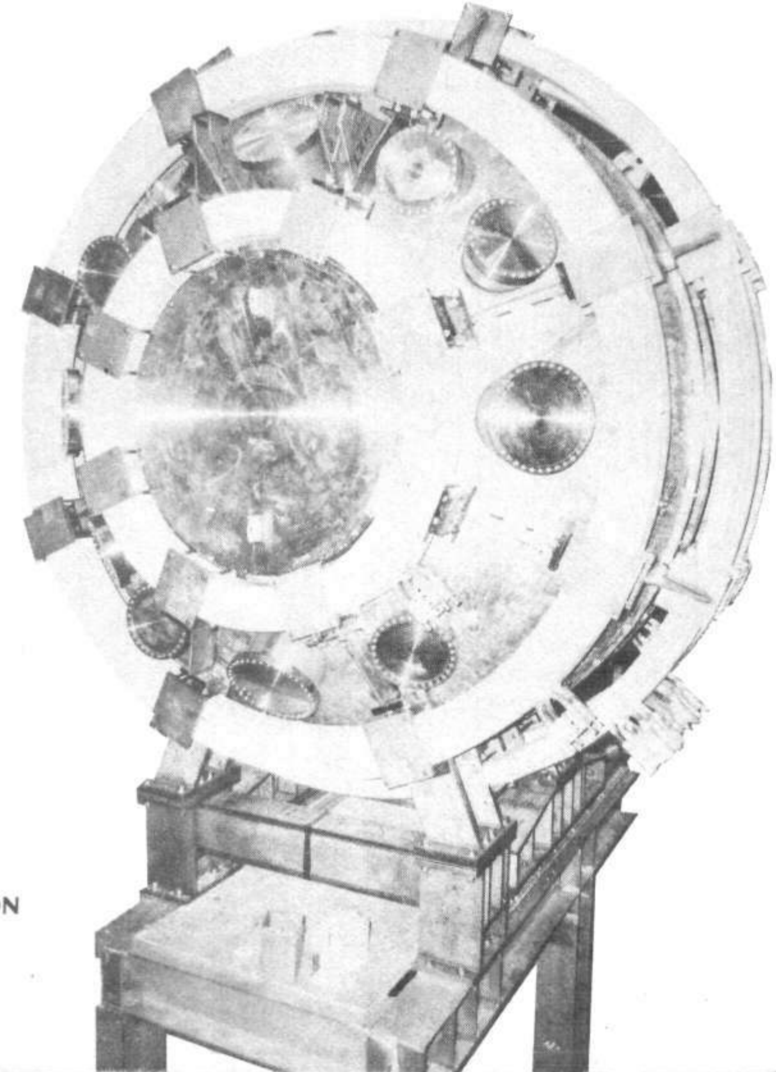
All of these factors make the ability to tailor the output from a fusion reaction a very powerful tool. There are, of course, some fusion reactor designs that require a large flux of neutrons, the fusion-fission hybrid, for example. This device uses the intense neutron flux of the fusion reaction to convert normal, unfissionable uranium into plutonium (or a similar conversion process starting with thorium). In this reactor, polarized fuel probably the D-T cycle would be used precisely because it increases the reaction rate and hence the production of neutrons. The essential point is that polarization provides a new degree of freedom for control and shaping of the fusion process that allows us to generate many kinds of fusion energy, not merely electricity.

(3) *Advanced reactor and energy conversion*. Fusion, like fission, is not a single technology, but rather a succession of increasingly complex and flexible machines and techniques for energy production in all its aspects. Many engineers project, in fact, that the greatest impact of fusion energy will be not in the production of electricity but rather in the production of synthetic fuels, cheap



Los Alamos National Laboratory

The Los Alamos ZT-40 reversed field pinch, whose geometry exploits the self-organizing properties of the fusion plasma, provided a series of spectacular, unexpected results recently.



process heat, and intense beams of high energy particles. The use of polarized fuel has a dramatic impact on each of these longer term applications of the fusion process, an impact that depends on the uniquely ordered and controllable form in which the polarized fuel produces energy.

The second and third generation of fusion devices projected on the basis of conventional (unpolarized fuels) were all chosen for their attractive engineering and maintenance features and for their flexibility in the production of different forms of fusion energy. These reactor designs include:

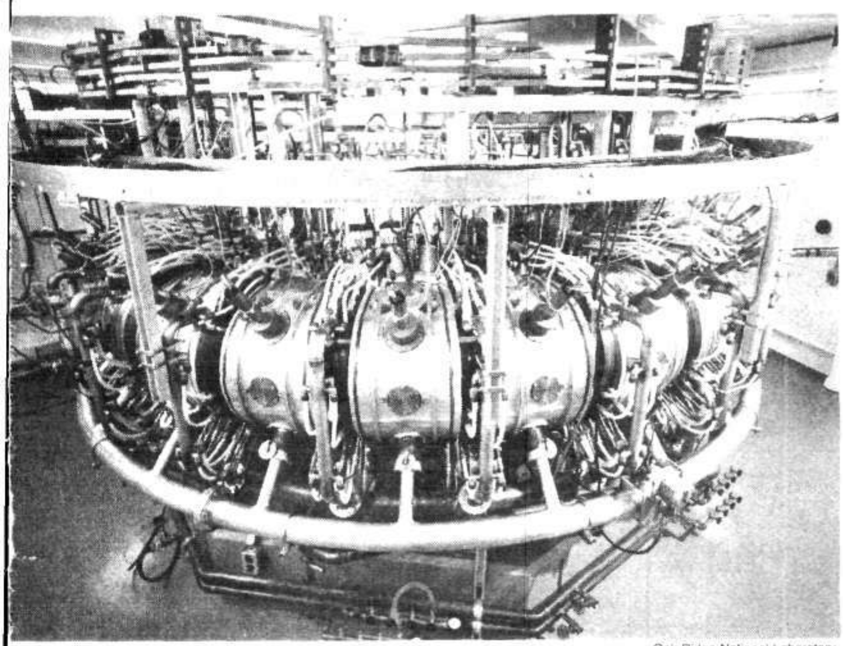
(a) The reversed field pinches. These machines make use of the plasma's inherent ability to create and sustain its own magnetic field. They are among the most efficient producers of plasma magnetic fields and so require small (and easily manufactured) field coils. The various members of the reversed field pinch family offer the possibility of self-sustaining magnetized fusion plasmas with vastly simplified construction requirements.

(b) Mirror machines. The mirror machines (tandem mirrors, the Elmo Bumpy Torus series, and so forth) all use variations on electrostatic confinement and linear magnetic field variations to produce a fusion plasma that has many advantages over a conventional tokamak plasma. In the case of the tandem mirror, for example, the size of the reactor scales independently from the magnetic field and area of the machine, so that reactors of almost any size can be made by varying the length of the machine. In addition, the energy extraction—if the energy is in the form of charged particles—is much easier from these machines than from the closed, toroidal geometry of either the tokamak or reversed field pinch.

(c) Spheromaks. These machines resemble a smoke ring generator, and they create a self-structured, toroidal plasma that needs no central support. The engineering advantages of a simply connected chamber (one with no hole in it) have generated great enthusiasm for this relatively new machine. When these engineering advantages are combined with the inherent stability of the spheromak plasma, many scientists identify the spheromak as the leading advanced fusion reactor contender.

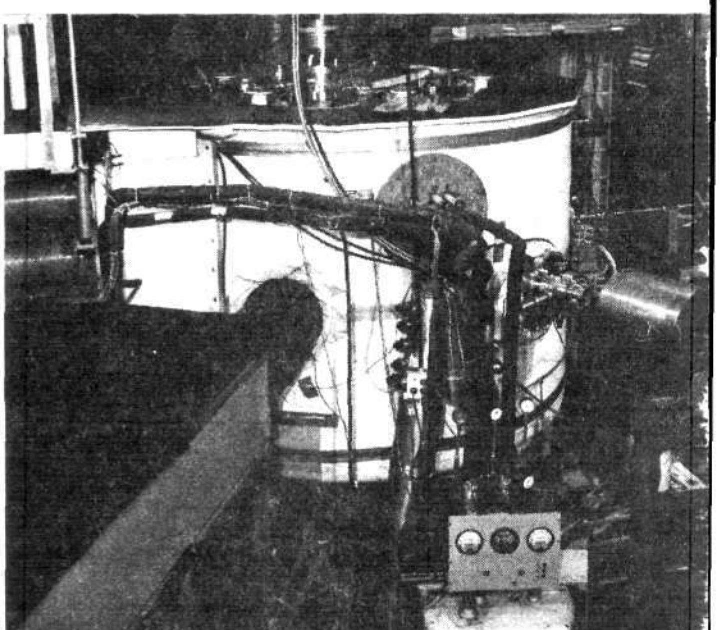
(d) Laser and inertial confinement strategies. In addition to the use of the long-lasting, magnetically controlled plasmas, fusion in the second or third generation will also be produced using an entirely different strategy. The idea of creating a small, very short fusion explosion, which would be ignited by laser beams or beams of subatomic particles, is being investigated in laboratories around the world. This attack on the problem of fusion represents a much higher energy density regime of plasma physics and, therefore, a whole different set of physical laws and interactions.

The only drawback of any of these schemes is that they have been slower to achieve the plasma conditions required for breakeven. The tokamak, partially as the result of having been investigated for a much longer period of time, is several orders of magnitude closer to achieving



Oak Ridge National Laboratory

Polarized fusion fuels can accelerate the timetable for mirror machines, next in line after the tokamak, and make designs like the spheromak possible sooner. Above, the Oak Ridge Elmo Bumpy Torus mirror experiment. At left, the Princeton Spheromak.



Massachusetts Institutute of Technology

In the case of the high-field, Alcator-type tokamak, which requires little or no auxiliary heating, lower ignition temperatures could ensure success. Above, MIT's Alcator C.

net energy production from fusion than any of its competitors. However, the possibility of polarized fuel changes that calculation sufficiently that the more advanced reactors become interesting in a technological as well as scientific sense. The possibility of accelerating the advent of neutron-free fuel cycles has an especially important impact on these advanced designs.

The spheromak, for example, requires an internal magnetic coil. In the conventional fuel cycles, such an internal coil would be destroyed quite quickly by the flux of neutrons unattenuated by any blanket. However, with the D-^{3}He cycle, the advantages of the spheromak could be put to full use; the internal coil could be easily insulated using a small magnetic field because the reaction products are charged. This condition is not even approximated by the D-D and D-T cycles, and so the spheromak has not been seriously discussed for use with any but the D-^{3}He cycle. Enhancing the reaction rate of the D-^{3}He cycle by a factor of 2.5 would immediately improve the situation of the spheromak class of reactor designs.

These various advanced reactor designs, when combined with advanced fuels, open up one especially exciting frontier technology for electricity production: direct conversion. In this technology, the motion of the plasma's charged particles is directly converted to the motion of charges in a wire—electricity. There is no intervening cycle of steam and turbines in direct conversion, but rather magnetic fields are used to directly create an electrical voltage. Magnetohydrodynamics is one direct conversion technology that has been successfully applied to the exhaust gases (a low temperature plasma) from the combustion of natural gas, but direct conversion comes into its own only with the exceedingly high temperature of the fusion reaction.

The great advantage of the direct conversion techniques is that they eliminate all moving parts in the generation of electricity and, hence, almost double the efficiency of the conversion from heat to electricity. Direct conversion, that is, extracts an additional 30 percent of the heat energy in a reactor (conventional steam cycle generators routinely achieve 30 to 40 percent efficiencies).

Polarized fuel complements direct conversion very nicely because of the spatial properties of the reaction products from a polarized fuel reaction. Since the reactor products are not uniformly distributed, but rather emerge in a roughly collimated beam, the requirement of directed motion of the exhaust gas for direct conversion is automatically satisfied by the polarized fuel cycle. Conventional applications of direct conversion (for all reactors except the mirror machines) require an additional magnetic field coil, nozzle, or other device to direct the motion of the exhaust plasma into the direct conversion field. With the polarized fuel cycle, this directed motion is a natural result of the preferential direction of the products from the reaction.

Direct conversion is the most natural way of extracting energy from a plasma when that plasma carries its energy in charged particles. For conventional first-generation fuels (like the D-T cycle), this condition is not satisfied, since the bulk of the energy is released in the neutrons. However, for the advanced fuels in polarized cycles, more than 99 percent of the energy is released in the form of charged particles and, hence, in a way accessible for direct conversion. Such direct conversion technologies could extract up to 65 percent of the heat energy from the polarized fuels in the form of electricity—twice the efficiency of conventional conversion schemes.

Advanced polarized fuel cycles offer similar advantages for two other second or third-generation fusion technologies: plasma torches and fusion propulsion. It has been the sense of many scientists that the energy impact of fusion will be dwarfed by the impact that fusion energy in nonelectrical form will have on the mining, chemical, and processing industries. The basic application of fusion in these industries uses the intense heat of the fusion plasma directly on the materials at hand. Thus, in a steel plant, the plasma from the reactor is used to heat and purify the the steel; in a chemical plant, the various forms of energy from the fusion reactor (X-rays, neutrons, charged particles) directly participate in various chemical transformations (production of synthetic fuels, disassociation of water, and so on); in a refinery, the fusion energy is used directly to ionize the ore or concentrate, with magnetic or plasma centrifuge separation techniques used to separate out the pure metals from the ores.

These technologies will have a revolutionary impact on the whole range of industrial processes, because they open up the entire electromagnetic spectrum for industrial application. In all past industrial processing, the only nonelectrical form of energy available in large quantities was infrared radiation (that is, heat energy). With the fusion or plasma torch, the whole range of the electromagnetic field spectrum becomes applicable, along with intense beams of particles, both charged and uncharged. For this reason, advanced polarized fuels acquire the additional significance of ushering in the full-blown *plasma age* in which plasma processing literally expands our resource base infinitely, by making artificial fuels and metals from the poorest ores.[1]

Last, the beamlike output from advanced polarized fuels has a natural application to one of the most exciting applications of fusion energy: fusion propulsion. It is well known that chemical propulsion was barely adequate to take men to the Moon and that Mars is really too far away to be industrially accessible by chemical rockets. Nuclear propulsion (using fission engines) seems realistic for solar system travel, but as unrealistic for travel outside the solar system as chemical propulsion is for travel outside the Moon's orbit. The design of pulsed thermonuclear engines has been undertaken by a number of research groups with the result that the production of beamlike fusion energy is the key to realistic fusion propulsion. Advanced polarized fuel cycles are the essential complement to these designs.

Note

1. See J. Schoonover, "The Fusion Torch: Unlocking the Earth's Vast Resources," *Fusion*, Dec. 1981, p. 42.

Technological Methods In Polarized Fusion

2

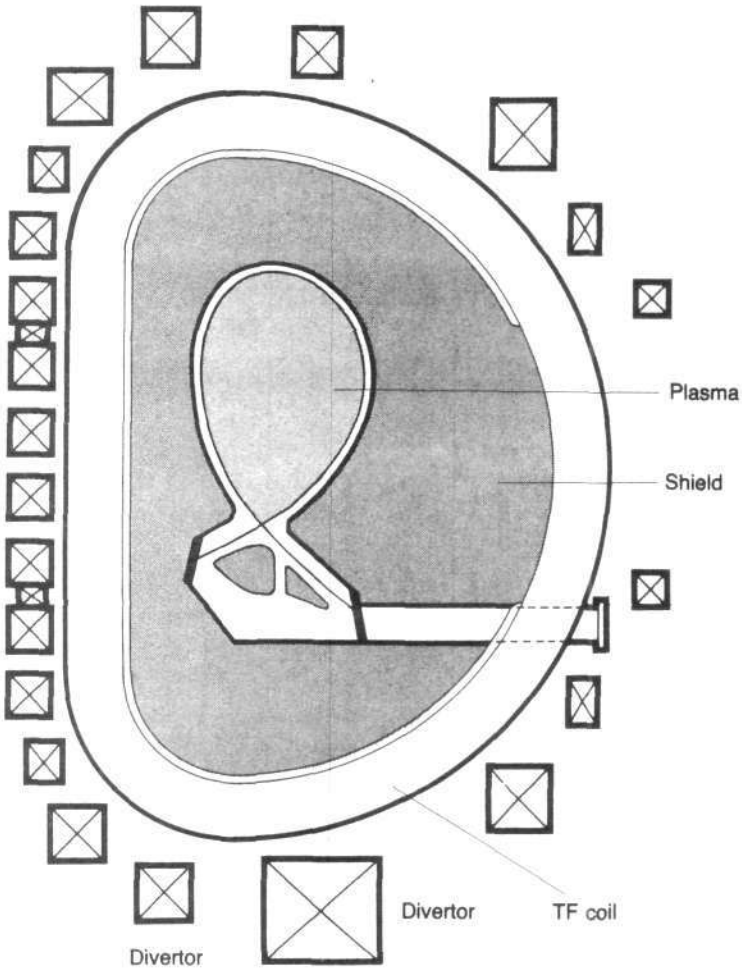


Figure 1
SCHEMATIC CROSS SECTION OF A TOKAMAK
The geometry of a fusion reactor is shown in this cross section of a typical tokamak reactor design. The energy-producing plasma is contained at the very center of the reactor, in a teardrop-shaped cavity that simultaneously contains the plasma, insulates it from the wall, allows it to be heated, and provides a "divertor" field to scrape impurities off the outside edge of the plasma. The vacuum vessel and the toroidal field coils surround the plasma. The final shaping, vertical field, and divertor coils are placed outside the inner coils.

Princeton Plasma Physics Laboratory

From a technological standpoint, in contradistinction to a scientific one, the spin properties of matter are well understood. It has been known since the 1920s that all subatomic matter has associated with it a small, irreducible unit of angular momentum; that is, it acts like a small, spinning top. This so-called spin of a subatomic particle is not, of course, really caused by "something" spinning, although it shares many of the properties of macroscopically spinning objects. The spin interacts strongly with any external magnetic field, and the energy state of the particle depends on whether the spin—its axis of rotation—is aligned parallel or antiparallel to the magnetic field. The spin is associated with a magnetic field generated by the particle (the so-called magnetic moment of the particle), and it combines with other forms of angular momentum in an assemblage of subatomic particles to give nuclei and atoms a net angular momentum.

The practical problem of preparing significant amounts

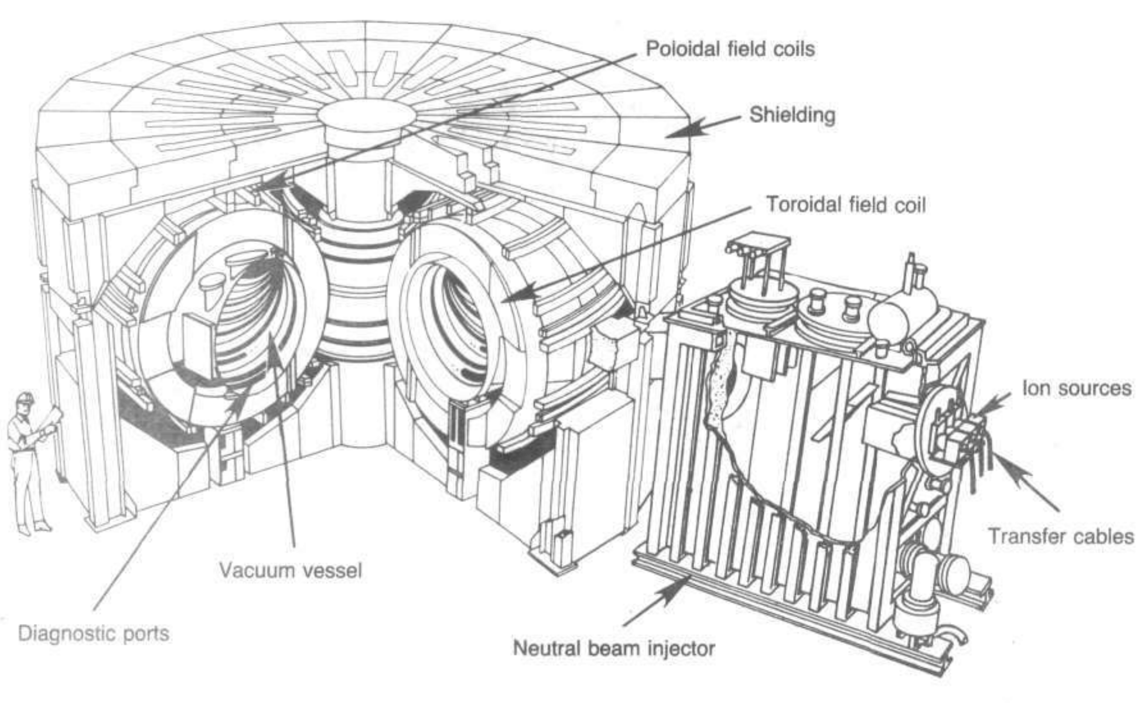


Figure 2
SCHEMATIC DRAWING OF THE TOKAMAK FUSION TEST REACTOR
This experiment, which is scheduled to begin operation in late 1982, will be the first breakeven machine for burning D-T fuel. With polarized fuels, the TFTR experiment could be accelerated into an experimental prototype reactor.

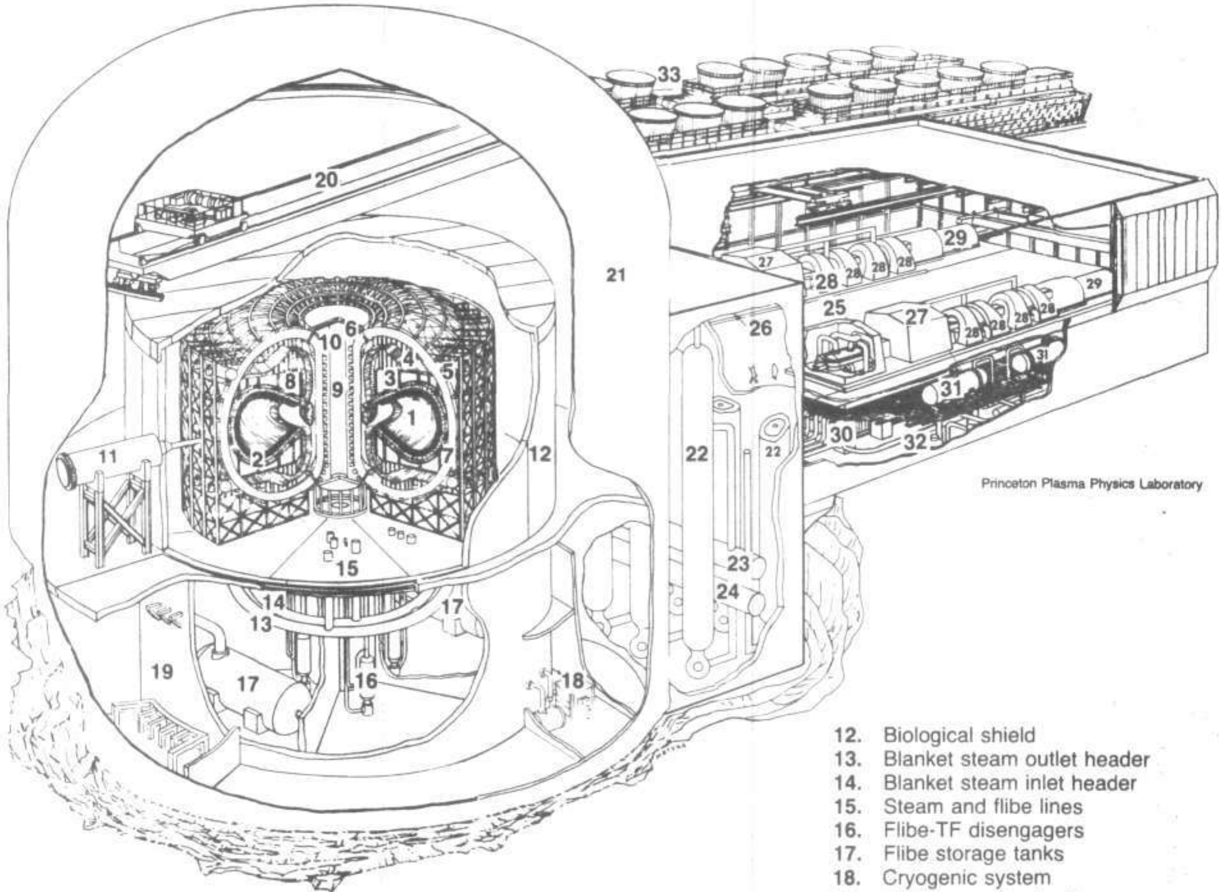
of matter—or fusion fuel—in a polarized state and injecting it into a fusion machine is near solution. If spin polarization can be maintained in the plasma itself, as the Princeton and Brookhaven scientists predict, then the engineers are ready to provide large quantities of polarized fuel.

Preparing Polarized Fuel

The older methods of polarization all used a brute force approach of strong, nonconstant magnetic fields to twist the magnetic directions of the nuclei into alignment. These methods were suitable for polarizing diffuse beams of particles in an accelerator, but not for preparing large quantities of polarized matter. Recently, two new and much more efficient methods have been discovered, both of which take advantage of the nuclear properties of the specific nuclei to be polarized and so can finesse the nuclei into alignment with a minimum of energy and machinery. The first approach uses lasers with a frequency of light tuned to the precise spin interaction of the nuclei to be polarized, and the second uses magnetic fields and extremely low temperatures to condition a chemical reaction that, in turn, produces polarized fuel.

The first approach is discussed in a recent article describing the use of a coherent laser light from a tunable dye laser.[1] The laser light is set at a frequency corresponding to the frequency at which the atoms in the fuel can flip the direction of their spin. When the atoms in the gas are then ionized, the nuclei retain the spin that was impressed on them by interaction with the laser light.

Although hydrogen could be directly spin-polarized in this manner, practically, it is easier to use lasers with a lower frequency, suitable for polarizing heavy nuclei. When mixed with hydrogen atoms, these heavy elements transform the hydrogen atoms into a polarized state through atomic collisions. In a background of a weak magnetic field (several hundred gauss), the collisions between the hydrogen and the heavy nuclei result in "spin-exchange" between the two species and in the polarization of the hydrogen. Once hydrogen has been



1. Vacuum chamber
2. Blanket
3. Primary shield
4. Divertor chamber
5. Vacuum pumps and exhaust manifold
6. Control field coils
7. Toroidal field coils
8. Poloidal field coils
9. Liquid helium tank
10. Toroidal coil support cylinder
11. Fuel injector
12. Biological shield
13. Blanket steam outlet header
14. Blanket steam inlet header
15. Steam and flibe lines
16. Flibe-TF disengagers
17. Flibe storage tanks
18. Cryogenic system
19. Maintenance hot cell
20. Polar crane
21. Reactor containment
22. Steam generators
23. Hot steam supply header
24. Cold steam return header
25. Very high pressure turbine
26. High pressure turbine
27. Intermediate pressure turbines
28. Low pressure turbines
29. 3,600-rpm generator
30. Steam lines
31. Feedwater heaters
32. Feedwater treatment
33. Cooling towers

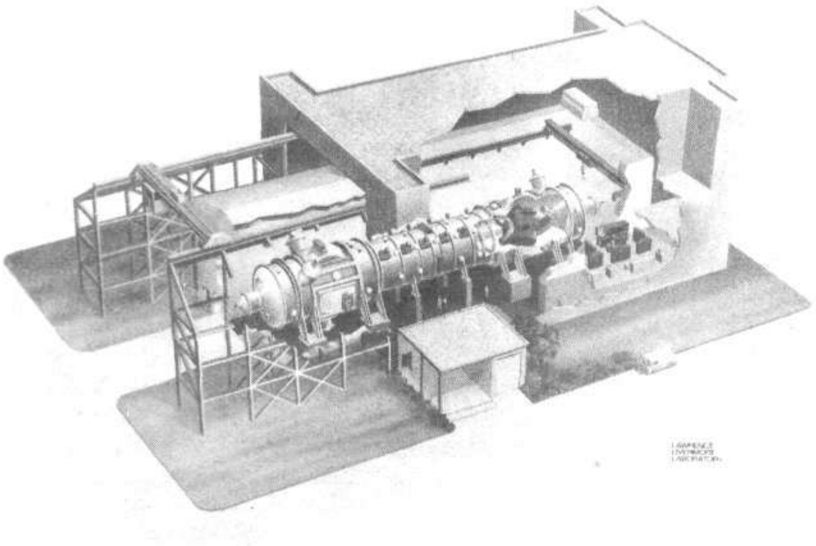
Figure 3
SCHEMATIC DRAWING OF A TOKAMAK FUSION POWER PLANT

This schematic shows one of the earliest designs for a tokamak fusion power plant, projected to produce 1,000 megawatts of electrical energy. The advent of polarized fuels would simplify this reactor design considerably. If the reactor were to use polarized D-T fuel, the amount of auxiliary heating could be dramatically decreased and the overall size of the reactor could be decreased as well. If this design were to burn a neutron-free fuel (such as D-^{3}He), the entire turbine and coolant cycles would be eliminated and replaced by a magnetohydrodynamics or direct conversion assembly. The use of neutron-free fuels would also eliminate the need for a containment vessel.

Figure 4
ARTIST'S CONCEPTION OF COMPLETED TANDEM MIRROR FUSION TEST FACILITY

The TMFTF is the mirror equivalent of the tokamak fusion test reactor (TFTR); both are experiments to create breakeven conditions using D-T conventional fuel. The TMFTF could be completed in the next two years if funding were continued on the original schedule. The TMFTF is now in a holding pattern, because construction funds for the machine have been delayed in the 1983 budget.

The use of polarized fuel in the TMFTF would change the machine from a plasma physics experiment into a full-fledged engineering test facility for D-T fusion, direct conversion energy production, and power reactor design.



polarized, it can be used as the fill gas for a magnetic fusion device, gas puffed into an operating machine, or the ion source for an auxiliary (neutral beam) heater for the reactor.

In the last case, auxiliary, neutral beam heating, the application of polarized fuel is especially promising. The use of a beam of high energy, neutral hydrogen (deuterium) atoms to heat a fusion plasma is already a well-developed technology and was used in the successful heating experiments at Princeton in 1978. Polarized fuel lowers the temperature at which ignition occurs; therefore, the amount of auxiliary heating needed to reach ignition temperatures is greatly reduced. This has important implications inasmuch as large, low-field tokamaks are entirely dependent on the additional heating provided by the neutral beam heaters.

In a neutral beam heater, ions of hydrogen are first extracted from a cold plasma source; for polarized fusion fuel, this cold plasma would also be polarized. These ions are then accelerated to very high velocities by passing the plasma though an intense electric field. The resulting beam of high-energy charged particles must be neutralized so that it can be transported through the magnetic field and into the reactor plasma. The beam traverses a gas cell in which the fast moving beam particles pick up electrons from the ambient gas. The neutral particles are then able to penetrate the magnetic bottle. Once in the plasma, they collide with the plasma, transfer energy from the beam to the plasma, and simultaneously become ionized themselves.

The second method of preparing a polarized plasma was reported about two years ago by scientists at the Massachusetts Institute of Technology.[2] Atomic hydrogen is lowered to 0.3 degrees above absolute zero in a high magnetic field (approximately 100,000 gauss). The atomic hydrogen begins to recombine to form molecular hydrogen and is deposited out onto the wall of the chamber. However, those hydrogen atoms that have their spins aligned in a specific direction with the magnetic field do not recombine, but remain as a spin-polarized atomic gas. This gas can then be used as feed for a neutral beam heater or can be puffed into the plasma chamber and then ionized by the confined fusion plasma.

First-step Experiments

For each approach to the production of polarized fuel, only a few hundred thousand dollars is required to construct the polarization system necessary to test the stability of a polarized plasma. In such simple, first-step experiments, the two critical questions about polarized fuel could be answered: Is the depolarization time sufficiently longer than the ignition time for a plasma under fusion conditions? And second, is the reaction rate enhanced by the factor predicted?

Dr. Bruno Coppi of the Massachusetts Institute of Technology is working on designing precisely such a simple experiment. The MIT tokamak, the Alcator, would be started up with ordinary hydrogen at a density of about 10^{12} particles per cm^3. Then polarized deuterium would be gas puffed into the chamber to raise the density by a factor of 100 (that is, only about 1 percent of the plasma would remain unpolarized). These experiments would then be

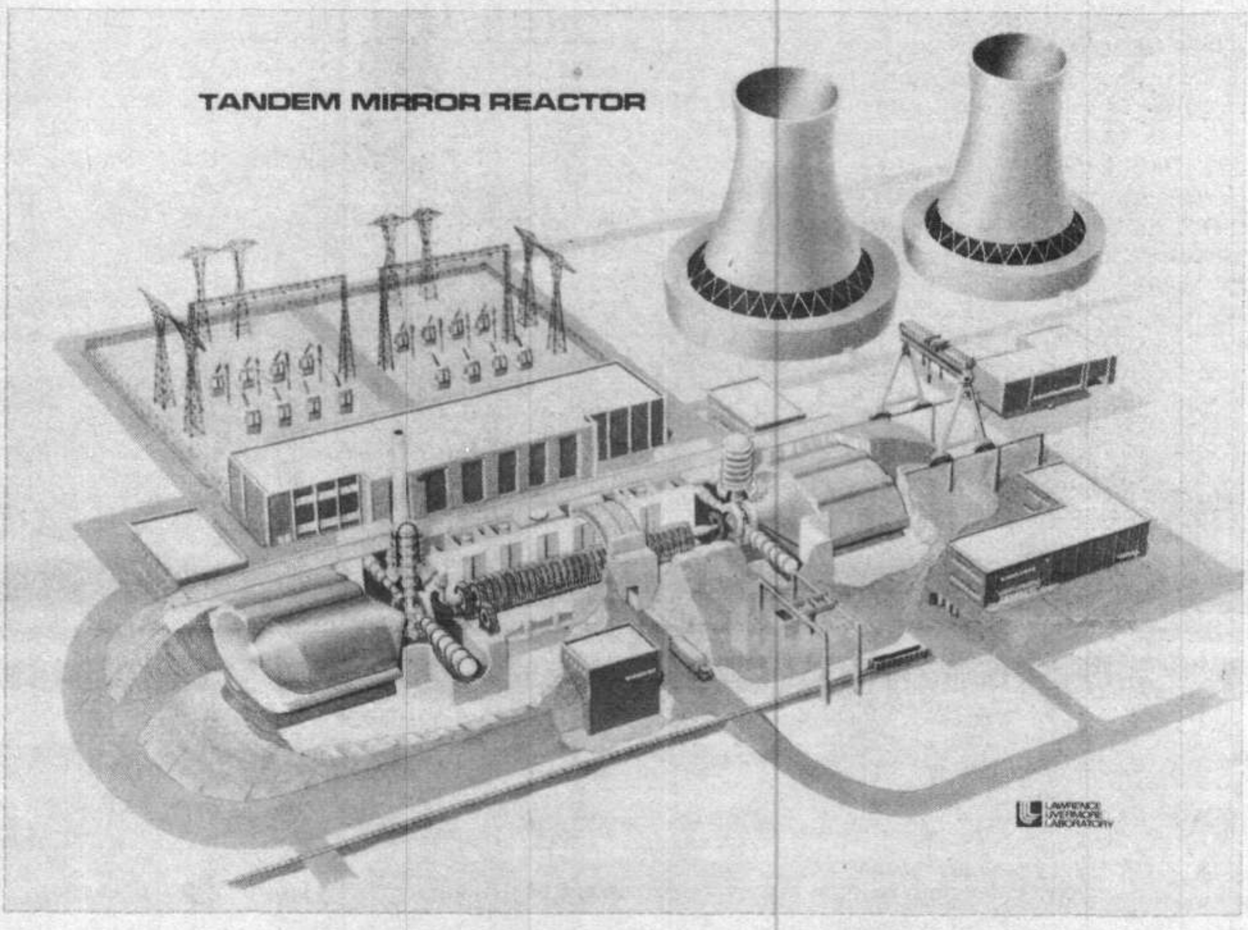


Figure 5
ARTIST'S CONCEPTION OF A TANDEM MIRROR POWER PLANT
The first-generation design for a mirror power reactor, shown here, would be dramatically modified by the use of polarized fuels. The cooling towers and turbine assembly would be eliminated entirely by the application of direct conversion. The tandem mirror is the optimal configuration of any of the advanced applications of fusion that take advantage of the beamlike output of energy from a tandem mirror using polarized fuel.

compared to otherwise similar preparations with unpolarized gas puffing. The simplest measurements of the neutron flux from the plasma should provide an unambiguous determination of the enhancement factor in the reaction rate with polarized fuel. Several similar experiments are planned in other laboratories, and results from these should be available in the next six months to a year.

Engineering Implications

Given the ability to produce a copious supply of polarized fusion fuel, the engineering implications will span the whole range of fusion applications. In every one of the major problem areas of fusion engineering, the use of polarized fuel significantly relaxes the engineering demands on a fusion reactor. The cumulative result of these advantages is to cut at least five years off the timetable for fusion development.

As both the proponents and critics of fusion have noted, the difficult engineering problems of fusion energy are concentrated in three areas.

(1) *The size and complexity of the first-generation reactors.* Presently, the leading contender for a first-generation reactor is the low-field tokamak. This machine requires a large minimum size for economical operation, and the resulting engineering demands are correspondingly great: Massive auxiliary heating is required, as are large amounts of neutron shielding, and the minimum unit is on the order of 3,000 megawatts thermal.

(2) *Neutron irradiation.* The intense flux of high energy neutrons produced by the fusion reaction in first-generation reactors using conventional (unpolarized) fuel makes the design of the interior of the reactor very difficult. A material must be discovered—there are at present several candidates, including special stainless steels—that can withstand the high rate of neutron bombardment without becoming brittle, porous, or intensely radioactive. Many

engineers regard the so-called first-wall problem as the most significant in fusion engineering. When these neutron fluxes occur in a pulsed mode (as in a tokamak)—in which the plasma must be shut off after a period of time and restarted—the problems are even more difficult.

(3) *Use of tritium.* First-generation fusion machines are all expected to use the deuterium-tritium fuel cycle. The tritium nucleus in this cycle is slightly radioactive and so must be handled with care. The technologies of tritium handling have been well developed as a result of the widespread use of tritium in the weapons program and in medical applications. Even so, the additional complications of tritium handling and control on top of the already complex fusion technology are a major concern of the scientists and engineers working on fusion.

Each of these three problem areas can be approached by technologies available today, and, in spite of the difficulties, the problems are by no means sufficient to prevent the development of fusion (as some of its critics have claimed). Nevertheless, the great importance of polarized fuel for the near-term fusion program can be gauged by the fact that its use directly addresses all of the problem areas mentioned above. The two main lines of reactor development, the tokamak and the tandem mirror, take advantage of polarized fuel in different ways, but both benefit by a significant shortening of their development time.

Lower Ignition Temperatures

In the case of tokamaks, the impact of fuel polarization stems first of all from the simple lowering of the reaction temperature required for ignition. Ignition temperatures for even unpolarized cycles have been achieved in tokamaks; however, in scaling the devices to commercial size, the neutral beam auxiliary heaters required to reach this temperature are a significant part of the cost and complication of a prototype fusion plant. A large fraction of these heaters would be eliminated by the use of polarized fuel, resulting in a significant decrease in the cost and complexity of a tokamak fusion reactor.

In the case of the high-field, Alcator-type tokamak—which, its designers predict, will require either minimal or no auxiliary heating—the introduction of a lower ignition temperature will ensure success. The Alcator tokamak has the advantage of small size, much higher power densities, and smaller power sources, compared with the mainline tokamak. The originator of this approach to tokamak design, Dr. Bruno Coppi of MIT, delivered several papers in spring-summer 1982 predicting that the application of polarized fuel to the high-field tokamak will produce a machine capable of economical power production well before the end of the century.

From Pulsed to Steady-state Fusion

We have already noted the importance of producing a neutron-free plasma cycle: Such a fuel cycle eliminates first-wall damage and neutron activation of the reactor and, therefore, the need for neutron shielding, remote maintenance, and complex neutron blankets for heat absorption. In addition, these reactions that produce all charged particles, when accessed through polarized fuels, may offer a way of circumventing the otherwise inherently pulsed nature of a tokamak. Since the plasma current in a tokamak is transient, induced by a large surge of current through a coil surrounding the tokamak, the operation of a tokamak is cycled by the repeated induction of that current. Because it requires external induction, the whole tokamak undergoes a pulsed stressing that amplifies considerably the mechanical, thermal, and electrical stresses on the machine. Polarized fuel offers the possibility of producing fusion energy in such a way that the burning plasma drives its own current. The reaction products from a polarized fuel are produced anisotropically (that is, they are directed in a weakly collimated beam); and scientists believe that if these products are charged, the result will be the production of a current. By suitably structuring the incoming neutral beam, the beam of reaction products can be used to maintain the plasma current required for stable tokamak operation. This variant of the so-called current drive mode of tokamak operation offers the possibility of making the tokamak a steady-state machine.

Implications for Tandem Mirrors

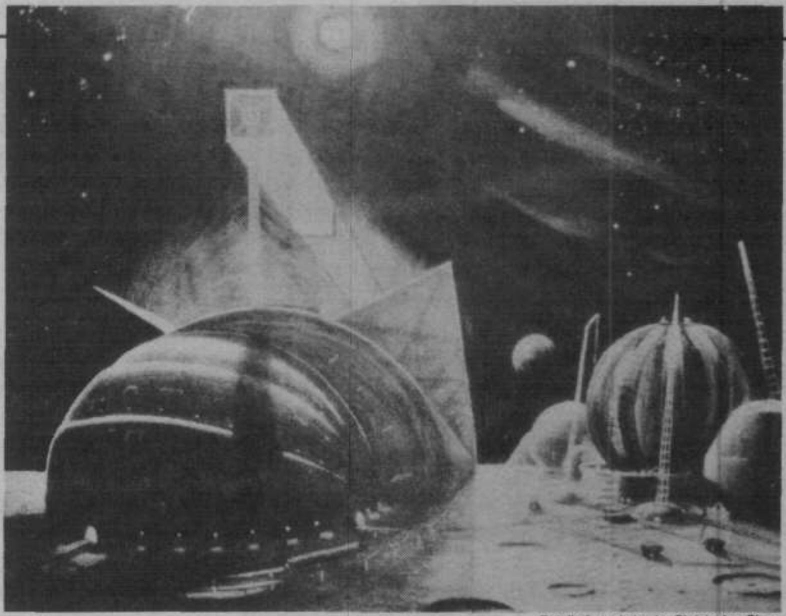
The impact of polarized fusion on the operation of the other major branch of magnetic fusion, the tandem mirror machine, is similarly profound. It, of course, also benefits from the lowered ignition temperatures; and the next major tandem mirror experiment, the Tandem Mirror Fusion Test Facility (TMFTF—previously known as MFTF-B) at Lawrence Livermore National Laboratory in California, should reach ignition temperatures for polarized D-T. If this experiment reaches the most optimistic of its design criteria, the ignition of deuterium-deuterium in polarized form should also be possible.

The unique linear geometry of the tandem mirror, however, is much more favorably affected by polarized fuels than the tokamak. By directing the neutrons out of the two ends of the mirror machine (a possibility with the directed output from the polarized fuel reaction), the two cones of neutrons need not intercept any magnet, wall, or blanket surrounding the reactor. Thus, the mirror machine allows engineers to circumvent the bulk of the neutron engineering difficulties even for the D-T reaction. Rather than having to wait for the D-D fuel cycle or the deuterium-helium-3 cycle to take advantage of neutron-free plasmas (as is the case with the tokamak), the mirror geometry naturally leads to a way of eliminating the neutrons from technologically sensitive areas of the reactor.

This same effect can then be used for the direct conversion of the plasma energy into electricity, as discussed above (see p. 16).

Notes

1. N.D. Bhaskar, W. Happer, and T. McClelland, "Efficiency of Spin Exchange between Rubidium and ^{129}Xe in a Gas," *Physical Review Letters*, **49** (July 5, 1982), p. 25.
2. R.W. Cline, T.J. Greytak, and D. Kleppner, "Nuclear Polarization of Spin-Polarized Hydrogen," *Physical Review Letters*, **47** (October 26, 1981), p. 1,195.



Detail of a painting by Christopher Sloan

An artist's rendering of fusion on the Moon, based on the concepts of Krafft A. Ehricke. On the right, the latest in a row of spherical fusion power plants is under construction. On the left is the end point of one of the climate-controlled hulls that house lunar civilization.

Producing Advanced Fusion Fuel on the Moon

The need for advanced fusion fuels, like the relatively neutron-free deuterium-helium-3, for terrestrial fusion reactors has been recognized by scientists for many years. Space scientist Krafft A. Ehricke has pointed out the tremendous advantages of the D-^{3}He fuel cycle for fusion reactors on both the Earth and Moon—as well as for interplanetary and interstellar travel—and the suitability of the Moon for producing ^{3}He, which is rare on Earth. In his extensive studies of lunar industrialization, Ehricke has proposed utilizing large deuterium-tritium reactors on the Moon as a veritable fuel factory for producing as much ^{3}He (from the decay of tritium) as is necessary for the advanced D-^{3}He fusion reactors of the Earth and Moon and for space travel.

The advantages of D-^{3}He fuel stem from the fact that, because no radioactive tritium is employed, the reaction is almost completely "clean." The reaction produces predominantly charged particles (protons and helium-4) that can be confined magnetically. Wall erosion problems and related engineering problems practically disappear. Moreover, Ehricke points out, the proton-helium reaction plasma is a valuable resource for processing heat for materials extraction and for waste recycling, as well as for generating further electric power.

Ehricke proposes the Moon as the "best candidate" for producing the rare isotope of helium; ^{3}He is potentially one of lunar industry's most valuable exports to Earth markets. For reasons he outlines in his writings, large-scale operation of D-T reactors is easier on the Moon than on Earth and more compatible with the lunar environment.* An excess of tritium can be bred in the Moon's D-T reactors and stored to decay into ^{3}He and an electron. Beginning in the latter phases of lunar industrialization, D-T fusion power plants will become the chief power source and export production facilities (breeding ^{3}He) of the Moon.

The D-^{3}He power plants are also of great interest for advanced lunar development, because the proton output, combined with the electron output from tritium decay and with lunar electrons, forms hydrogen—a valuable reducing agent and component of water when combined with lunar oxygen.

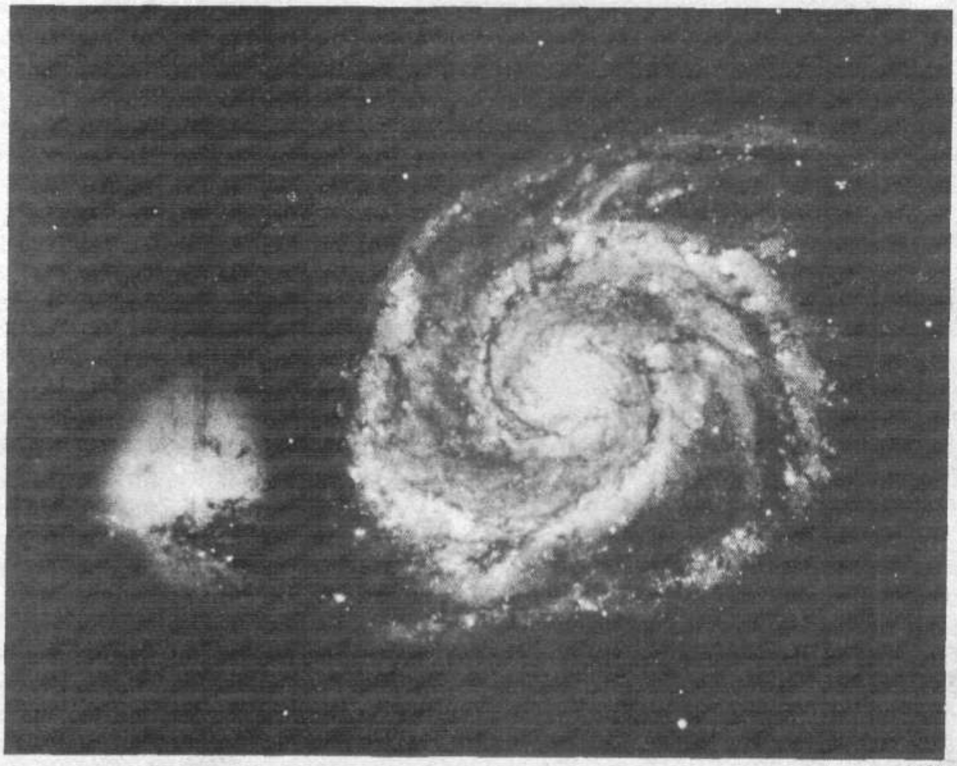
Finally, Ehricke points out that the D-^{3}He reaction is the best suited for a steady-state fusion drive for interplanetary and possibly interstellar spacecraft. The D-^{3}He reaction can operate in a magnetic mirror reactor, whose aft end permits discharge of the reaction plasma, heating up deuterium and producing thrust by the exhaust of a very hot plasma-deuterium mix. A steady-state fusion drive of this type is possible only because with D-^{3}He fuel almost no energy is lodged in neutrons. The neutrons cannot be confined or directed and would create an almost insurmountable heating problem and little thrust in a fusion engine that must be lighter than a stationary reactor.

Note

* For example, the lunar high vacuum facilitates maintenance of a high vacuum in the plasma chamber without size restrictions, reducing neutron flux density per unit of wall area—and associated wall erosion and embrittlement and impurities problems. It also simplifies reactor construction and maintenance and the use of superconducting magnets.

Dr. Ehricke elaborates these advantages in the second part of "Industrializing the Moon: The First Step into a New Open World" (*Fusion* [dated] January 1981, p. 32) and his book *Der Siebente Kontinent: Industrialisierung und Besiedlung des Mondes* (Munich, K. Thiemig Verlag, 1982). His proposals regarding D-^{3}He fusion are also found in these sources.

Scientific Frontiers in Polarized Fusion 3



NASA

"It has been recently established that the areas of star formation in a galaxy are also the areas of lowest angular momentum density. That is, galactic matter is able to agglomerate and form stars in the areas where the angular momentum is least problematic for structure formation."
Shown here is a spiral nebula in the constellation of the greyhounds of Helvetius.

Revolutionary new technological developments have historically maintained an uneasy relationship with a scientific understanding of "how it works." The steam engine preceded the science of thermodynamics by at least a century; X-ray tubes existed and were in general use a generation before the most basic atomic properties of matter were understood; the nuclear reactor exists today although scientists have no rigorous understanding of the stability and decay processes of heavy nuclei. In fact, in each of these cases, the scientifc understanding of the basic processes applied in a given technology is not experimentally accessible without that technology. The experimentally determined energy balances in engines are the central empirical evidence relevant to thermodynamics; the early experiments in nuclear physics depended on X-ray tubes and fluorescent diagnostics; a host of nuclear science depends on nuclear energy or the technologies developed for nuclear energy production.

The same reciprocal relationship exists between polarized fusion technologies and the nuclear physics of the fusion process. The traditional attitude of plasma and fusion physicists to the problem of fusion development has made a careful separation between the problem of generation, control, and maintenance of plasma ignition conditions and the problem of the actual fusion of two fuel nuclei. The problems of plasma control have been considered the proper topic—and the most difficult—part of the fusion process. If, the argument goes, we can achieve a plasma in which a sufficiently large number of fuel nuclei have the energy required for ignition, then the simple two-body collisions of the nuclei will take care of the fusion itself. The problems of the fusion of two colliding nuclei—specification of what makes fusion occur, the most favorable geometric arrangement of the nuclei, and so forth—have been dealt with agnostically in the belief that the statistical average of the billions of fuel nuclei collisions would make prediction of the properties of a single collision irrevelant in an essential way.

The theoretical discovery of polarized fuel, with its potential for dramatically simplifying fusion engineering, is an interesting refutation of the prevailing prejudices in the fusion community. Unfortunately, the nuclear physics community is not much closer to an understanding of the processes governing the fusion of light nuclei either. The state of knowledge in the field is summarized in the following excerpt from a review article of the problems of understanding the causal foundations of fusion between light nuclei.

> . . .a number of polarization experiments had been carried out in the two nucleon system. It soon became clear [in about 1957] that these experimental data not only required a strong two-body spin-orbit interaction, but required it to be of the right sign for the shell-model spin-orbit splitting! Since one-pion exchange had produced no such interaction, the theorists began looking for it in the simultaneous exchange of two pions between the two nucleons, with nucleon intermediate states. In other words, the shell model splitting had previously been considered to be due to a higher order nucleon-nucleon effect in the many-body system. Now it was assumed to be due to a higher order pion-nucleon effect in the two-body system. However, before this could be confirmed or disproved, the elementary-particle physicists entered the land of baryon and meson resonances. Since these strong resonances have been virtually unforeseen by strong-interaction [the putative force between nuclei and their components] theory, the old methods of calculation were discarded. Most theorists lost interest in trying to work with the very complex nucleon-nucleon interaction when they had their hands full with the similar, but algebraically much simpler, pion-nucleon and pion-pion system.
>
> . . .In the present state of elementary particle theory, then, there is no reason to believe that we are about to turn the corner on understanding the P-wave nucleon-nucleon spin-orbit interaction.[1]

Some History

For the several decades of nuclear research preceding the 1920s, the optical spectra of the elements were the primary tool for exploring the structure and properties of the elementary particles. One of the most powerful variations on this technique was the study of the spectra of these atoms in a magnetic field.

In 1925, S. Goudsmit and G. Uhlenbeck put forward a hypothesis that simultaneously explained the most thorny of the problems in spectral analysis in those decades, and itself posed a new set of problems. Physicists had been plagued by what was called the "anomalous Zeeman effect"—an inexplicable doubling of the splitting of some spectral lines in a strong magnetic field. Only under certain not well-understood conditions would this double splitting occur; Uhlenbeck and Goudsmit proposed that there was a new degree of freedom associated with the electrons responsible for the observed spectra, a new kind of angular momentum-magnetic field interaction that supplied the missing factor of 2 in the splitting of the lines. They somewhat misleadingly called this internal angular momentum *spin*, in analogy with the internal angular momentum of a mechanical body like a spinning top.

The hypothesis of Goudsmit and Uhlenbeck was very successful in describing the anomalous spectra that had been observed, but it failed as an explanation. Indeed, the concept of spin as internal, *mechanical* angular momentum was completely overturned when all calculations of the magnetic interaction that would result from the angular momentum of the spin by itself were themselves small by a factor of 2. The so-called anomalous magnetic moment of the electron—the fact that the spin of the particle, if interpreted as spinning charge in a small sphere, gave a magnetic interaction only half of that observed—became, in turn, one of the major paradoxes of the 1920s.

This paradox was resolved, or rather buried, in the 1930s with the discovery by P.A.M. Dirac that if the existing theory of the electron (given by the Schrödinger equation) were modified so as to obey Einstein's relativity theory, then the resulting equations implied a new, internal degree of freedom, which measured internal angular momentum, with precisely the factor of 2 missing in the old mechanical theory. Dirac's equation still did not resolve the fundamental character of spin—or account for its existence—but it did allow the properties associated with the spin of a single particle to be consistently described.

Using Dirac's equation, the most perplexing features of spin soon became clear: Spin not only could not be described as mechanical motion of a charged sphere, as early researchers had hoped, but it was an inherently relativistic feature of elementary particles. W. Pauli showed, in fact, that the spin of a particle is intimately associated with the most fundamental interactions of particles. Whether particles condense into superfluids at low temperatures or not is determined by their spin; the behavior of the particles in collisions with other elementary particles depends on the spin of the particles; and, most troubling, there is a very close connection between the spin, the charge, and the left-handedness (parity) of a particle. This result, called the CPT Theorem (and also originally hypothesized by Pauli), asserts that every elementary particle is not an arbitrary collection of ingredients (so much spin, a little charge, and so forth) but that these properties are combined in an intimate way.

A Non-Newtonian View

In what direction, then, do we look for a theory of spin and the nuclear processes affected by it, such as nuclear fusion? Certain basic conclusions follow immediately from a rejection of a Newtonian atomic view of the problem.

(1) Spin cannot be viewed as some dynamic quantity comparable to spin in a macroscopic object. The model of a spinning charged particle is internally contradictory, as the first researches on spin showed.

(2) From a theoretical as well as an epistemological standpoint, spin shares the properties of charge much more than it does those of angular momentum. That is, spin seems to be basically a topological or symmetry property rather than a mechanical property like angular momentum. The superficial similarity between angular momentum and spin in the energy equations describing elementary particles is misleading; the real nature of spin must rather be derived from its close association with relativity theory and the interconnection between spin

Wideworld

P.A.M. Dirac (left) and Wolfgang Pauli helped clarify the "spin paradox" of the 1920s. Dirac's equation allowed the the properties of the spin of a single particle to be consistently described, and Pauli showed that the spin of a particle is intimately associated with the most fundamental interactions of particles and cannot be separated out.

and the identity-interchange ("statistics") properties of the particles.

(3) However, there is also no question that the close connection between angular momentum, spin, and magnetism is real. Angular momentum on all scales of interaction in physics is intertwined with structure formation and singularity properties. Thus, in a fluid, the basic unit of interaction is fruitfully considered to be a vortex, the simplest unit of structure in a fluid. Since the concept of a vortex is, in an essential way, singular, countable, and discrete, the causal position of a vortex in fluid mechanics is a pregnant starting point for understanding the causal significance of spin. What is significant is *not* that both share angular momentum or that both might be rotating singularities, but rather that both are "simple" singularities in the sense that they are topologically irreducible to simpler pieces. There is no such thing as half a vortex, just as a particle with spin 1/2 never appears with any amount of angular momentum besides plus or minus 1/2. That is, in spite of the fact that the spin angular momentum of the particle is a vector, with magnitude of 1/2 and a direction determined by its polarization, there is no direction onto which that polarization vector might be projected so as to give 0 net spin.

Spin, and perhaps angular momentum in general, is a kind of directed mass. It appears with other quantified amounts of these elementary particles—charge, mass, and parity—as an inseparable part of a stable manifold. As Pauli showed in his famous theorum concerning the connections of spin, charge, and parity symmetries, these aspects of a particle cannot be disentangled.

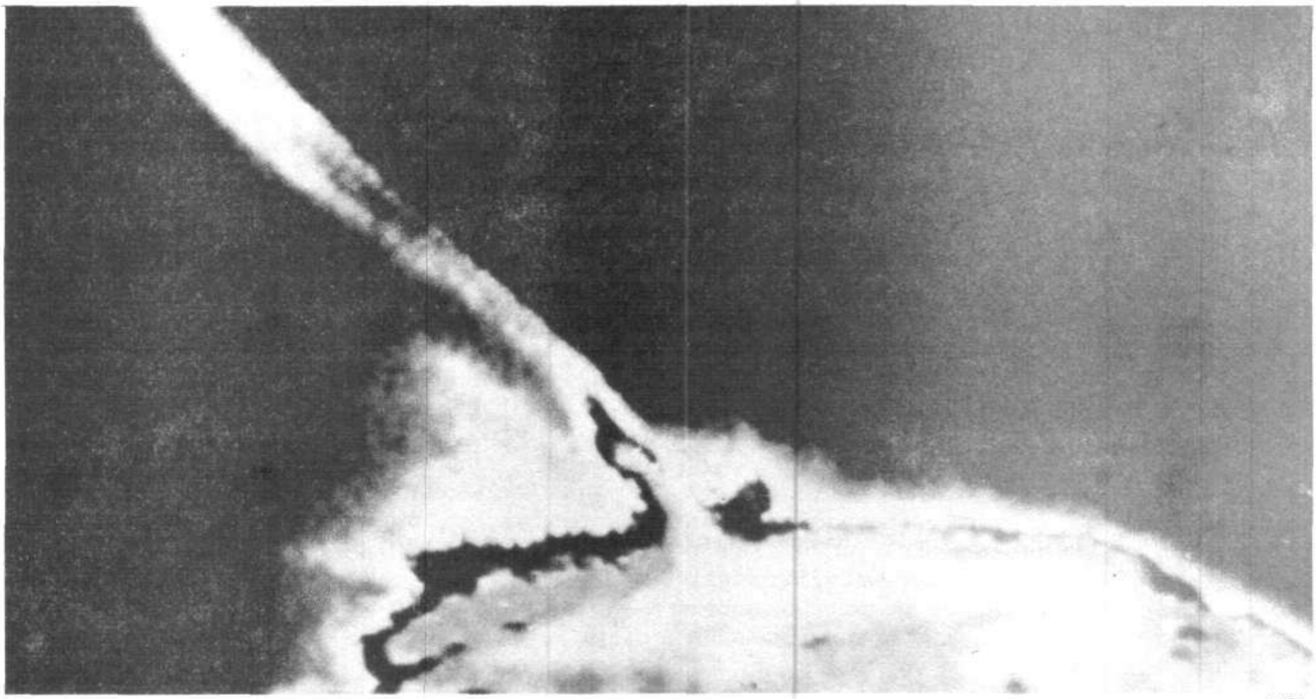
The Universe in the Large

The same connection appears in the largest scales of the universe. Some very provocative recent research on the connection between angular momentum and structure shows that the critical determinant of the ability of a mass of gas to form an astronomical structure is its ability to shed enough angular momentum to reach the "plateau" of maximum angular momentum per unit mass for the total mass of the forming object. That is, there is a determinate relation between the angular momentum density and mass of any object if it is to exist as an object. *If the angular momentum density is greater than this* maximum, the object cannot remain intact—it spins itself to pieces.

This phenomenological observation is "quantized" in the sense that only discrete masses are observed. On each of the observed scales of the universe—planets, solar systems, nebulae, clusters, galaxies, and clusters of galaxies—the same relation between mass and angular momentum density is observed. At the same time, it is observed that structure forms only at discrete points in mass. An attractive hypothesis for the striking discontinuity in the levels of structure in the universe is provided by the observation that the mechanisms for shedding angular momentum are different at each scale, and that there are some levels at which no such mechanism exists. The empirical evidence for the hypothesis is quite detailed in the case of star formation in galactic environments. It has been recently established that the areas of star formation in a galaxy (the spiral arms in the case of a spiral galaxy) are also the areas of lowest angular momentum density. That is, galactic matter is able to agglomerate and form stars in the areas where the angular momentum is least problematic for structure formation.

Spin in nuclear particles may play a similar role. The spin properties are, of course, not responsible for a nuclear interaction "spinning itself apart," but the close relation between possible structures and minimal levels of angular momentum is very suggestive of exactly the role of spin in the microscopic realm. In both cases, the relevant time scales of physical phenomena go hand in hand with the angular momentum possible at that scale. On the one hand, the properties of rotation have since antiquity been recognized to be closely intertwined with the conception of time and its measurement, because (at least) circular motion is the simplest harmonic motion possible. But the deeper connection between the possible evolution of a system and its angular momentum or spin is more systematically significant. As Plato forcefully points out regarding the most basic prerequisite for a scientific methodology concerning time, time can only be understood as a property of ordered evolution. Without that "direction" to time, it cannot run backwards or forwards indifferently (with all the implications of that statement for causality), nor can it be rigorously measured.

The essential problem is that time is not uniform but rather is closely connected to the scales of phenomena and causality that the differentiations in angular momentum illustrate. The time scale of evolution in a cluster of galaxies, for example, is a product of the interactions possible in a structure of matter with that characteristic density and mass. That characteristic density and mass is, in turn, determined by the angular momentum of the



NASA

"Plasmas have continued to confound physicists because plasmas resist Newtonian reduction to particle-fields in almost every regime." Here, an ultraviolet photo of a solar prominence taken by Skylab's Solar Telescope in August 1973.

cluster and the ability of the cluster to transfer angular momentum.

The role of spin in nuclear processes must be of a qualitatively similar sort. And, indeed, the evidence provided by the experimental evidence available about spin-polarized collisions, the effect of spin-orbit interactions, and the relation between spin and fusion reactions is all indicative of the importance, if not dominance, of spin in nuclear interactions. Is it perhaps not the case that a collision that results in fusion is fundamentally different from a simple Coulomb (electrostatic) collision? This would seem to be necessarily the case because the stability of the resultant fused nucleus (an alpha particle, say) is accessible only through some surprising, subtle interaction between the spin, magnetic, angular momentum, and charge properties of the interacting nuclei. The role of spin in this process is critical, and it remains our inability to describe the real theoretical basis for spin that prevents an understanding of the fusion of two nuclei.

The Question of Many Particles

With a few noteworthy exceptions, all nuclear physicists view their subject as one realm in which the Newtonian reduction of physics to the interaction of particles and their fields remains unassailable. The intrusion of many-body, or collective, effects remains an exotic formalism, irrelevant in an essential way, they believe, to the interaction of many nuclei in an accelerator beam, target, or bubble chamber. That the nucleons within a nucleus interact is obvious, but it is absolute dogma that each nucleus is unto itself.

The experiments to be done for the testing and development of polarized fuel will provide an important first test of this assumption. All calculations concerning polarized fuel have made the same assumption: They all view a fusion plasma as a collection of individual fusion reactions. The overall conditions necessary for ignition are calculated on the basis of each fusion reaction being probabilistically determined by the charge collision of two otherwise unconnected particles. This is certainly the most conservative assumption to make in the case of predicting the conditions required for fusion, and it must be a "worst case" scenario for the temperature and densities required for ignition.

But, plasmas have continued to confound physicists, because plasmas resist Newtonian reduction to particle-fields in almost every regime. The plasma nuclei do not act independently of each other in terms of their magnetic, electric, or hydrodynamic properties. A plasma is the most non-Newtonian nonliving collection of matter accessible to physicists. Why should the nuclear aspect of a fusion plasma be *immune* to this collective character? Most physicists' intuition is strongly pointing in the opposite direction, and they remain firmly convinced that the fusion in a fusion plasma occurs one collision at a time. But, this same intuition assured physicists for many years that any collective interaction that might occur in a polarized fuel plasma would make the use of polarized fuel even more attractive.

Note

1. P. Signell, "The Origin of the Spin-Orbit Interaction," Proceedings of the Third International Symposium on Polarization Phenomena in Nuclear Reactions, Ed. H.H. Barschall and W. Haeberli (Madison, Wis.: University of Wisconsin Press, 1970), p. 6.

Keyworth's 'Short, Unhappy Reign' Threatens Testing of New Breakthrough

In the 18 months since Dr. George Keyworth was appointed President Reagan's Science Adviser, Japan has surpassed the United States as the world's leader in inertial confinement fusion, and the joint European fusion program is now on the verge of surpassing the U.S. magnetic confinement fusion program as the world's leader in that field. This development seems to have been welcomed by Keyworth, who has been instrumental in bringing it about by his support for slowing down the U.S. fusion effort and flattening its budget to prohibit engineering advances.

A fusion scientist, Keyworth has been uniquely positioned to shape U.S. fusion policy "over the heads" of the Department of Energy officials directly in charge of the program. As made clear by the dismal minutes of the June 1982 Magnetic Fusion Advisory Committee meeting excerpted below, Keyworth has done just that. But far from giving President Reagan a sense of the unparalleled contribution to human energy development needs that the United States could make by leading fusion development, Keyworth has set the achievement of commercial fusion energy "70 years away"—in direct opposition to the 1980 fusion legislation, which mandated the development of a commercial fusion reactor by the year 2000.

Other elements of the "Keyworth line" are that "the country will not support" any increase in fusion budgets even to match inflation, despite the near unanimous passage of the Magnetic Fusion Energy Engineering Act of 1980, and that since all nations' fusion programs have to cut back, fusion research in the 1980s will increasingly be a "one-world" endeavor, split up among various nations.

Other nations, however, have *not* cut back their fusion programs. The Joint European Torus program of the European Community has been upgraded, both in real levels of funding and in engineering status, since Keyworth was appointed; so have the national programs of several European nations and, of course, of Japan. As Keyworth knows, these developments are entirely lawful responses to the spectacular proof-of-principle progress of *the U.S. fusion program* since 1975!

The only way Keyworth and other shortsighted austerity-minded officials could possibly justify the "go slow" fusion policy is to debunk the very progress in the American program that has inspired Japan and the Europeans.

The following excerpts from the June 1-2 MFAC meeting serve to convey the flavor of the despondent soap-opera to which Dr. Keyworth has reduced the once-aggressive Fusion Power Coordinating Committee (now renamed the Magnetic Fusion Advisory Committee,) an advisory body to the DOE Fusion Office comprised of representatives of the national laboratories and industry and university fusion programs.

Excerpts from the MFAC Meeting

Dr. Keyworth commented on fusion in general. . . . He noted that there was no more difficult technological problem than producing fusion power. . . . that no one could predict when that payoff would occur.

He stated that the present level of funding is viewed as adequate and should remain steady.

Most countries are tightening their belts in long-term R&D programs, but if we work together we may be able to achieve a demonstration of fusion power.

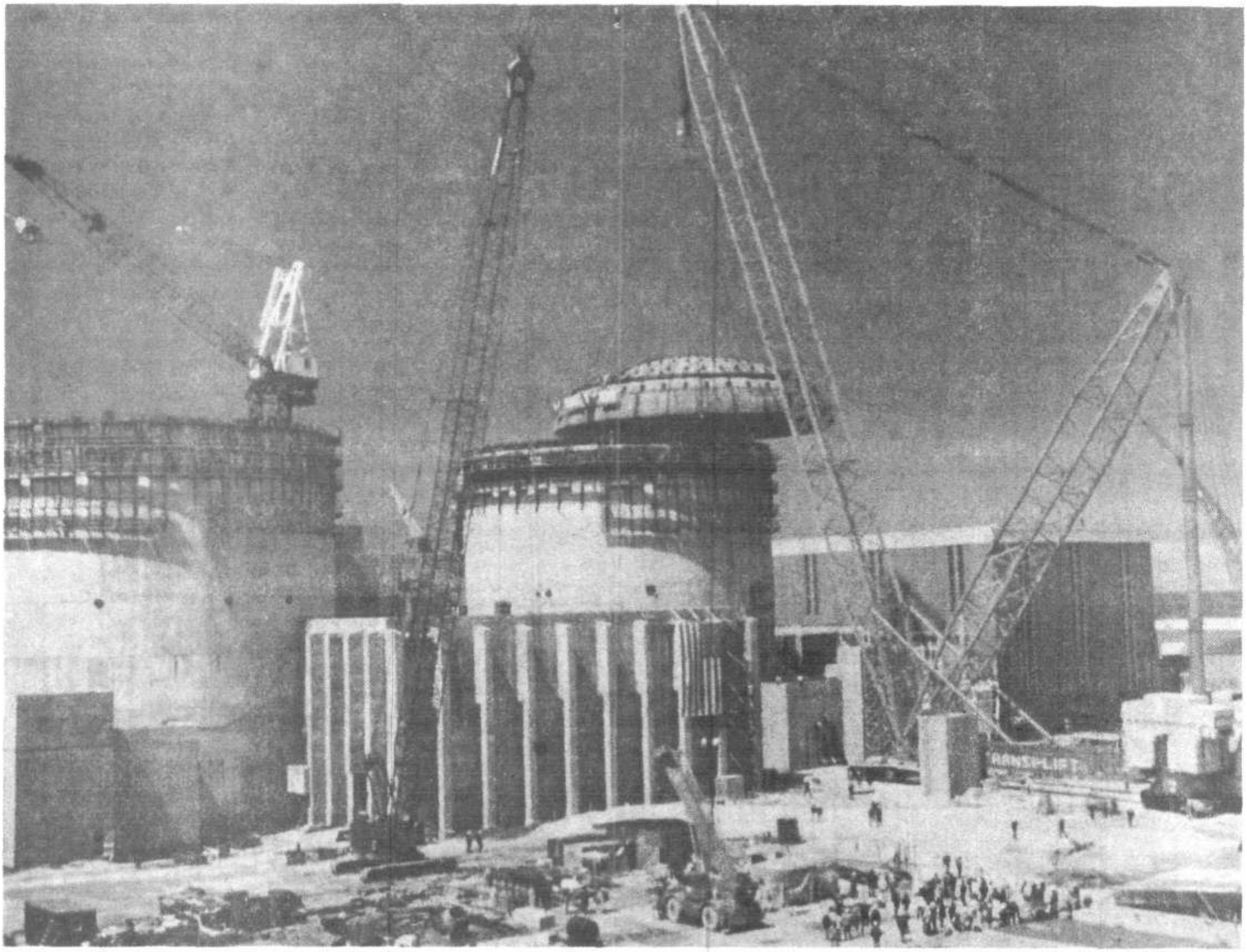
Dr. John Clarke, Associate Director, Office of Fusion Energy: . . . Until 1980, the program was aiming at a large expansion, based on solid scientific progress. . . . The Office designed the present program with the expectation of increased budgets and now is faced with the question of appropriate balance and whether it can maintain existing projects with flat budgets.

He reiterated what Dr. Keyworth said. . . . the Administration perceives that we do not need a new power source before the turn of the century. . . . He likened the new strategy to how a company markets a new product. There must be sufficient scientific and technical data to demonstrate feasibility, which leads to product definition, which leads to sufficient belief in the product to justify investment at the product development stage.

Professor Bob Conn asked whether scientific success would assure a greater budget. Dr. Clarke responded that the value the country puts on fusion is the prime determinant.

Dr. John Gilleland asked if we want to do anything qualitatively different, such as designing an ignition device. Dr. Clarke answered that since we don't need a reactor until after the turn of the century, if doing something different is just a matter of creating a spectacular event, no. What would make an impact is to develop a system with such desirable features that everyone would want it. It is not yet clear what that is.

Professor Maury Tigner asked how many years it would take a level budget to complete all the projects on the chart. Dr. Roberts responded that by 1988 you could finish all the projects on the chart but do nothing else.



Photograph of Transi-Lift crane placing dome on Perry, Ohio nuclear plant courtesy of Neil F. Lampson, Inc.

Do you believe

- that economic growth is essential to America's future?
- that nuclear energy is a necessary part of ensuring continued economic growth?
- that science and technology are the most important tools for continuing human progress?
- that given a political and social will, there is no task too difficult for man to solve?

We do.

If you can say the same, and if you want to contribute to the realization of the two most important concrete goals toward these ideals – the support of fusion energy development and space exploration – join us as members of the Fusion Energy Foundation.

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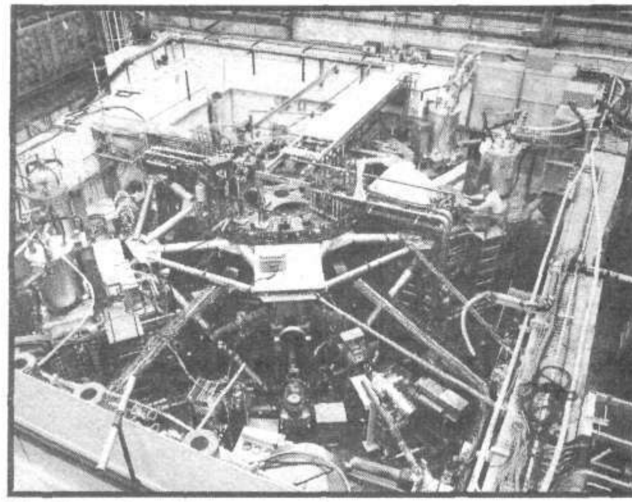
In This Issue

FUSION BY 1995

This special issue of *Fusion* is the first public report on polarized fuel, a new development in fusion that would speed the commercialization of this cheap, unlimited, and safe form of energy that uses seawater as a fuel source. *Fusion* is also the first to elaborate on the industrial revolution polarized fuel would bring about by taking us into the "plasma age."

Using polarized fusion fuel, U.S. scientists could develop commercial fusion reactors by 1995—five years earlier than assumed by the 1980 fusion legislation, the Magnetic Fusion Energy Engineering Act. In a polarized fuel, the direction of the magnetic axes of the atoms of fuel is arranged so as to increase the rate of the fusion reaction. This means that fusion ignition can take place at significantly lower temperatures and densities. In fact, the use of polarized fusion fuel makes scientific breakeven possible *today*, with fusion machines like the Princeton PLT tokamak.

Princeton Plasma Physics Laboratory

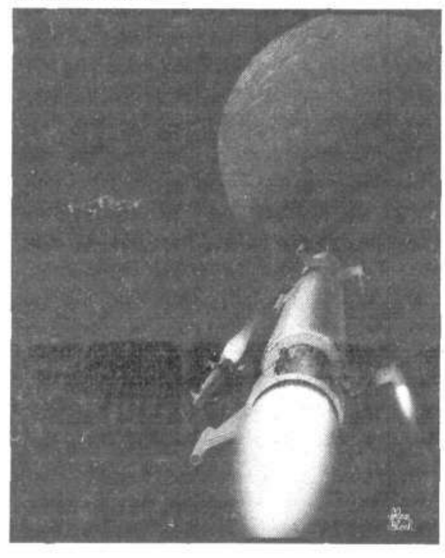


The Princeton Large Torus, which attained record temperatures for a tokamak device in 1978, would be at scientific breakeven using polarized fuel today. That is, more energy would be produced by the fusion reaction than the amount of energy necessary to heat and confine the fusion fuel.

PLASMA AGE TECHNOLOGIES

The use of polarized fuel promises an industrial revolution. Polarizing the fuel suppresses the production of neutrons in the fusion reaction and increases the production of charged particles. This permits the fusion reactor to directly convert its output to electricity, simply by collecting the charged particles at opposite electrodes. No steam turbine is necessary, and the efficiency is twice that of conventional methods. Even more spectacular, polarized fuel will allow scientists to tailor the intense heat of the fusion reaction output for specific tasks, such as a plasma torch that could turn ordinary dirt into its valuable constituent elements, or chemical processing, or space propulsion.

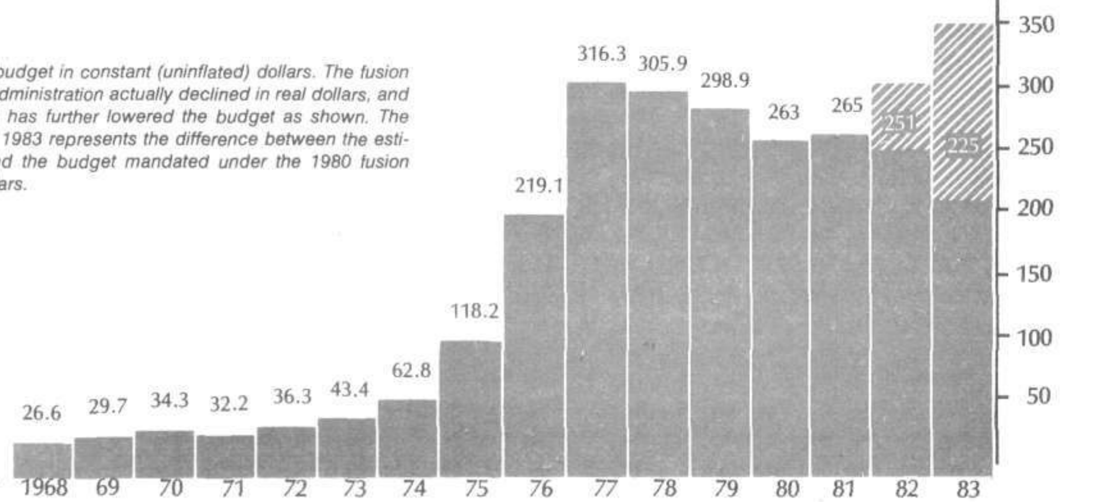
Polarized fuel permits output of the fusion reaction in the form of a beam of charged particles, with applications for chemical processing and space propulsion. Without such fusion propulsion, long-distance space flight outside the solar system or to faraway planets would require prohibitive time schedules. Shown here is an artist's conception of a fusion-propelled spacecraft headed for Mars.



Drawing by Alex Bloch

A POLITICAL QUESTION

Turning the polarized fuel potential into a reality is a political, not a scientific, problem. President Reagan's science adviser, George Keyworth, says that the government's present strategy will not achieve commercial fusion until 2050. Under the rubric of budget austerity, this policy not only contravenes the Magnetic Fusion Energy Engineering Act of 1980, but dooms the country to permanent energy shortage and industrial decay.



The U.S. magnetic fusion budget in constant (uninflated) dollars. The fusion budget during the Carter administration actually declined in real dollars, and the Reagan administration has further lowered the budget as shown. The shaded area for 1982 and 1983 represents the difference between the estimated Reagan budget and the budget mandated under the 1980 fusion legislation, in constant dollars.