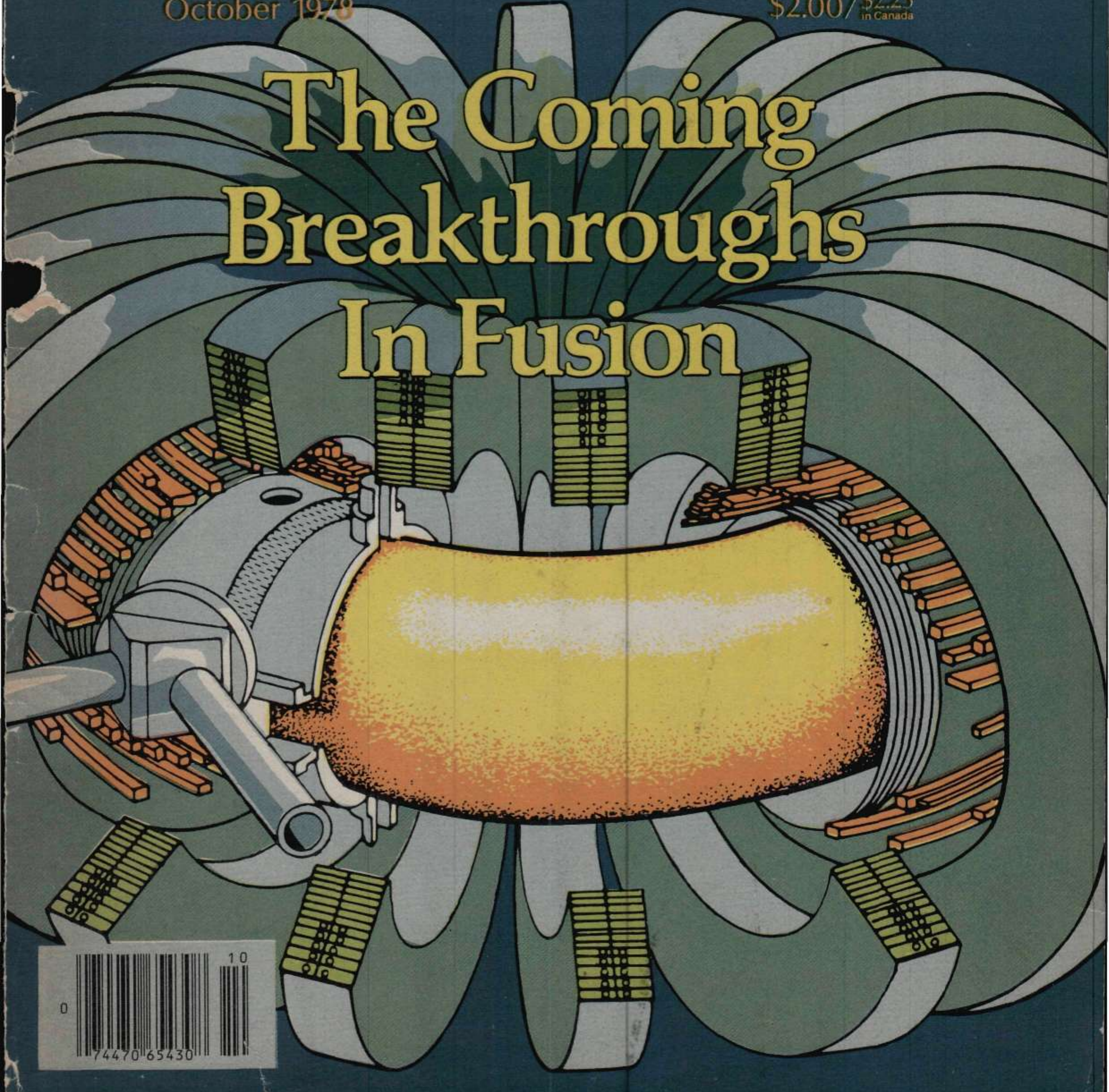
# FUSION

MAGAZINE OF THE FUSION ENERGY FOUNDATION

October 1978

$2.00/$2.25 in Canada

## The Coming Breakthroughs In Fusion



# FUSION

October 1978

ISSN 0148-0537
Vol. 2, No. 1


# Features



# Departments





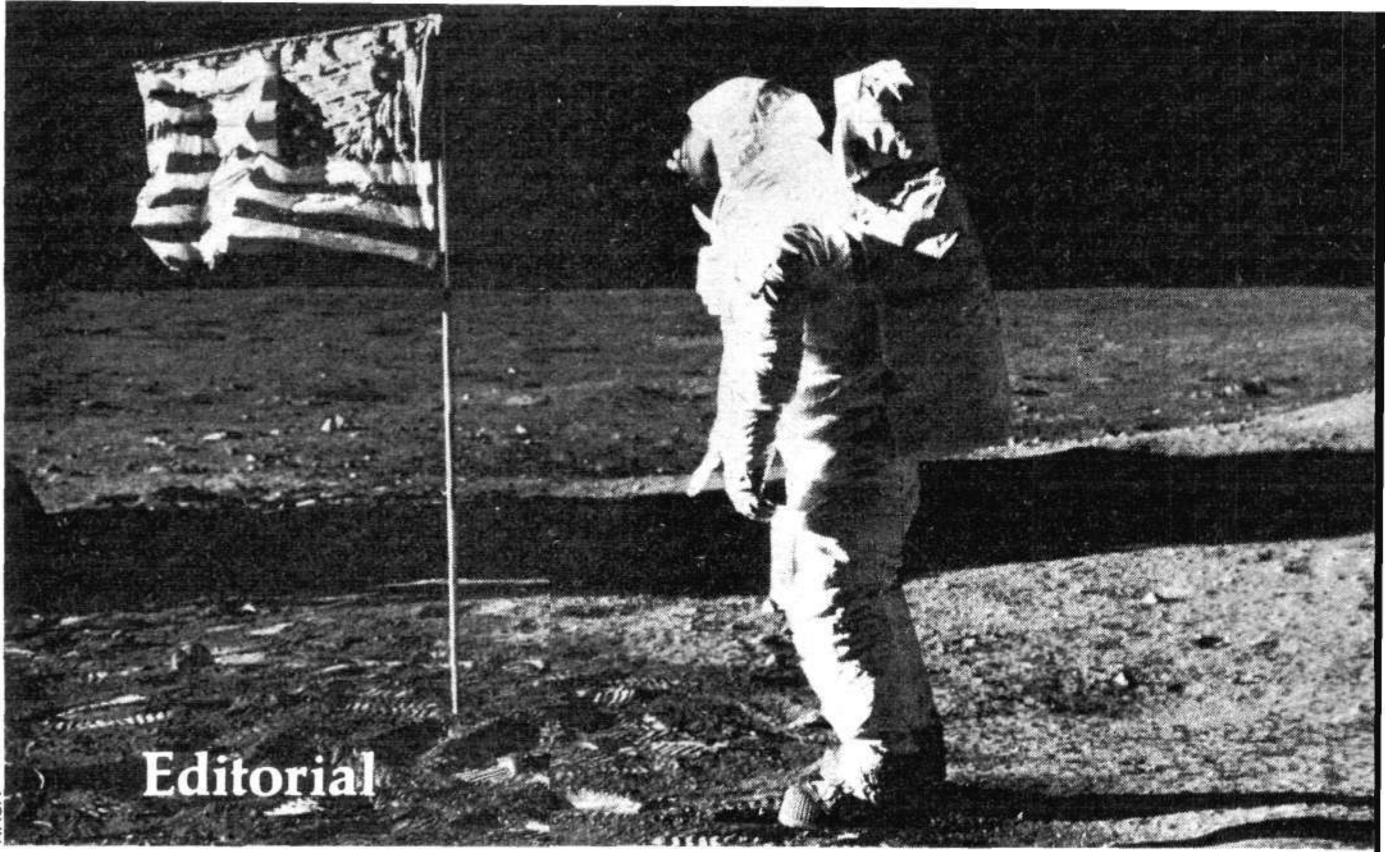

**FUSION** is published monthly 10 times per year except September and April by the Fusion Energy Foundation, 231 West 29th Street, 13th floor, New York, New York 10001.

Subscriptions by mail are $18 for 10 issues or $34 for 20 issues in the USA and Canada. Airmail subscriptions to other countries are $36 for 10 issues.

Address all correspondence to Fusion Energy Foundation, P.O. Box 1943, New York, New York 10001.

Second class postage paid at New York, New York.

The FEF publishes a wide variety of material for the benefit of decision makers and the interested public. The views of the FEF are stated in the editorials. Opinions expressed in signed articles are not necessarily those of the FEF directors or the scientific advisory board.



NASA

# An Apollo Program for Fusion

In the past month we have seen what one faction of the U.S. Department of Energy has accurately characterized as the "most important development in the 27 years of the fusion program"—the achievement of fusion ignition temperatures by the Princeton Large Torus tokamak. What is more, the Princeton results are but a prelude to equally exciting, fundamental fusion results expected in the coming year, breakthroughs that are reviewed in detail in this issue.

In a very real sense, the magnitude of this Princeton breakthrough puts the *difficult* part of the fusion problem-solving process before the policy makers and citizens of the United States: Now that the fusion research effort has shown that we can have fusion as soon as we want, will the nation make a commitment to translate that possibility into reality?

All the scientific components are in place for developing a commercial fusion reactor, a fact acknowledged even by traditionally cautious scientists and engineers, such as the University of Wisconsin fusion reactor design group. At the recent Innsbruck meeting of the International Atomic Energy Agency on Controlled Nuclear Fusion and Plasma Physics, the Wisconsin group proclaimed that we could begin building a prototype fission-fusion hybrid reactor now that would be producing commercial quantities of energy by 1985! Mark that number—in six and one-half years!

There can be no doubt that the time has come for a crash program for fusion development like the Apollo space effort. Based on studies conducted by the Department of Energy and its predecessors, it is certain that with funding on the level of $5 to $10 billion a year the United States could build the first prototype pure fusion reactor by 1990—no more than five years after the first fission-fusion hybrid. At this point, the determining factor in the fusion timetable is only money.

The possibility of an Apollo fusion program is now being discussed in congressional circles, and a number of influential congressmen and caucuses are mooting the necessity of such a crash program to solve the nation's energy problems. Astute observers in the press and on Capitol Hill also have noted that such a program and commitment to fusion research would be the basis of strengthening the dollar overseas, of revitalizing our domestic economy, and, most of all, of restoring America's place as the technological and scientific leader of the world.

Given the stakes in the fight for unlimited energy, a crash program for fusion development under the guidance of an agency like NASA is a modest proposal. A mission-orientation coupled with a broad-based scientific research effort would guarantee that fusion and its spinoffs would power this country, and the world as well, prosperously into the 21st century. Another Apollo program is a small price to pay for the future of the human race.

In testimony last year, Dr. Edwin Kintner, the director of the U.S. fusion effort, told Congress that it was the consensus in the fusion community that the question of fusion was no longer whether it could be done, but "when, where, and by whom it will be done."

The Princeton results and fusion's prospects for the coming year now make this obvious. Kintner's speech at the Innsbruck fusion meeting, where he delivered the first Artsimovich Memorial Lecture, eloquently posed the challenge:

> If we in the fusion community can build on the great beginning which has been made and carry forward with the development of fusion—hopefully, optimistically, enthusiastically working together toward providing unlimited energy, the fundamental energy of the universe—. . .we can once more believe in ourselves and in science as the noblest most constructive activity to which the mind of man can be turned. We may help reestablish that no one need fear shining the bright searchlight of the human mind on the many remaining dark corners of our understanding of the universe around us.

# Calendar

**October**

2-6
IAEA International Symposium
on Nuclear Material Safeguards
International Atomic Energy Agency
Vienna

5-9
Energy Expo 78
National Society for
Energy Awareness
Washington

16-19
International Meeting
on Nuclear Power Reactor Safety
American Nuclear Society
European Nuclear Society
Japan Nuclear Society
Brussels

# Letters

### THE SCIENCE OF EVOLUTION

To the Editor:

In every magazine received to date there have been articles relating to evolution as though it were fact instead of fiction. Please cancel our subscription to your magazine immediately. . . .

Gary L. Inman
Executive Secretary-Treasurer
New Mexico Baptist Foundation
July 18, 1978

**The Editor Replies**

The research results published in *Fusion* have strongly and consistently attacked the Darwinian ideas of evolution and the descent of man. The fundamental presumption of Darwinian evolution is that the biosphere, and most important, man, have developed solely by chance. A growing number of biologists are convinced that such a view of the billions of years of life's existence on the earth is *scientifically* absurd (see especially the research reported in the article "The Origins of Life," June 1978).

As for the more basic *philosophical* implications suggested in your letter: The Fusion Energy Foundation's conviction in the necessary progress of mankind would be untenable if man and his place in the world were only the result of a lucky set of mutations. To put this in religious terms: We have faith in man's unique role in the universe, a faith parallel to the religious faith that man is created in the image of God. Man's task today is to *continue* the process of creation. Without a commitment to and responsibility for continual striving for progress and development, man becomes a beast.

I will cite one example here of how the deeply religious implication of scientific research has affected some *Fusion* readers. Rev. Arthur Farrell of the Ninth Street Baptist Church in Cincinnati has prepared a series of sermons on the religious implications of recent scientific research reported in *Fusion*. In his view (and mine) these results show clearly that modern science corroborates the religious conviction that man has both free will *and* a moral responsibility to use that free will for the further progress of the universe.

Steven Bardwell
Associate Editor

### THE SEABROOK LINCHPIN

To the Editor:

I am currently working at the Seabrook Station nuclear power project. As you well know, the future of this project is questionable. . . .

Seabrook Station is the linchpin of the nuclear industry in the eyes of the zero-growth movement. They believe that both the utility company and the state government are too small and weak to fight back.

My vocation is the testing of construction materials. I have worked on roads, airfields, hospitals, schools, etc. I consider nuclear power plants to be the most important projects on which I have worked. I believe that we have a choice between continued industrial growth and societal stagnation. I prefer the former. The issue is not simply one of nuclear power. The issue is the choice between a guided growth of technology, or zero-growth coupled with conservation and ultimate collapse of an already faltering system. Conservation is vital, but it is not a means to a utopian end. "A barrel saved is *not* a barrel produced." It is only an intelligent method of buying time. If we do not use this time, we will have wasted the barrel thus saved anyway.

Seabrook, N.H., is a good location for the power plant. We already have a water shortage problem along the coast and when the plant goes into operation we have the option of desalinating sea water with the waste heat, using water taken from the intake tunnel. If this is done, the plant will not have to compete with the towns for water, but can produce enough to aid the existing water supply. In the winter, when the water is not such a problem, the waste heat can be circulated to the ocean to maintain an optimum temperature for the ocean life. No other plan will solve the water problem and, simultaneously, the energy problem. The plant is being built on the site of the town garbage dump and a forested swamp at the edge of a salt marsh. If the nuclear plans are scrapped, either a coal or solar plant will be built. Both options would be far more harmful to the local ecology. . . .

Your magazine emphasizes the negative aspects of the British while they have gone on to build helium-cooled reactors and continue research and our own country calls a moratorium on nuclear development. You are also critical of NASA's space power satellite and colony project. This is a small gamble which must be tried. Even if it fails to produce the projected results, the knowledge gained will be valuable provided the investment is not permitted to go wild.

Raymond J. Finley
Exeter, N.H.
July 14, 1978

**The Editor Replies**

The zero-growth environmentalists and antinuclear terrorists made it clear that Seabrook was their crucial test case against technological and economic growth—and fortunately for our future, they failed the test.

The Seabrook battle is much more than a national issue, however; it is a fight that must be fought and won on the battlefield of international economics and politics. America's economy can survive and expand only through the production, sale, and distribution of its high-technology products (like nuclear reactors), here in the United States and, most importantly, as exports worldwide.

The agreement reached at the recent Bonn summit meeting, which initiated a new credit institution, the European Monetary Fund, that is explicitly designed for funding these high-technology exports, was a major victory in this international battle. Our fight now is to see that the United States fully supports and expands this credit institution.

There are two aspects to the Fusion Energy Foundation's policy on nuclear energy: the mass production for export of nuclear technology to build nuplex cities across the globe, and the continuous development of the whole spectrum of more productive technologies. This will enable us to solve two basic problems: developing the labor power and cultural levels of the entire world's population and opening up a limitless resource base.

As for your comment on the British, it is true that Great Britain has a well-developed nuclear power industry based on the gas-cooled reactor concept. It is also developing the liquid metal fast breeder reactor, which is necessary since its available domestic sources of fossil fuel are severely limited. However, this nuclear development has nothing to do with the international financiers based in the City of London who stand to lose their control over a large portion of the world economy if the Bonn agreements and fusion power are implemented. This British faction is doing everything in its power to sabotage the European Monetary Fund and an expanded export policy for nuclear power plants and technology.

We agree with you about the necessity of planning for large-scale space exploration and colonization, but that will require a rapid transition to a fusion-based economy here on earth. That future defines the fight for Seabrook and progress in the United States.

Jon C. Gilbertson
Nuclear Engineer
Member, FEF board of trustees

# The Lightning Rod

My dear friends,

I find among my monthly mail a number of items that confirm my suspicion that an epidemic of lost wits has hit the continent. We have:

*The *New York Times* reports on research published in *Science* magazine: "The goal was to test the controversial hypothesis that such inhabitants of North America as the mammoth, mastodon, giant beaver, giraffelike camel, and elephant-sized sloth were victims of human overkill. . . . Proponents of the human overkill explanation describe finely chipped spearheads as 'the first weapons of mass destruction.'" [Fortunately, aboriginal man was not yet saddled with the National Environmental Protection Act.]

**Scientific American* reports in a special issue on evolution that: "Altruistic [that is, social] acts do not appear to contribute to the survival of the animals performing them. . . . The gene associated with an altruistic act will increase in frequency because of the act only if the coefficient of relationship between the performer and the beneficiary is greater than C/B, where C is the cost (in Darwinian fitness) of the act to the performer and B is benefit (in Darwinian fitness) of act to beneficiary."

Old Adam Smith and Jeremy Bentham worked out the very same equation in my heyday, albeit without the genetic absurdity, when they weren't busily plotting the overthrow of the American Republic. Perhaps the publishers should change their magazine's name to *Unscientific American*, or *Scientific Unamerican*, or *Unscientific Unamerican*.

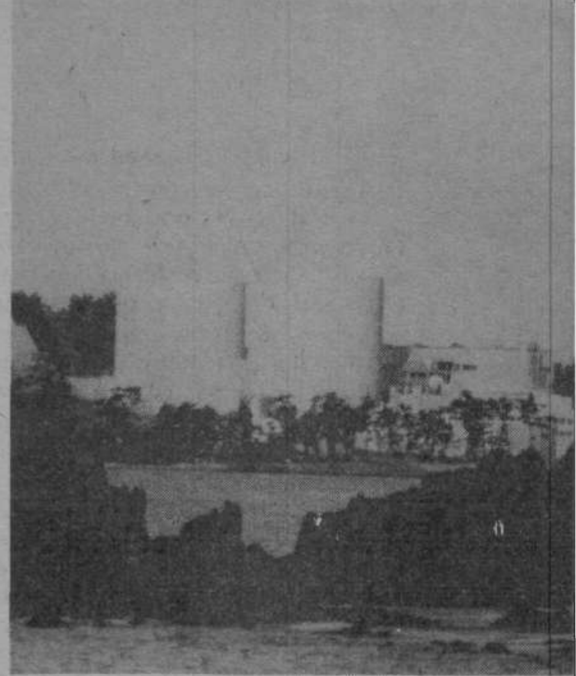
Benj. Franklin

# News Briefs

**UNITED STATES AND JAPAN AGREE ON FUSION PRIORITY**

After a three-day meeting in Tokyo in early September, U.S. and Japanese delegations agreed that nuclear fusion will be the priority area of a joint research program in energy development. A joint communique issued in Tokyo stated that both nations also agreed to cooperate in coal liquefaction research, solar energy photosynthesis, geothermal energy, and high-energy physics. The program has been under discussion since May when Japanese Prime Minister Takeo Fukuda proposed a $1 billion joint effort centering on fusion. In an earlier negotiating meeting in Washington Aug. 2, the U.S. Department of Energy had made coal conversion the top priority, not fusion, but the Japanese insisted on fusion.

John Deutch, DOE director of research, headed the U.S. delegation, and Hiromichi Miyazaki, deputy foreign minister, led the Japanese group. In a public statement, Miyazaki said that the specifics of the research projects and financing were to be decided jointly by the Japanese Diet and the U.S. Congress. A follow-up meeting is scheduled for October.



*A Westinghouse-built nuclear power plant in Japan.*

**ENERGY BILL MAY FINALLY PASS**

After months of rough going, parts of the administration's unpopular energy bill may finally find their way out of Congress. Congressional leaders now seem determined to pass the natural gas compromise in order to show some support for President Carter. A Senate vote is expected Sept. 19 on whether to commit the compromise bill back to committee—a sure death sentence—and the bill's supporters expect it to pass then and in a future vote.

Nobody likes the bill in its present form. The compromise would create 17 different categories of natural gas pricing, and according to industry spokesmen is a "regulatory nightmare." Even the White House is now lobbying on the basis that the natural gas bill is bad, but it's the only thing around and after it's out of the way Congress can start moving with a real energy program. Many congressmen, however, are prepared to take this a step further, voting for the bill along the lines Senator Adlai Stevenson outlined before the Illinois State AFL-CIO convention Sept. 13: "The President's energy program is not enough. But it is all we have. It could be the beginning of a global effort to expand production of fuels led by the United States."

**SCHLESINGER TIES OWN FATE TO ENERGY BILL**

Energy Secretary James Schlesinger has threatened to resign if his energy legislation is not put into effect. Speaking on the national television program "Face the Nation" Aug. 20, the energy czar said: "If we don't get either the natural gas compromise or the crude oil equalization tax, I will consider my usefulness as energy secretary to be at an end."

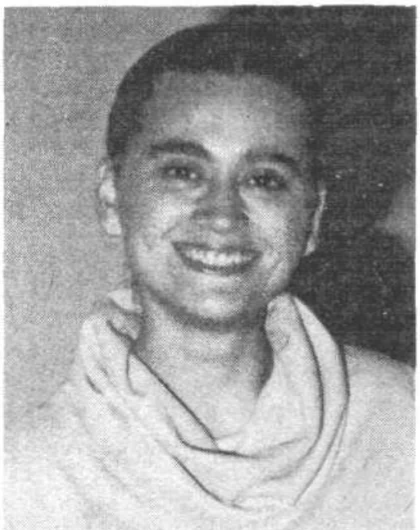
Experienced Washington observers believe that Schlesinger is so discredited in Congress and the Executive branch that he will be forced to resign whether or not the energy bill limps through.

*On the way out?*

**GILBERTSON TESTIFIES BEFORE VERMONT NUCLEAR PANEL**

Nuclear engineer Jon Gilbertson, a member of the Fusion Energy Foundation, presented expert testimony before the Vermont State Nuclear Advisory Panel Sept. 8 in Montpelier, urging the panel to continue on its nuclear path. In what one industrial representative called the "best testimony I ever heard," Gilbertson made the case for nuclear energy as the most economical power source and debunked the popular myths about solar energy.

Gilbertson's testimony, invited by the panel, was interrupted by six masked and costumed protesters who said they were from the Clamshell Alliance and the Public Interest Research group. The environmentalists, who were forced to desist by the meeting chairman, alleged that they had been "harassed and terrorized" by the FEF, the U.S. Labor Party, and the National Caucus of Labor Committees. In a later interview Gilbertson pointed out that environmentalist groups often provide safehouses for actual terrorists, a fact documented by a variety of independent and government sources here and in Europe. "These groups have a record of illegal antinuclear activity, and they are upset because they know the FEF has been effective in mobilizing that majority of the population that favors full use of fission power and the development of fusion power."



*Cecilia Soto*

**FEF LAUNCHES MEXICAN ORGANIZATION**

The Fusion Energy Foundation held the founding conference of its Mexican branch in Mexico City Aug. 24, with 80 representatives of business, industry, government agencies, trade unions, political parties, and press in attendance. The main speakers at the conference were Dr. Morris Levitt, executive director of the FEF, and Cecilia Soto de Estevez, a member of the board of directors of the Mexican FEF. Levitt told the group: "It's most appropriate that this is the first major FEF event after the announcement of the Princeton results. The real significance of fusion is that it is the essential technology for global development, and the roles of the U.S. and Mexico will be intimately linked in this process of development."

Three Mexican dailies reported on the conference, *Universal*, *La Prensa*, and *El Sol*.

**GOVERNORS CONFERENCE CALLS ON U.S. TO GO NUCLEAR**

At an annual meeting in Boston Aug. 28-29, the National Governors Association passed a near-unanimous resolution calling on Congress to rapidly implement all aspects of nuclear fission. The governors specified that this includes programs for nuclear waste storage and shipment, the expediting of nuclear plant siting procedures, the construction of more light water reactors, and the development of the fast breeder reactor.

Governor Ella Grasso of Connecticut was alone in an unsuccessful attempt to foist solar power on the conference. The fight for a nuclear energy policy was led by Governors Dixy Lee Ray of Washington, Meldrim Thomson of New Hampshire, and James Edwards of South Carolina.

**OCTOBER LOUSEWORT LAURELS TO SCIENCE MAGAZINE**


Unfortunately for humanity, the 20th century is burdened with some disadvantaged individuals whose minds are so small that they cannot encompass even the idea of an unlimited energy source. In fact, the very thought of fusion energy seems to send them to all lengths to explain it away as insignificant, so that their lives can continue on undisturbed by big, new discoveries.

Take the Sept. 1 issue of *Science* magazine, for example, which titles its news story on Princeton, "Report of Fusion Breakthrough Proves to Be a Media Event." Aside from some scientific inaccuracies, what the article conveys most strongly is a fundamental desire to stop progress.

This fusion breakthrough is just an ill wind blown up by the media, *Science* reporter William Metz tells readers. "Now that it is over," he concludes, "people can resume reading their solar energy catalogs again, continue with plans to insulate their houses, and put aside a little longer the dream of cheap energy. It may not have been the last word on fusion, but it sure was a good story."

Appropriately, we award *Science* with October's "Lousewort Laurels."

# International

# IAEA Innsbruck Meeting Charts Fusion Progress

More than 600 scientists gathered at the International Atomic Energy Agency's Meeting on Controlled Nuclear Fusion and Plasma Physics Research in Innsbruck, Austria Aug. 23-28 to discuss recent progress in fusion research and to map out the immediate future in the march toward commercial fusion power.

The optimistic tone of the meeting was set in the keynote address by Dr. Edwin Kintner, director of the U.S. fusion office. Kintner delivered the first Lev Artsimovich memorial lecture in honor of the leader of the Soviet fusion effort, who died in 1972. (See this issue for text of the Kintner speech.)

Appropriately, the first scientific report at the meeting was from the Princeton research team, who described in detail how they had overcome the last essential scientific barrier to harnessing the unlimited energy of fusion reactions by obtaining temperatures beyond 60 million degrees.

As the Princeton researchers emphatically stated, these temperatures were achieved with a stable confinement of the hydrogen plasma 100 times better than that minimally needed for commercial fusion power plants. With the PLT, as with the Massachusetts Institute of Technology tokamak, the Alcator, the most optimistic result appears to exist: There is no limit to the temperatures that can be reached in a tokamak.

The importance of the Princeton results to the world fusion effort was also noted in the audience response to the report—a standing ovation.

In addition to reports on continued progress across the entire spectrum of fusion research programs, a chief activity of the meeting was charting the course to commercial fusion power in the next decade.

The Japanese delegation met at length with the leadership of the U.S. fusion program to discuss the proposal of Prime Minister Fukuda for joint fusion research, while other informal gatherings worked out how to implement the IAEA International Fusion Research Council 1977 resolution to accelerate and broaden the world fusion effort.

### Fusion Feasible Now

At the session on fusion power reactor design, Dr. Robert Conn, director of the University of Wisconsin fusion reactor design group, said that the PLT and other experimental results have demonstrated that current projections for a commercial fusion timetable are much too conservative. "Already, today, the physics of tokamaks is understood well enough to construct fusion-fission hybrid reactors."

Conn noted that tokamak reactor designs have progressed technologically to the point where only a linear step in scale is required to build reactors larger than the generation of experiments now being constructed. The Princeton Tokamak Fusion Test Reactor, scheduled to begin operation in 1981, is only half the size of current reactor design projects, he noted. And the current designs are more than economically competitive, Conn said, since their capital costs would be about the same as those for present fission reactors, and there are virtually no fuel costs.

The tremendous rate of scientific-technological progress can be gauged by the fact that neutral beam heaters used on the PLT did not even exist in 1971, Conn said. He pointed out that no further significant technical developments are needed for the application of neutral beam heating to full-size fusion power plants.

Most significant, this session demonstrated that progress in reactor design is not being limited to tokamaks. Other systems, such as the tandem mirror, whose scientific principles of operation are about to be demonstrated in laboratories in the United States, the Soviet Union, and Japan this fall, are following in the footsteps of detailed tokamak reactor design leading to economical and technically feasible systems.

One dramatic example was given by Dr. Harold Furth, director of research at the Princeton laboratory. Taking the advanced theoretical and experimental work of researchers Winston Bostick and Dan Wells on force-free plasma structures, Furth detailed the design for a very compact and economical reactor system.

Although tokamaks were the center of attention, it was clear from other reports that other approaches, such as laser inertial confinement systems, are rapidly advancing and could possibly overtake the tokamak.

—*Charles B. Stevens*

## Colombia Plans First Nuclear Plant by '85

Colombia will have its first nuclear-powered electricity generating plant installed by the year 1985, according to the director of the country's Institute of Nuclear Affairs, Ernesto Villareal Silva. By the 1990s, Colombia will have fully entered the nuclear age, he said, with its own supplies of uranium and the development of a series of nuclear-related industries including metallurgy, quality-control, and manufacture of heavy components.

Villareal's announcement, which was widely covered in the Colombian press, also noted that "the introduction of controlled nuclear fusion in the first decades of the next century could provide an almost inexhaustible energy source for worldwide growth."

"A nuclear project," Villareal said, "implies the acquisition of technologies in a whole range of industries and would permit Colombia to prepare itself to make use of nuclear fusion—of which the sun is the best example—by the beginning of the next century."

# Washington

# Seabrook Work Resumed

Construction of the Seabrook, New Hampshire nuclear power plant is back in swing, following the Aug. 10 decision by the Nuclear Regulatory Commission to order immediate resumption. The commission ruling followed a determination a week earlier by the Environmental Protection Agency that Seabrook complies with the requirements of the Clean Water Act.

The commission had ordered a halt to construction July 21, pending an EPA review on the plant's proposed cooling system, which discharges water into the ocean through a series of 2.5 mile-long tunnels. In its ruling, the EPA disputed the environmentalist opposition, arguing that the water discharge system "would not have a significant effect on the population of fish, shellfish, and wildlife in and on the receiving waters."

Four members of the commission—Peter Bradford, John Ahearne, Victor Gulinski, and Richard Kennedy—participated in the decision. Kennedy said in a concurring separate opinion that construction at the Seabrook site should not have been halted pending the EPA decision and that stopping construction constituted an unwarranted and frivolous intervention into the plans of participating companies and their construction workers.

### Environmentalists Shocked

A spokesman for the electric utility, Public Service of New Hampshire, which has spent more than $400 million on the plant, said, "we're very, very happy" and called the series of legal challenges by environmentalists nothing but "legal harassment."

Governor Meldrim Thomson of New Hampshire was less polite. Responding to an announcement that the militant antinuclear Clamshell Alliance will now resort to illegal demonstrations against Seabrook, Thomson said: "The great majority of our citizens who do want Seabrook are tired of having a filthy, a foul and un-American minority interfering with their lives. I suggest that this gurgling, spurting bunch of nonproductive individuals who have no understanding of our constitutional form of government might best change their ways or leave the country."

*Thomson*

Initial reactions from the environmentalists were of shock and demoralization. A spokesman for the Friends of the Earth told a reporter: "My comments are not printable....It is a dark day around here...." The spokesman said his organization was stunned by the EPA ruling and was certain that it involved "arm twisting" from the White House.

### Editor's Note

*In an article on the Seabrook decision in the August 1978 issue, we were incorrect in quoting Washington sources who said Commissioner Joseph Hendrie had abstained from voting on the Seabrook case because of public attacks from environmentalist James Cubie. In fact, Hendrie had disqualified himself from the case when he joined the commission. This was a matter of standard procedure, because of his prior involvement with the Seabrook plant.*

# National

# Bomb-Proof Plutonium Developed


*The development of bomb-proof plutonium should put an end to antinuclear propaganda like this sample from the* New York Times Magazine.

Scientists at Allied General Nuclear Sciences have designed a nuclear fuel reprocessing system that guarantees commercial reactor plutonium cannot be used in an atomic bomb. The company is the owner and operator of the nuclear fuel reprocessing facility at Barnwell, South Carolina.

The Fusion Energy Foundation learned from sources within the scientific community that these results will completely eliminate the possibility of making atomic bombs from *commercial reactor plutonium* by intentionally contaminating plutonium with an isotope that has high heat generation.

**How It Works**

The process is very simple. It consists of initially enriching new, unirradiated reactor fuel with U-236, a nonfissionable isotope of natural uranium. During the irradiation of the fuel over its two-to-three-year lifetime in the reactor, some of the U-236 atoms will absorb a neutron, becoming neptunium, Np-237. This subsequently also absorbs a neutron to become Pu-238, a nonfissionable isotope of plutonium. Since it has an 89-year halflife, the Pu-238 will remain with any plutonium removed from the reactor for many years.

The important thing about Pu-238 is that it decays with a high-energy alpha particle, and if it is enriched to between 5 percent and 10 percent of the total plutonium content, it will heat plutonium metal up beyond its melting point in any conventional atomic bomb configuration.

This heating is what eliminates such a material as a bomb component. The only possible alternative would be to divide the critical mass up into tiny segments that could be cooled below the melting temperature, a procedure that would drastically complicate the triggering and timing mechanism of the bombs. In fact, the mechanism would become so complicated and *difficult to perfect that the* U.S. weapons experts have reportedly judged it to be impossible to build, even by them!

The response to this breakthrough from the Department of Energy has been to put the results under the wraps of a security classification, therefore temporarily keeping it from public perusal. However, if all indications check out as fact, as seems to be the case, the new system will end nuclear proliferation as an antinuclear issue.

In an article in *Nucleonics Week* reporting on the new process, Senator Strom Thurmond, a South Carolina Democrat, called the Allied discovery a "breakthrough" that would "add a measure of deterrence, such that subnational and national groups would be discouraged from considering reactor spent fuel and the plutonium therein as a source of weapons material."

# Ohkawa: 'U.S. Must Develop Universal Energy Resources'

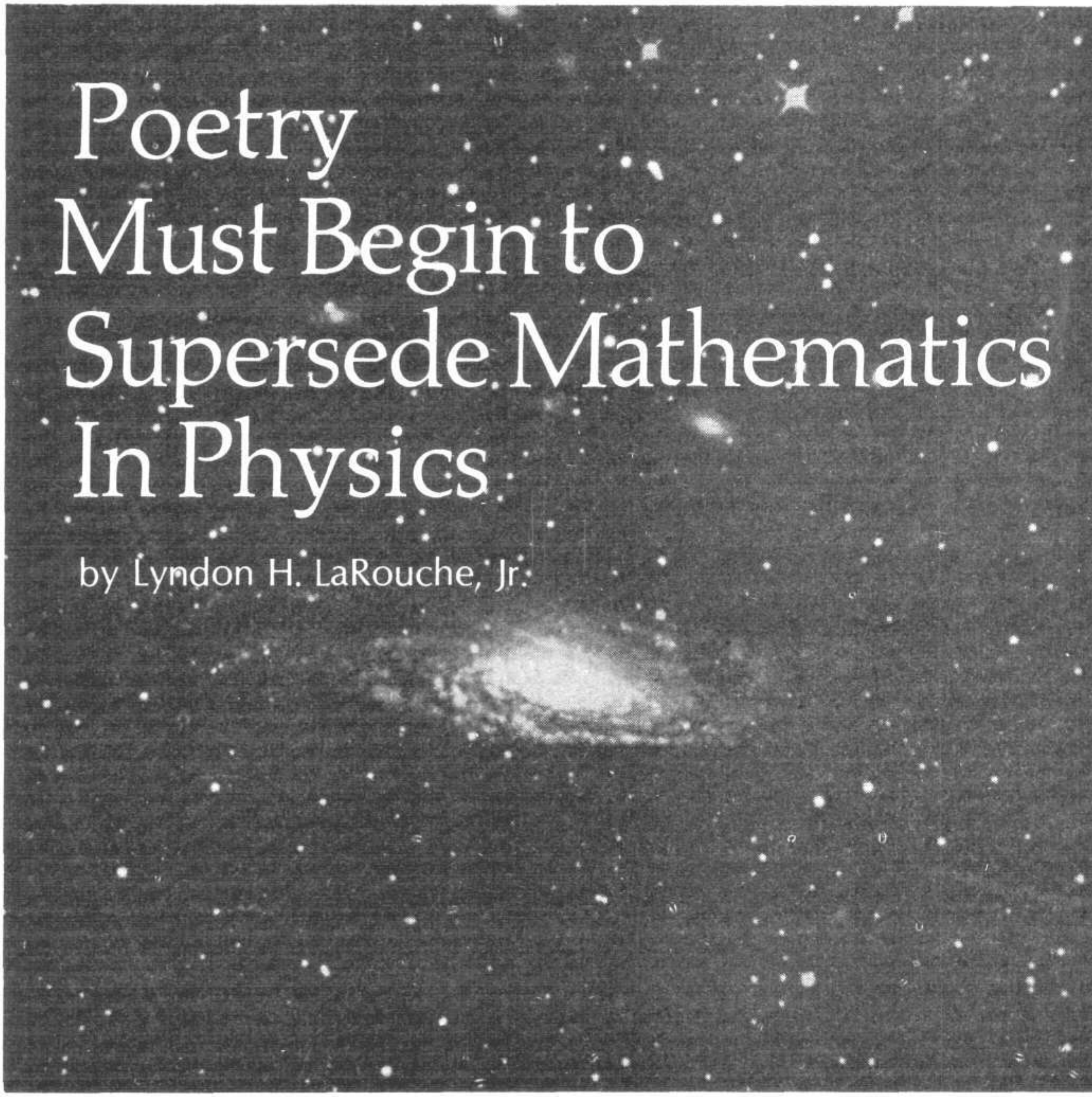
The failure of the United States to develop universal energy resources—fusion and fission—in cooperation with the rest of the world "will invite the decline of U.S. power and threaten its security," said Dr. Tihiro Ohkawa, vice president of General Atomic Company. Ohkawa's remarks on U.S. energy strategy appeared as a statement of personal views in the latest issue of *Fusion Forefront*, the newsletter from the Department of Energy's Office of Fusion Energy.

There are *universal* energy sources, which are available almost anywhere or are easily transportable, and *local* energy sources, which are the opposite, Ohkawa said. If the United States goes with its present stated emphasis on coal power and solar power, "the U.S. economy will be more low technology . . . based on agriculture and on low technology industries. . . ." Since the world economy will probably be dominated by those countries which developed high technology, he said, "*The world power balance will* shift towards those countries."

Ohkawa attributes the problem to the "apparent inconsistency between the present U.S. world policy and the U.S. energy policy. . . The U.S. world policy is not an isolationist policy. It is well recognized that the rest of the Western world is important for the U.S. economy and security. However, the U.S. energy policy is tending to be an isolationist policy. The argument that the reduction of import oil by coal conversion or conservation will free Middle East oil for consumption in the rest of the Western world forgets the fact that the problem is merely shifted to the other countries. This is not an acceptable solution for these countries. They must and will develop their own universal energy sources. For example, Japan has designated the breeder reactor and fusion power as top priority national projects."

# Poetry Must Begin to Supersede Mathematics In Physics

by Lyndon H. LaRouche, Jr.



*"...The machine of the universe has, so to speak, its center everywhere—its circumference nowhere, because God is circumference and center, He who is circumference and nowhere."—Nicholas of Cusa*

*In his work on Learned Ignorance, from which this quotation is taken, the Renaissance intellectual Nicholas of Cusa uses analogies from geometry (in this case a circle with infinite diameter, whose circumference approximates a straight line) to discuss the paradox of the infinite. It was Cusa's work on the physical continuum, in which he develops the Archimedean tradition in mathematical physics, that laid the basis for Leibniz's development of the calculus and for the specific concept of the transfinite later developed by Cantor and Riemann.*

*As LaRouche notes, and as these scientists themselves were aware, mathematical reductionism does not permit such creative breakthroughs; creativity requires the activity of human reason.*

*EDITOR'S NOTE*

*It is most appropriate that we lead off the second year of* Fusion's *publication with some of the best fusion news in recent years and with this theoretical article by Lyndon H. LaRouche, Jr.*

*The recent Princeton breakthrough and the impressive lineup of fusion breakthroughs expected in the next weeks have made us even more aware of the major task of* Fusion *magazine: educating scientists and potential scientists to make full use of their creative abilities for generating an increasing rate of discovery. How to do this is the question LaRouche addresses.*

*A noted economist, LaRouche is chairman of the U.S. Labor Party and the National Caucus of Labor Committees.*

Fusion *welcomes comments on science and epistemology from other public figures.*

* * *

THE COMING, QUALITATIVE ADVANCE in outlook upon physics will begin to occur soon, and will be aptly described as the emerging hegemony of the principles of *the Neoplatonic science of poetry* within the so-called physical sciences. We shall begin to accomplish what the followers of the cult of Apollo and of Francis Bacon have always been terrified we Platonics-Neoplatonics might succeed in accomplishing. *Poetry will rule science.*

For purposes of reference, I select two features of the recent year's published work by Dr. Steven Bardwell. First, I refer to Bardwell's formulation of the way in which plasma phenomena such as solitons divide inorganic physics into two distinct, multiply connected subdomains.* These domains are causally linked in the practice of experimental plasma physics and are otherwise mutually efficient. However, they are respectively so ordered that the mathematical determinism of the lower domain does not accompany causality in the emergence of the higher domain. Second, I refer to the recently published treatment of the many-body problem.** Whether or not Bardwell was thinking of this implication as he wrote, the approach to the use of phase space he employs is a proper borrowing of little-understood principles of the Neoplatonic *science of poetry.*

I now turn the reader's attention to several writings of the past 12 months interval in which I have treated the proper distinctions among the domains of knowledge corresponding presently to "inorganic physics," "organic physics," and "reason"—which I have denoted, respectively, by the *transfinite* denotations "n," "n+1," and "n + 2."† I also refer to two of my recent writings in which I have treated Edgar Allan Poe's conception of poetry and Neoplatonic method.‡ I propose to outline now the direct connection among Neoplatonic poetry (for example, Dante and Petrarch), the double-fugal method of contrapuntal development exhibited by Beethoven, and the proper *application of poetry to the so-called physical* sciences. I shall make this connection by focusing on the relevant aspects of the preconscious processes of the mind.††

The reader must emphasize what I have outlined previously concerning the most accessible empirical features of the preconscious processes. I have emphasized, first, the *point in the process of recollection* in which *memory* has not yet seized upon the name of the thing being recalled, but has that thought nonetheless "on the tip of my tongue." It is the form of preconscious thought so empirically accessed that is the easiest first step in study of preconscious processes—the most accessible aspect of preconscious psychology.

At this level, we study the way in which preconscious conceptions act as *transfinites,* such that they are associated implicitly with alternative communicable predicates, each predicate appropriate to the conjunction of the preconscious thought with either another preconscious thought or a definite circumstance of practice. The operation known as *deduction* depends entirely upon the way in which preconscious transfinites are linked to their associated arrays of communicable predicates. The second, next-higher order of inquiry into the preconscious focuses upon the condition of problem-solving in which a person has a correct solution, original to his or her experience, "on the tip of my tongue." This latter is a *preconscious act of insight,* as formally distinct from a preconscious act of recognition (memory).

This aspect of knowledge is essentially very ancient and is recorded in medieval studies of the "arts of memory." One can make no proper sense of Giordano Bruno's work on the "arts of memory" unless this content and purpose of *the matter is the point of reference for study.*

*In first approximation,* preconscious thought is unutterable, as distinct from the utterable, conscious predicates of conscious thought. One can identify a nameless preconscious thought in communication only indirectly, by listing sufficient of its diverse, logically unconnected, conscious predicates to suggest to the mind of a reader or listener that only the preconscious conception corresponding to that logically ambiguous array of conscious predicates is intended.

That principle is the essence of poetry. Poetry is not

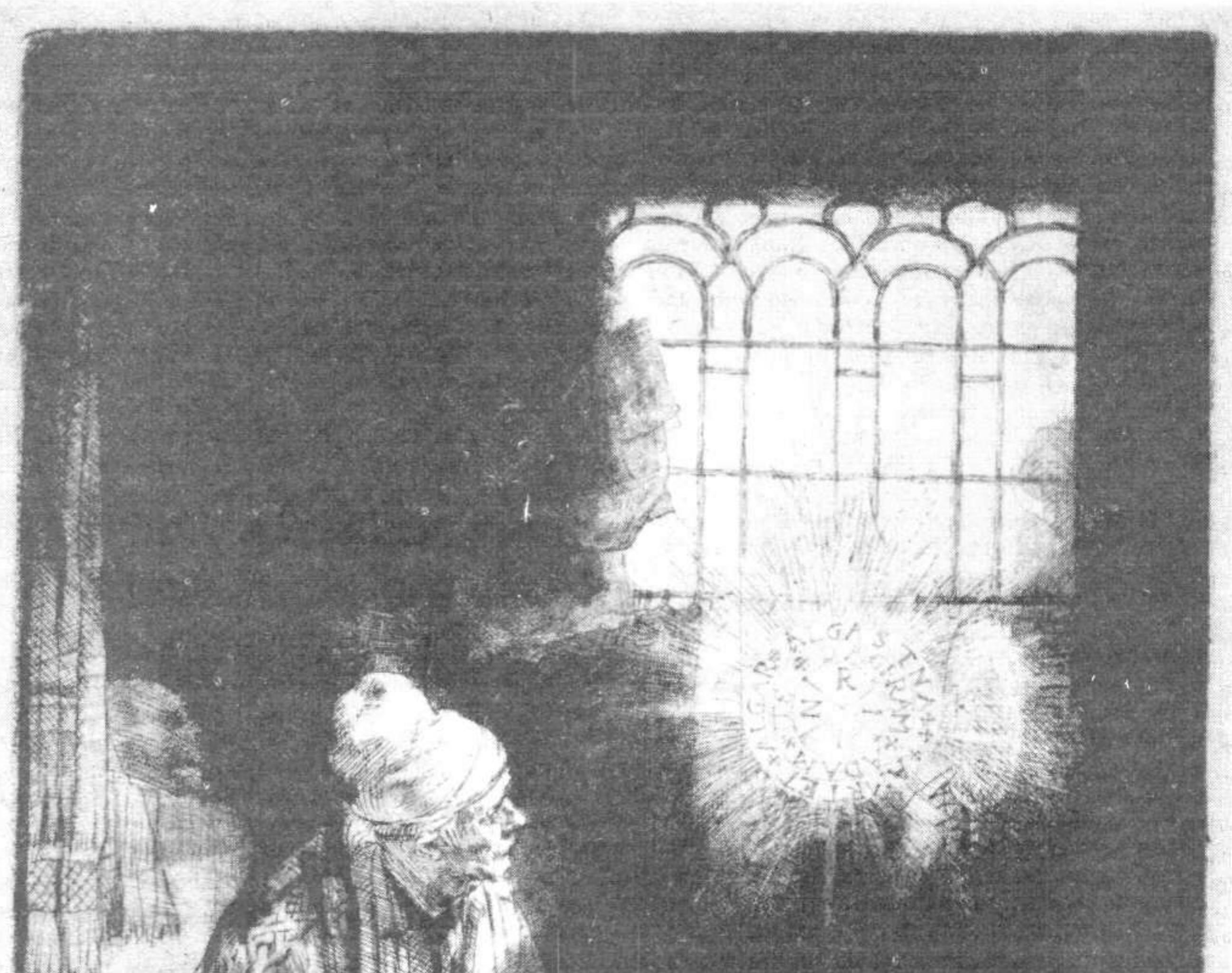
* See Bardwell's series of three articles. "Frontiers of Science in Plasma Physics." *FEF Newsletter*, Vol. I, no. 6 (June 1976); "The History of the Theory and Observation of Ordered Phenomena in Magnetized Plasma." *FEF Newsletter*, Vol. II, no. 2 (September 1976); and "The Implications of Nonlinearity." *FEF Newsletter*, Vol. II, no. 2 (March 1977).

** "Solving the Three-Body Problem." by Steven Bardwell, *Fusion*, Vol. I, no. 8 (June 1978).

† See, especially, "The Secrets Known Only to the Inner Elites," *The Campaigner*, Vol. 11, nos. 3-4 (May-June 1978). For an early treatment of these transfinite denotations, particularly as they relate to music and poetry, see "The Science of Music," *New Solidarity*, Jan. 20, 1978 and Jan. 24, 1978.

‡ "The Clinical Significance of Poe's Critics." *New Solidarity*, May 23, 1978 (Part 1) and May 25, 1978 (Part 2). See also "Poe's Conception of Poetry," *The Campaigner*, Vol. 11, no. 6 (September 1978).

†† I could also include an account of the notion of the consubstantiality of the Trinity as put forward by Plotinus et al., but that would be perhaps a bit much of a strain for most readers at this point in the process of education.



properly symbology, or any sort of ambiguity that uses one literal form of expression to indicate merely another literal form of expression. The ambiguity intrinsic to *true* poetry identifies the function of poetry as that of definitely indicating the preconscious conception that corresponds to such a logically inexplicable array of communicable terms. Edgar Allan Poe is explicit, and correctly so, in explicating the method of composition of "The Raven" according to such poetic principles. *There is no "Lenore" in fact—just as an existent "Beatrice" or "Laura" have no significance for the actual content of the poetry of Dante or Petrarch.* These are predicates, combined with other predicates, *configured poetically* to reach past ordinary consciousness to a definite preconscious conception in the mind of the audience.

The same Neoplatonic principle of poetry is expressed in a concentrated way by the principles of music running through Al-Farrabi, John Bull, Bach, and Beethoven. First, the notes in themselves are of no literal significance. Rather, linear configurations of notes correspond to *preconscious musical ideas*. The contrapuntal development of these configurations produces altered musical (preconscious) ideas, which are essentially in a preconscious process relationship to preceding musical ideas. The listener knows that he has reached a musical idea corresponding to Beethoven's intent if the stretto or strettolike elements of the composition as presented conform, as an array of predicates, to the preconscious musical idea the audience is intended to reach through experiencing the composition as a whole.

Then, using that agreement in musical conception as a reference point, the audience's mind runs through the entire composition once more, now from the vantage point of "understanding" the stretto preconsciously. The musical composition is not, however, the stretto, not merely a way of getting to the stretto as a musical-idea resolution. The stretto-idea serves as a crucial keystone for assimilating the process of development represented by the composition as a whole—as a preconscious musical idea.

It is for that reason that the late Wilhelm Furtwangler was a relatively great conductor, and Herbert von Karajan bereft of actual musical thinking in his mode of conducting. Furtwangler conducted by reading "between the notes," by performing the composition according to the musical (preconscious) ideas in a process of development. Karajan has aimed at "Prussian" reading of the literal score. Furtwangler's conducting of Beethoven is "alive"; Karajan's conducting presents us with the canonically arranged corpse of Beethoven. The late Arturo Toscanini, although not as unpoetic as Karajan, nonetheless erred in the same general direction as Karajan by comparison with Furtwangler. In Karajan's conducting, there is no poetry, and hence no music.

We have stated that *in the first approximation* preconscious conceptions are not of the form of utterable, communicable, *conscious* conceptions. This does not imply that they are not capable of *being made conscious* in the second approximation. By giving a name to an *abstract* (preconscious, transfinite) conception, the name of the conception becomes utterable. It is merely necessary that the persons who agree upon that name make such an agreement under conditions in which the corresponding preconscious conception is known to be present as an empirical object of reference in the mind of each. After that, the named preconscious conception is called forth by its name. It is now *abstract conscious* thought, of the sort employable for mental operations of deduction.

For example, the *universal* "brother." Brother is not an intrinsic quality of a person as an individual person. From the standpoint of mere deduction, there is no existent reality corresponding to the transfinite conception (abstraction) "brother." Rather, "brother" is a transfinite that defines all its specific predicates ("that is my brother," "that is his brother") in a well-ordered way. From the standpoint of rules of deduction, deduction (deductive consciousness) does not know the existence of "brother" as an actuality, but knows only the procedures under whose governance a specific person is or is not a predicate of the abstract notion "brother." There is also a higher abstraction for the name "brother." The quality of relationship preconsciously associated with "brother" in its first-order usage can be meaningfully extended (named) to persons not "brothers," such that one can include "John's sister" under the *ethical* relationship of "brotherhood."*

In the given illustration, the significance of the abstract notion "brother" rises in order of notion by *metaphorical* steps, each of which is transfinite with respect to the lower-order notion. Thus, "brotherhood" is a higher-order notion than "brother," and so forth. Hence, contrary to a philistine tradition, the sort of punning enjoyed by William Shakespeare pertains to the highest form of humor, not the lowest. A pun is good or bad as it does or does not depend upon a metaphorical connection. If the former, it reflects the highest intellectual order of humor; if otherwise, it reflects sophistical banality.

*Metaphor is the predominant practice by which we select appropriate names for preconscious notions brought into the domain of abstract consciousness.* The employment of phase-space notions in Bardwell's treatment of the many-body problem is a form of such uses of metaphor, as

*This Rembrandt etching, known as "Faust," uses light to mediate the scholar's recognition of the tetragammon, a Neoplatonic symbol for secret knowledge.*

* Radical feminists and others might object foolishly to that latter extension of the notion of "brother." Yet, few sensible women wish to be treated as "sisters" in the way many cultures define the state of women. Rather, they demand the status of "brothers." To demand a "sisterhood" among women means, in most prevailing cultures, to institutionalize the inferior ethical status of women in those cultures, to make the norms of inferior status *appear* to be superior to what they are inferior to.

is the use of phase-space notions as a means for dealing with so-called imaginary and complex numbers.*

The activity of science is both the constant production of new preconscious conceptions and the *naming* of these newly created abstractions in such a way that deductive forms of analysis and ordering of predicated experimental and related practice can incorporate these new notions to the effect of establishing logical consistency within the body of scientific practice so transformed. In this crucial, determining aspect of scientific work, we are confronted with two principal sorts of problems. *The first class of problems* is that of educating the scientist (and prospective scientist) to be able to marshal his creative-mental potentialities to effect a high rate of fruitful discovery. *The second class of problems* is defined by the inability of the deductive systems of thought to incorporate fully the essential features of a valid preconscious (that is, scientific) conception.

*With respect to the first class of problems*, the principles of Neoplatonic poetry are the exemplar of the developed means for making the person willfully conscious of his or her preconscious creative processes. Training in the arts of memory, along the lines modeled by Giordano Bruno, is the background for this. Poetry of the type associated with Dante and Petrarch, and Poe's "The Raven"—is the practice of the combined, willful preconscious powers of memory and insight. A scientific education based on these principles is the key to fostering a higher ratio of fruitful creativity among potential scientists.

*With respect to the second class of problems,* the difficulty is axiomatic. No deductive system can adequately represent the kinds of notions that, for example, lie beyond Bardwell's outline of the causality and determinism problem in plasma physics, or in his approach to the many-body problem. Looking at both illustrative cases from the vantage point we are advancing here, the "genetic" connection among the preconscious conceptions behind both cases ought to be clear. To go directly to a point to be explicated, the preconscious ordering of scientific conceptions does correspond to the underlying lawful ordering of events in the universe, whereas the deductive reflection of those conceptions, such as axiomatic mathematical methods, does not. The limits of mathematical physics, as we presently define it, is not a matter of the limits of refinement of human experimental knowledge of physical processes. The limit for deductively ordered knowledge is the "region" of physical process-reality in which the axiomatic mathematical (deductive) ordering of process-conceptions loses practicable correspondence with the real process under investigation.

For example, the Copenhagen doctrine respecting so-called uncertainty. The problem of "uncertainty" does not exist with respect to experimental physics, but only with respect to mathematical physics practice as heretofore axiomatically defined. What Niels Bohr and others did, in fact, was not to announce a discovery, but to shriek like Dionysian maenads against the thrusts provided by Erwin Schroedinger, de Broglie, et al. By accepting the paradoxical evidence respecting the electron, and so forth as "particles"—"wavicles"—Schroedinger and de Broglie arranged the existing evidence and direction of further hypothesis and experiment in the course suitable to future progress in overcoming the inability of any axiomatic deductive system to deal with crucial phenomena at "the edges" of multiply connected domains. While the work of Dr. Winston Bostick, et al., respecting a nonparadoxical model of the electron is thus far only a useful working hypothesis,** it does illustrate the importance of the direction taken by Schroedinger and de Broglie in enabling future scientific progress. Bardwell's overview of that same matter points in the direction of such solutions.

This is precisely the methodological problem I confronted constantly in political economy (and other spheres), and the point acknowledged in at least a negative fashion in Rosa Luxemburg's ridiculing—in her *Anti-Kritik* and *Accumulation of Capital*—of the notion of extended reproduction outlined in the concluding chapter of Karl Marx's *Capital*, Volume II.† By 1952, I already had the germ of the solution to the entire problem, but required the aid of Cantor to appreciate the implications of Riemann's work before being able to make the preconscious notion of a solution efficiently conscious.

As I have indicated in other locations, political economy is the highest form of scientific knowledge—on condition that political economy is defined as I have defined it.‡ I summarize that proof here since it bears directly on the authority of our progress for the so-called physical sciences.

**Political Economy and Preconscious**

The very nature of the quality of isolated experiments, as the "null hypothesis" prescribes, prevents us from attaching the value of certainty to any sort of statistical results from ordinary isolated experiments. Only experiments that, by their nature, test the laws of the universe in a crucial (*unique*) way provide positive knowledge. Where statistical methods of design of experiments succeed in isolated experiments, this is because the design of the experiment is governed by general principles adduced from crucial experiments. Does the isolated case perform in a manner consistent with those principles of causal relationships as determined through crucial experiments? *Is the consistency of scientific knowledge as a whole maintained in each aspect of practice?*

On such grounds no existing body of scientific knowledge, in the sense associated ordinarily with textbook knowledge, has any secure authority in itself. Indeed, in the final analysis, all such knowledge is intrinsically *fictitious* (inadequate) at best. Any existing body of accredited textbook sort of knowledge is a reflection of existing knowledge of general principles as defined in terms of existing and prior modes of general social practice, of existing and preexisting technologies of social practice in general. As the successive overthrows to date of authoritative, particular scientific knowledge in the past have shown, all deductive forms of knowledge prevailing at any point in history—including the present time—are at best conditionally true, in the sense of being conditionally efficient. They will be broadly superseded in their authority-as-knowledge by advances in practice.

Textbook knowledge of successful experimentation is not a sound authority for determining truth. Either one concludes from this that truth is unknowable, as Immanuel Kant and the British empiricists concluded in different, antagonistic ways, or one must find a higher, more durable premise for truth, outside the domain of textbook forms of scientific knowledge. What is proven by history—by combined paleontological, archaeological and literary history—is that our species has secularly increased its power over the lawful ordering of the universe through the progress it has effected in social practice under the guidance of scientific and subsumed technological advances.

No existing body of textbook sorts of scientific knowledge adequately proves truth, nor the truthfulness of the creative processes of the human mind. However, the progress of civilization from lower to higher orders of technologies implicitly does prove the truth sought. The truth lies not in the particular (communicable, deductive) knowledge man achieves at any point in history. The truth lies uniquely in those creative-mental processes through which successive advances in scientific knowledge are ordered. We measure what is and what is not an advance by the crucial experiment of human existence, by the manifest increases in the rising thermodynamic negentropy of useful productive and per capita powers of human individuals.

Political economy defined in such thermodynamical terms, according to such negentropic criteria, defines the crucial experiment of human existence in the manner uniquely required to determine what is truth and what is falsehood in the policies and methods of developing human knowledge.

On the level of inorganic physics knowledge, as presently accredited generally, the level of the "n" domain, as we have defined the transfinite denotations "n," "n + 1," and "n + 2," the proof of scientific progress is a persistently rising reducing power of the per capita individual of an expanding population. This quality is peculiar to the "n + 1" domain of existing knowledge, to the domain of organic physics. However, as no species other than man is able to willfully increase the characteristic negentropy of its species-reproductive behavior, the ordering of such negentropic self-development of the human species defines the process as situated in the "n + 2" domain, the domain of *reason*.

However, the fact that this measure of scientific progress does have parameters in the domains of inorganic and organic physics attests to the efficiency of reason with respect to the two lower domains. In the lowest domain of physics knowledge, we perceive scientific progress in terms of the parameters of increasing "reducing power" per capita of an expanded population, as negentropy most crudely conceived. In the domain of organic physics, we see scientific progress as man's willful mastery of the evolutionary process otherwise characteristic of the self-development of the biosphere as a whole. It is necessary to see *reason for itself*.

Once we have discerned that the course of manifest scientific progress is accomplished through rigorous principles of syntheses of new hypotheses, those principles of hypothesis which order successive advances in scientific knowledge (and levels of technology) in particular are thus demonstrated to be approximately in correspondence with man's increasing willful mastery of the lawful ordering of the universe.

Thus, it ought to be clear, no logical-deductive form of science can be in direct correspondence with the lawful ordering of the universe. The contrary assumption is *fictitious*, inadequate. The only aspect of human behavior that can be proven to be in correspondence to the lawful ordering of the universe is the processes that account for man's increasing willful mastery of the universe, for successive revolutions to that effect in logical-deductive forms of scientific knowledge. Hence, only those developed (educated) processes of preconscious synthesis of fruitful hypothesis, especially crucial hypothesis, are the aspect of mental life (and knowledge) that is in correspondence with the lawful ordering of the universe. This process of agreement—preconscious agreement—is classically termed *perfection*, or also the process of securing *atonement* with reason.

Reason is not logical knowledge as we ordinarily define logic. Reason is the rigorous processes of scientific preconscious thinking that order successive and successful arrays of logical scientific knowledge. The former is *reason*, the latter is *mere understanding*.

The principled breakthrough in scientific knowledge to be accomplished is to free man from enslavement to mere understanding by making preconscious processes the willful object of conscious knowledge, by giving the name to an abstraction that is preconsciousness of scientifically efficient preconscious thought. The feasibility and necessity of this breakthrough is ancient knowledge. This is the notion of the *hypothesis of the hypothesis* known to Plato from his Ionian and related predecessors. This is the "hidden knowledge" of the Platonics and Neoplatonics.

Thus, the adequate political-economic theory which views the progress of political economies from this vantage point is the formal expression of the highest form of

* For related reasons, it is a pedagogical monstrosity to teach differential calculus as a prerequisite to instruction in the integral calculus. The reason for this commonplace blunder is clear from history, just as that same history shows us why this choice of pedagogy is wrong, and relatively destructive of the creative-mental powers of the student.

*** "Toward Understanding the Nature of Fusion Energy," *Fusion*, Vol. I, nos. 6-7 (May 1978).

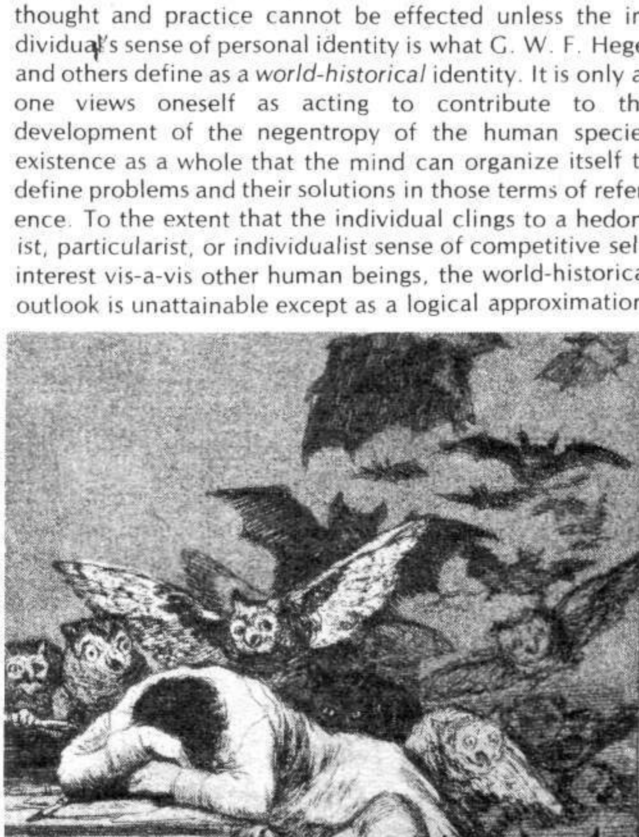
† The first English translation of Rosa Luxemburg's *Anti-Kritik* was published in *The Campaigner*, Part 1 in Vol. 5, no. 1 (January-February 1972) and Part 2 in Vol. 5, no. 3 (May-June 1972). A subsequent elaboration of these points by Lyndon LaRouche appeared under the title "In Defense of Rosa Luxemburg," in *The Campaigner*, Vol. 6, no. 2 (Spring 1973).

‡ Unpublished dissertation for the second session of the Academy of Humanist Studies, Wiesbaden, West Germany, 1978.

scientific knowledge, under whose guidance physics knowledge, for example, is properly assessed and advanced. That, of course, always has been the "secret source" of potency of the National Caucus of Labor Committees and is the essential potency of the U.S. Labor Party. What we are engaged in accomplishing now, in this newly opening phase of our work, is to make that connection fully conscious to the membership, and through the comprehension of this by the membership to a broader population.

### The Role of Neurosis

For reasons we shall merely identify here, the block against mastering the preconscious in modern culture is not so much any difficulty inherent to the subject of inquiry itself. The willful control of the preconscious processes determining predicated forms of conscious thought and practice cannot be effected unless the individual's sense of personal identity is what G. W. F. Hegel and others define as a *world-historical* identity. It is only as one views oneself as acting to contribute to the development of the negentropy of the human species existence as a whole that the mind can organize itself to define problems and their solutions in those terms of reference. To the extent that the individual clings to a hedonist, particularist, or individualist sense of competitive self-interest vis-a-vis other human beings, the world-historical outlook is unattainable except as a logical approximation.



*Francisco Goya's etching, "The Sleep of Reason Produces Monsters," shows remarkable insight into what LaRouche calls "noisy" preconscious processes. The original caption reads: "Imagination abandoned by reason produces impossible monsters; united with her, she is the mother of the arts and the source of their wonders."*

Nor can one be half a world-historical person and half an alienated hedonist. In that latter condition, as we have noted, a certain logical-deductive parody of a world-historical analytical outlook can be assembled, but not a preconscious world-historical outlook.

The particularism, the hedonistic outlook we have indicated is the general expression of the psychopathology termed neurosis. All incapacities of cultured persons of modern society for creative work are of a neurotic origin. The "noisy" preconscious processes, thus made *irrational* preconscious processes as a whole, preclude the sort of coherent, sustained-concentration focus indispensable to creative synthesis of fruitful new preconscious conceptions.

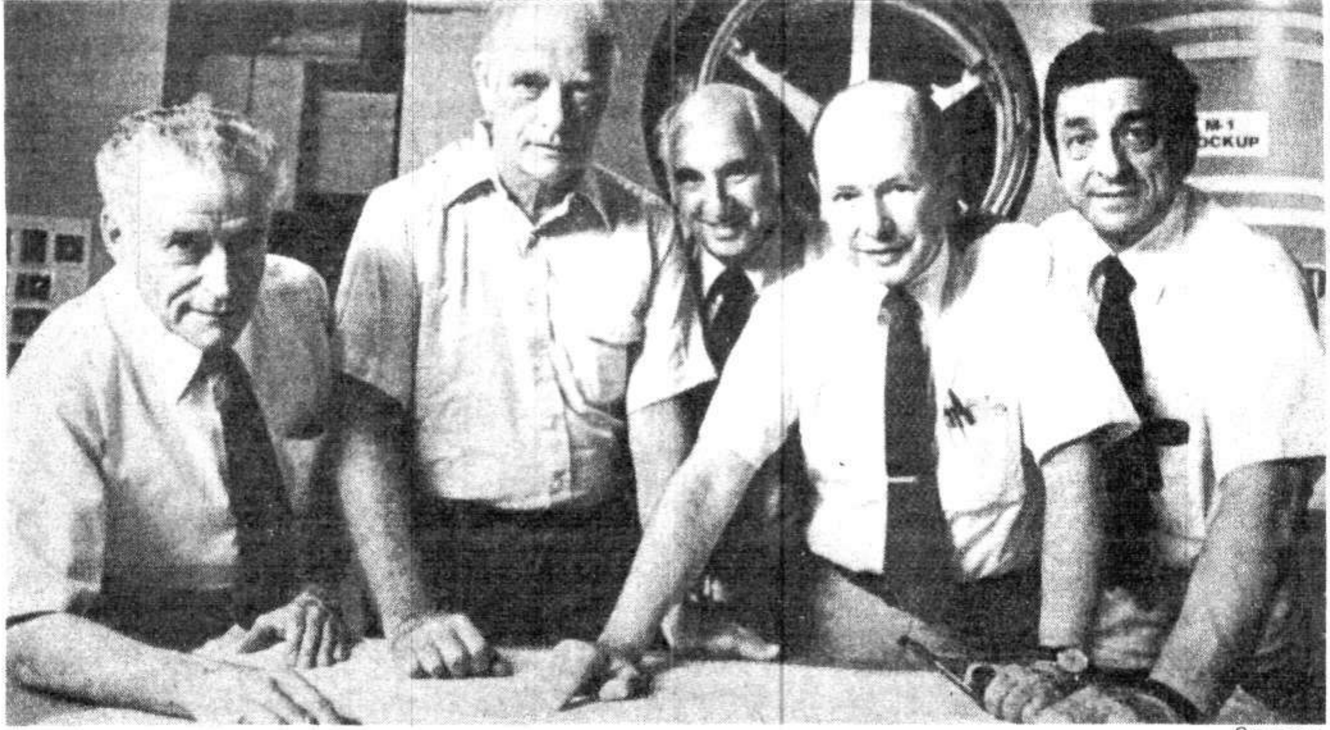
For the same reason, indoctrination of youth in the so-called pluralist outlook ensures a destruction of their potentialities for coherent thought and for creative work. The effort to equate William James's foolish concoction of the notion of "pluralism" with "freedom" is pure absurdity. *Freedom* does involve a certain kind of diversity of outlook. Freedom is essentially, in the first moment, the synthesis of new conceptions, overturning previous or prevailing judgments, on the condition that these new, "deviant" conceptions either are correct or are fruitful to the purpose of furthering the development of knowledge for practice.

Freedom, in its second moment, is a matter of the latitude given to individuals and groups to realize their "deviant" discoveries through public controversy, dissemination of these conceptions, and otherwise, through appropriate channels of social practice. Freedom is not *irrationalism*; it is essentially the process of making discoveries that correct the errors and inadequacies of previously prevailing knowledge and practice. It is, therefore, politically, the social processes needed to nurture the kinds of experimentation in ideas and practice through which new insights are nurtured and tested for assimilation into general knowledge and social practice.

### The Science of Poetry

As I have indicated above (and in other locations), the proper function of poetry and musical poetry, properly conceived, is to enable the preconscious processes of one mind to communicate with the preconscious processes of another through the mediation of ambiguous arrays of predicates of preconscious ideas. The general function of poetry and musical composition like Beethoven's is to enable the culture to aid its developing members to become conscious of their preconscious processes. Not merely to make the individual conscious of their existence, but to enable persons to bring preconscious thoughts into consciousness as abstractions by a rigorous method of naming such thoughts. In that way, by bringing preconscious notions into consciousness as named abstractions, preconsciousness is made conscious (*determined*) and preconscious processes become the objects of willful consciousness.

The object before us is to make the process of synthesis of new, fruitful preconscious conceptions itself the named, conscious object of willful thought. This conception is not new. Plato comprehended it, as have the




Grumman

*A team of Grumman engineers, all veterans of the space program, now working on Princeton's TFTR tokamak project. Reproducing the important contributions of scientists like these and producing the future breakthroughs required by humanity means educating scientists and potential scientists to master the process of reason.*

leading Neoplatonics. This is the inner core of the secret knowledge of the Neoplatonics. The point is to make this inner secret available to a broader population.

The relevance of this undertaking for physical science, so-called, today is indicated by those aspects of experimental work in which the evidence adduced to preconsciousness cannot be "translated" into the "logical" forms of axiomatic, mathematical physics. In these aspects of experimental work, society is essentially at an impasse—an impasse that must persist until we supersede axiomatic, deductive forms of communication of scientific notions, through naming those mental processes that are in fact in correspondence with the kinds of problems set forth in the indicated writings of Bardwell, for example.

The creative preconscious synthesis of fruitful new conceptions by the informed mind is a self-developing process of exactly the "logical" form represented by a true Riemannian universe. That is, a universe in which "n," "n + 1," and "n + 2" are denotations of transfinite orderings of higher-order-ranked characteristics of multiply connected domains evolved out of action by a self-elaborating, transinvariant form of causal principle. If that aspect of our mental processes is named, made an abstraction for consciousness, those abstractions supersede axiomatic mathematical forms as the appropriate conceptions for communicating and being conscious of the kinds of processes we must now deliberately master.

There is nothing to be termed merely speculative in this proposal.

I have wrestled with this problem over decades. I have been governed by conceptions of which I was fully conscious, and which conceptions I have demonstrated to be valid through their predicated applications. Yet, generally speaking, I have not found these preconscious conceptions communicable to others.

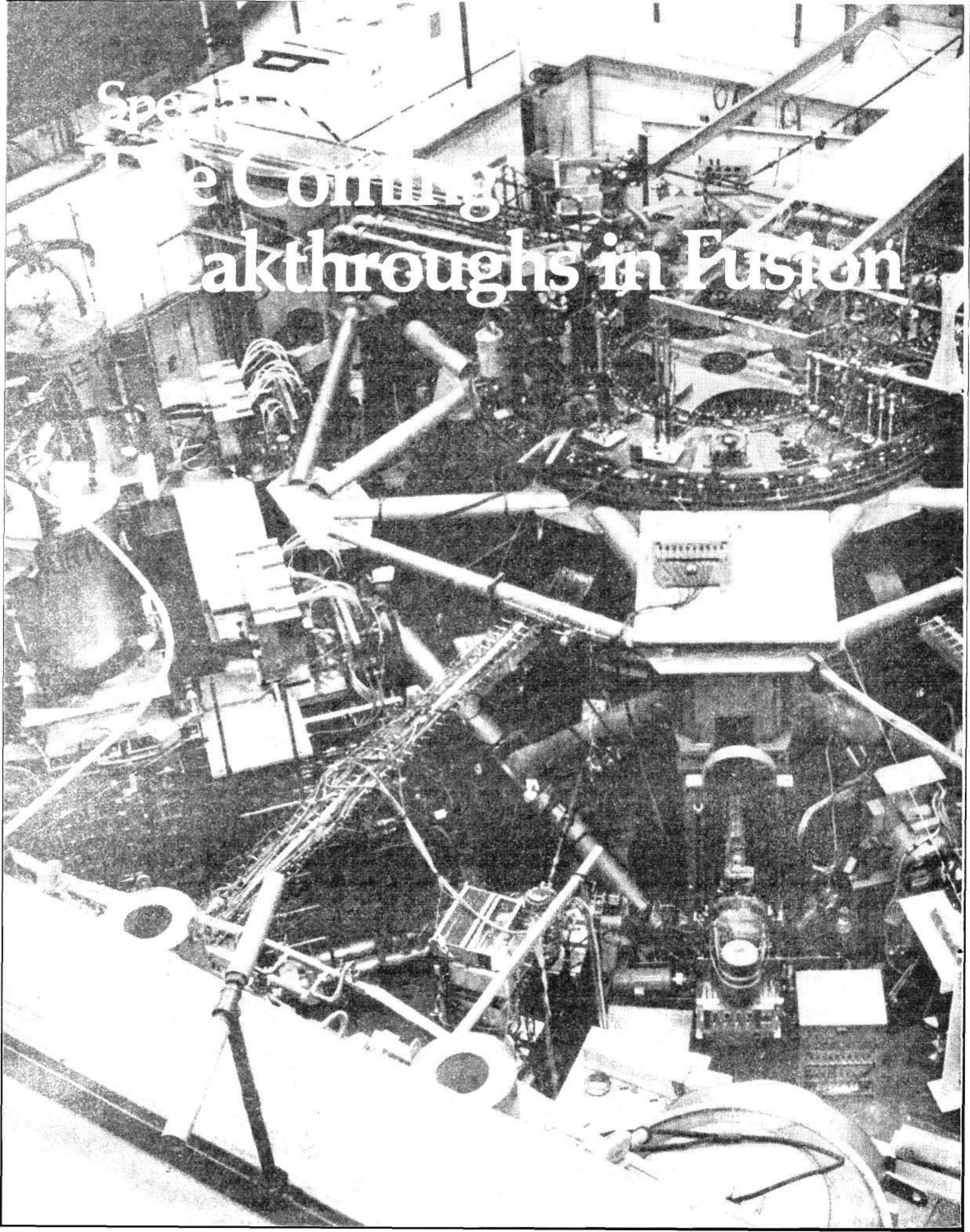
Second, this problem has not remained the same for me over the past dozen years in which the organizations I now head have developed. The social process of development of the persons in these organizations has not only enlarged the scope of what I can explicitly communicate, as preconscious thoughts have been made socially thus named, willfully employed abstractions, but by enlarging the language of thought in that way, the organization's development has enabled me to advance in willful mastery of my own preconscious processes.

At this point, there is among my associates a core of persons who, to varying degrees, have mastered the rudiments of the inner secrets of the Platonics and Neoplatonics, such that we communicate policy and related conceptions to the handfuls of the Neoplatonic elite outside our organization on that level, on that basis. I know that these persons—both inside and outside the organization—are thinking in a certain preconscious way by virtue of the kinds of abstractions they employ and, more important, by the way in which they employ them.

If this core of experienced and developed social forces is mobilized to apply the fruits of its development and shared experience to the task I have projected, we can anticipate that this directed effort will lead us quickly toward the kinds of conceptual breakthroughs in scientific work I have indicated, beyond the field-particle paradoxes intrinsic to the inferior level of thought, the mere understanding.

Poetry, and forms of music, painting, and sculpture ordered according to Neoplatonic poetic principles serve as part of the essential training of the mind to master preconscious processes. In turn, only those aspects of artistic effort that serve that notion of the poetic principle are to be regarded as art.

Norman Mailer, T. S. Eliot and Leonard Bernstein are not artists, because they are not scientists.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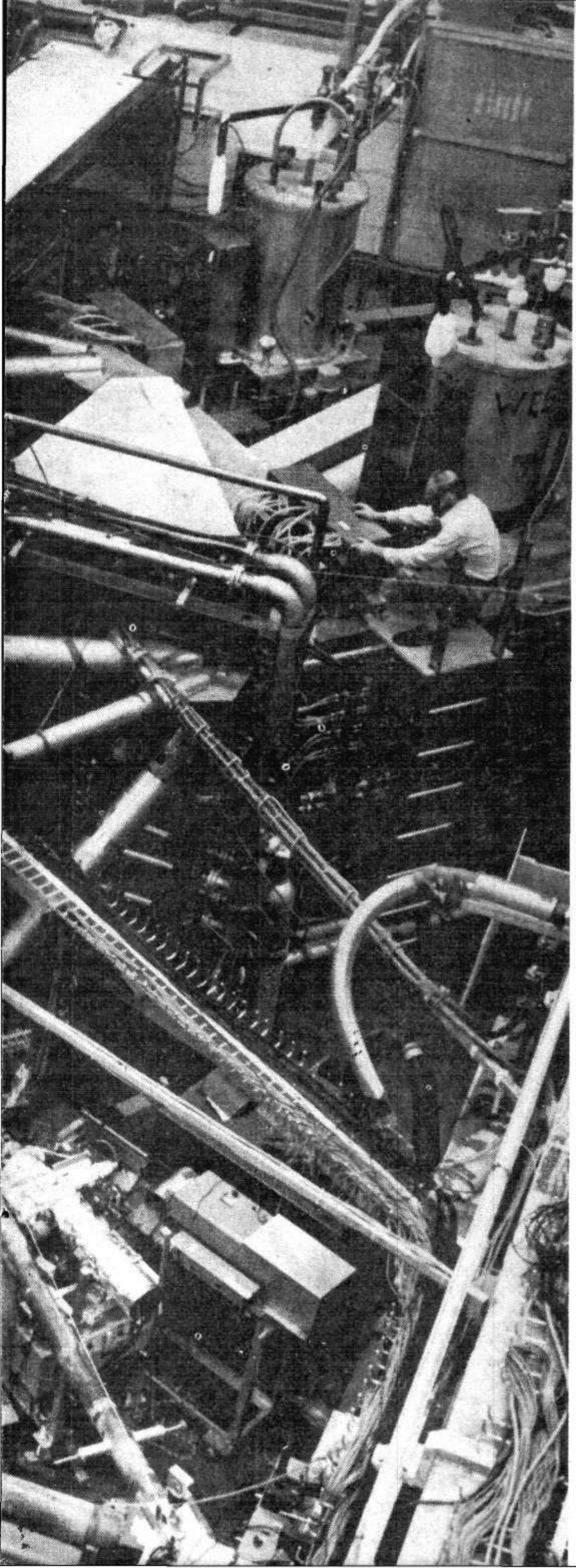


# *The Princeton Story*

## Breakthrough Sparks Fight Over Fusion Timetable

IN A WASHINGTON press conference Aug. 14, Dr. Melvin Gottlieb, head of the Princeton University Plasma Physics Laboratory, and Dr. John Deutch, Director of Research in the Department of Energy, formally announced that the Princeton Large Torus tokamak had reached record temperatures upwards of 60 million degrees Celsius, well past the fusion ignition temperature of 44 million degrees.

In effect, this means that the Princeton fusion team has broken through the scientific barriers to achieving the temperatures required for continuous thermonuclear reactions and opened the door to the production of a virtually unlimited supply of clean, cheap electrical power. After the coming round of research breakthroughs, all that will remain are engineering considerations—problems that could be quickly solved by a U.S. fusion program along the lines of the Apollo Project.

### The Breakthrough

As Gottlieb described the Princeton feat, a first in fusion history: "It took us seven years to go from several million degrees to 26 million in December 1977, and then just six months to go another 35 million."

The high temperatures occurred in July, Gottlieb said, after the hydrogen fuel for the PLT tokamak had attained sufficient conditions of purity and the neutral beam apparatus, the main heating source, could be turned up in power. The lowered impurity level reduced the heat energy losses caused by the entry of the impurities into the plasma fuel; and the 2 megawatt deuterium heating beam, a system designed by Oak Ridge National Laboratories, then shot the plasma temperature up to 60 million degrees.

Even more important than the high temperature, no

*A view from the top of the fully installed Princeton Large Torus, the tokamak machine shown schematically in the cover illustration. The neutral beam injectors are at the lower left and upper right.*
DOE

PPPL

*The Princeton team in the PLT control room. Standing are Melvin Gottlieb, director of PPPL (l.), and Harold Furth, head of the PPPL research department; seated are Harold Eubank (l.), head of the neutral beam heating on PLT and Wolfgang Stodiek, head of the PLT project.*

instabilities or excessive leakage from the plasma occurred in this high-temperature regime, a fact that is in agreement with the theoretically predicted tokamak behavior. With these results in hand, Gottlieb noted, there was little doubt that the larger Tokamak Fusion Test Reactor, now under construction at Princeton, would achieve better than energy breakeven conditions (the production of more energy than that required to produce fusion) when it begins operation in the early 1980s.

Gottlieb also noted that although there are about 100 tokamaks in the world, the Princeton success is a unique U.S. result.

Just what the Princeton results mean was summed up by Dr. Stephen Dean, director of the magnetic confinement systems division in the Department of Energy, which oversees the Princeton project. "The question of whether fusion is feasible from a scientific point of view has now been answered," Dean stated in an interview on CBS national news Aug. 12. "It is the first time we've produced the actual conditions of a fusion reactor in a scale-model device."

Dean's statement was followed by a burst of front-page press coverage internationally, much of which hailed the breakthrough and reported the significance of the results for the hastening development of fusion (see press section for details).

### The Schlesinger Downgrade: The Inside Story

While the fusion community wordwide applauded the historic Princeton achievement, the office of Energy Secretary Schlesinger had been actively working behind the scenes to downgrade the Princeton results, to keep them out of the press, and to keep the news from the president.

Why would the energy secretary attempt to suppress news of the biggest fusion breakthrough in the history of U.S. fusion research? The answer was contained in an article by Harry B. Ellis in the *Christian Science Monitor* the morning of the press conference. The promise of unlimited energy from fusion might prejudice Americans against energy conservation and an oil shortage, which are at the center of Schlesinger's energy policy. "...U.S. energy officials do not want a 'wrong signal' sent to Americans by reports calling the Princeton work a 'nuclear fusion breakthrough,'" Ellis wrote.

The evidence of Schlesinger's sabotage on behalf of an energy austerity policy becomes clear in examining the chronology of events in the making of the Princeton story and the press conference. In brief, here is the inside story, compiled from *Fusion* interviews with reporters, scientists, and government officials.

According to reports from Princeton, the high temperature results were obtained July 24. In the following week, these were disseminated widely, on a private basis, throughout the fusion community. It was understood that a public announcement of the results was embargoed until Princeton formally released the information at a press conference planned for Aug. 23 at a meeting of the International Atomic Energy Agency's Controlled Fusion and Plasma Physics Conference in Innsbruck, Austria.

On July 31, Robert Thorne, DOE Assistant Secretary for Technology, sent a memo to Schlesinger saying it was likely that the major press would get hold of the story soon and, therefore, the department would hold the press conference Aug. 15, instead of waiting for the Innsbruck meeting. According to DOE sources, Thorne's memo said that the PLT experiments had reached temperatures of 80 million degrees; that this was a most significant development and breakthrough; that it was unique to the United States; that it assured that the Princeton TFTR would reach, and possibly go beyond, breakeven; and that the scientific feasibility of fusion was virtually assured.

Thorne's thinking proved accurate. That same day the Washington-based newsletter, *Energy Daily*, broke the story, reporting "persistent reports of a major breakthrough in the U.S. program in magnetic fusion" and attributing its information to "industrial sources."

On Aug. 9, Dr. Stephen Dean and Dr. Harold Furth, director of research at Princeton Plasma Physics Laboratory, drafted a press release for the scheduled press conference, and this was sent through the proper DOE channels and approved for release.

The Fusion Energy Foundation learned of the Aug. 15 press conference in a telephone call to Dr. Gottlieb Aug. 10. *Fusion* staff then called several reporters and government officials about the press conference, and FEF executive director Dr. Morris Levitt sent a memo to the White House urging presidential participation in the press conference.

By the next day, Aug. 11, official DOE press spokesmen were telling callers that there was no press conference scheduled. Jim Bishop, head of the DOE Press Office, told one reporter "no press conference was planned or contemplated." Furthermore, according to DOE fusion office sources, Bishop warned leading officials connected with the DOE fusion office that "heads would roll."

But by this time the national media had gotten hold of what they knew was a big story. The Knight-Ridder newspapers broke the story in the morning editions of the *Miami Herald,* the *Chicago Tribune*, the *Baltimore Evening Sun*, and United Press International picked up the news; and CBS contacted Stephen Dean for an interview, aired nationally that evening.

The following day, Sunday, Aug. 13, news of the Princeton breakthrough was on the front pages of leading newspapers around the world, and the Schlesinger pressure escalated. Under orders from Schlesinger's office, Princeton scientists were now declining to make any comment on the results. In fact, sources indicated that the DOE told Princeton people that they should tell press there was no press conference and they should not discuss the matter. At the same time, DOE sources said that Schlesinger's office was frantically soliciting scientists who would publicly downgrade the Princeton results.

Furthermore, in what appeared to be an effort to cover their good tracks, CBS national news Aug. 13 interviewed John Sawhill, president of New York University and former Federal Energy Agency head, who praised the Princeton results but stuck to the Schlesinger line that commercialized fusion would not be possible until the 21st century.

By Monday, Aug. 14, pressure from favorable press coverage and the scientific community, including the Fusion Energy Foundation, had made the situation too hot to be ignored by the official DOE channels. After a meeting between Schlesinger and high-ranking officials in the DOE fusion office, a press conference was hastily called for 3:30 that afternoon, barely allowing time for Gottlieb to arrive.

### The Press Conference

The press conference, attended by 75 reporters from major media around the world, reflected the Schlesinger pressure to downgrade the Princeton results. In the first place, the official DOE spokesman was Dr. John Deutch, Director of Research, and not the head of the DOE fusion office, Dr. Edwin Kintner, as might have been expected. Deutch consistently advanced the position that the Princeton results would make no difference in the Schlesinger DOE fusion budget or fusion timetable; that is, there would be no fusion energy until the year 2025.

The results were not a breakthrough, Deutch said, just a "significant result"; only the actual production of breakeven would be a "breakthrough."

Although Deutch recently had headed a favorable study of the DOE fusion policy review committee and is familiar with the field, when a reporter asked him about the studies done by ERDA (the predecessor to DOE) demonstrating that the fusion timetable could be moved up to the 1990s, Deutch denied knowledge of the studies.

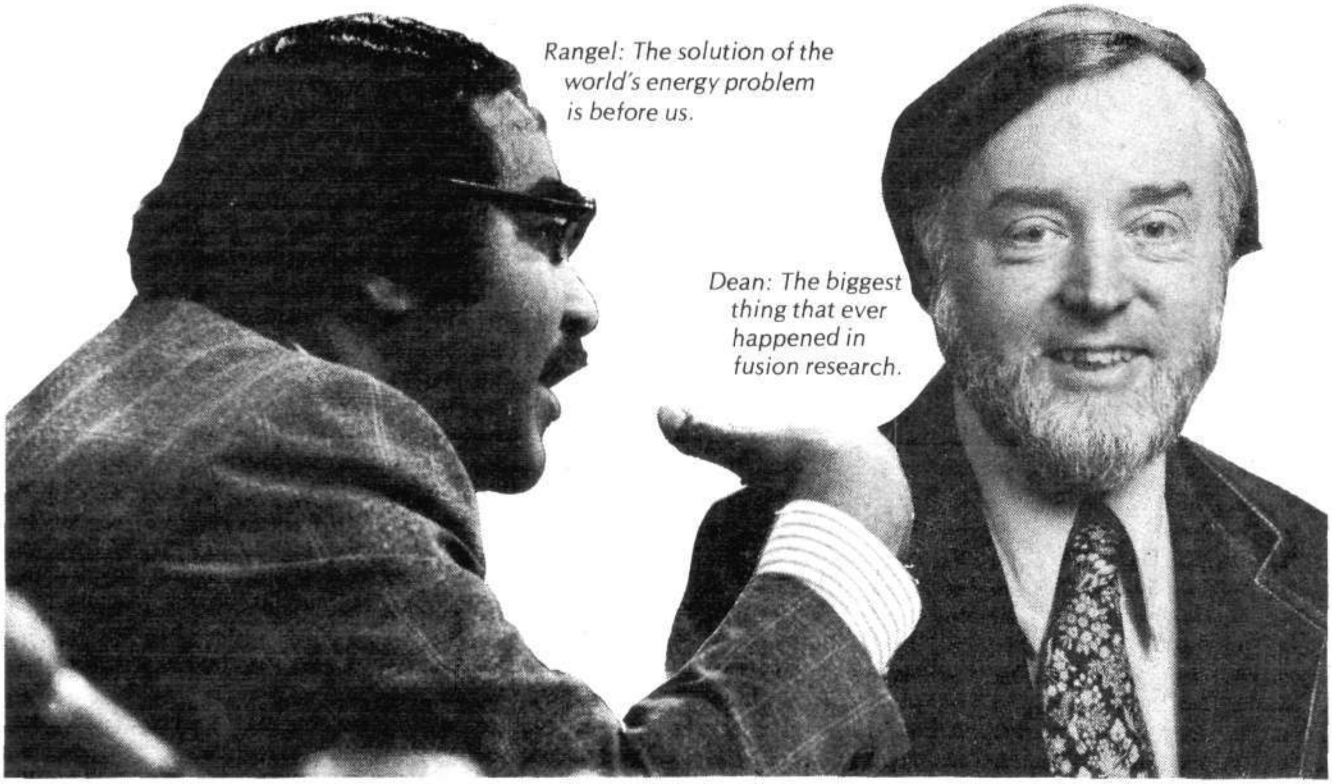
Press reports immediately following the press conference fell into two categories: articles and editorials that lauded the results and noted their importance in making it feasible for the United States to have a fusion-based economy in the 20th century and articles and editorials that focused on the Deutch downplay and the Schlesinger 21st century timetable (although this was not necessarily with the witting complicity of the authors).

By Aug. 16, despite the Schlesinger attempts to dampen any enthusiasm for fusion, a good number of the world's leading papers had communicated to their readers the significance of Princeton, putting the breakthrough in exactly the perspective Schlesinger was trying to avoid. For example, in an editorial titled "Fusion's Unlimited Promise," the *Baltimore Sun* wrote that since "the promise is for unlimited energy," instead of cutting the fusion budget, "it is time for the administration to review its attitudes toward the fusion energy budget."

There was also some strong congressional reaction, exemplified by the statements of Charles Rangel, New York Democrat, Oil Teague, Texas Democrat, and Carl Pursell, Michigan Republican, inserted into the *Congressional Record* (see press section). "This breakthrough compels us to redirect our energy and funnel further funds and attention to highly promising and vitally important nuclear fusion research," Rangel said.

Schlesinger personally continued to downplay the results. In a press conference Aug. 18 at the White House he acknowledged that the results were "great," but he told the press that they had "overplayed the Princeton results. . . They are a step toward feasibility," he said, "but they don't demonstrate feasibility."

Two days later on the CBS "Face the Nation" television and radio show, Schlesinger was asked "why there was




such apparent confusion at your department last week when information became available that there had been a significant advance in thermonuclear fusion experiments at Princeton University?" The energy secretary replied: "There was no confusion on that. We regarded it as a substantial step forward, one that we welcomed. . . . It was a major step forward, but it is not yet a demonstration of scientific feasibility. . . while we wanted to take note of this achievement in an orderly way, we did not want to hype it up in such a way that the public got the impression that the problem of developing fusion energy was solved."

Most incriminating, considering the magnitude of the energy crisis and the potential of fusion to solve it, there apparently was no briefing from Energy Chief Schlesinger to President Carter on the Princeton results and their importance throughout this time period. At a White House press briefing Aug. 15 when a CBS reporter questioned White House press representative Rex Granum as to whether the president had been briefed on the Princeton result, Granum said—three times—that he could not say.

**Sabotaging the Japanese Fusion Offer**

Exactly what strategic considerations were motivating Schlesinger in his attempts to downplay fusion became clear the following week when a top Japanese government official told reporters that the Energy Department had refused the written proposal of Japanese Prime Minister Takeo Fukuda, which put fusion as the top priority in a joint development program for new energy sources. Instead, the U.S. representative at a meeting Aug. 2 put forward an alternative proposal that had coal liquefaction—of all things—at the top of the list of energy sources to be jointly developed.

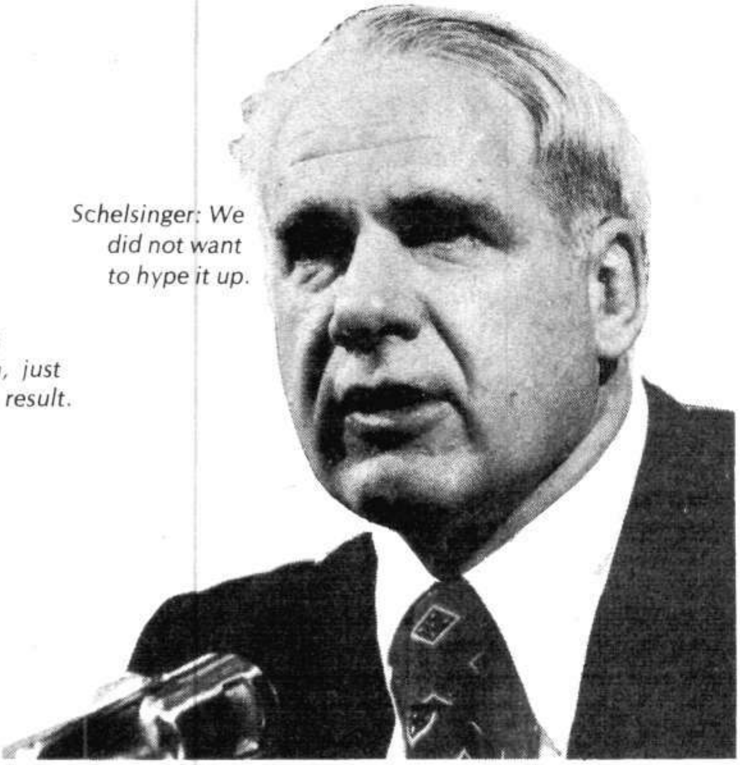
At the heart of this issue is that Schlesinger and National Security Advisor Zbigniew Brzezinski are collaborating to block the $1 billion Japanese proposal. Instead, Schlesinger and Brzezinski want to sell oil to the Japanese—offshore Chinese oil, to be exact, that the United States and Great Britain plan to develop in the near future.

Strategically, the aim is to pull Japan into a U.S.-China-Great Britain bloc against the Soviet Union. A crash program for fusion development, especially at a time when the U.S. fusion program is making significant breakthroughs, would make it impossible to consolidate such a deal.

Sources in the Energy Department and the State Department subsequently made it clear to representatives of the Fusion Energy Foundation that the policy directive came "from the top"; that is, right from Energy Secretary Schlesinger. Additional pressure against the fusion deal has come quite openly from Brzezinski's office. An official of the Department of Energy's Office of Fusion was telephoned by a representative of Brzezinski who stated: "People in the highest level of government will not cooperate with Japan on energy on a scale that will lead to undue benefits to Japan unless we get assurances that Japan will stop screwing us on the balance of trade."

Despite Schlesinger's machinations, the Japanese have made it clear privately that they will stick to their offer making fusion top priority for joint development. "Why

Deutch: Not a breakthrough, just a significant result.



Schelsinger: We did not want to hype it up.

should we subsidize coal gasification when the U.S. government is not willing to subsidize it?" one Japanese official asked.

Even more important, the Japanese are clear on exactly what China card Schlesinger and Brzezinski are playing. They know that Schlesinger is going to China soon, in a trip admittedly coordinated by Brzezinski for stategic purposes, and they know that his specific mission there is to make a major deal on the offshore development of Chinese oil. They also know that this Anglo-American operation is designed to beat the Japanese out of their offers to develop the offshore Chinese oil.

According to one Japanese official, the Department of Energy is "sneaky" but its ploy won't work either with Japan or China. China is not about to hand its oil resources over to the United States and Britain, although it might string Schlesinger along. As one Japanese official put it, the Schlesinger policy is "a high school theory. . . . They [Schlesinger and Brzezinski] do not understand the Chinese mind."

The Japanese had specifically named three areas of cooperation in their proposal for fusion research: the Princeton TFTR tokamak, scheduled to come on line in 1981; the Doublet III tokamak device of General Atomic in San Diego, which should soon be making breakthroughs similar to those of the Princeton machine; and fusion devices that are not tokamaks.

Sources in the Department of Energy and the State Department told the Fusion Energy Foundation that coal liquefaction was at the top of the U.S. list because at the moment the U.S. synthetic fuel program "is not moving." During the winter, in fact, Schlesinger's antinuclear hatchet man, Assistant Secretary John O'Leary, had stumped around the country for the coal conversion program. Coal conversion, it should be noted, is thermally inefficient as a major energy source, except in situations like those of Hitler's Third Reich, where it was a chief fuel source.

Ironically, the U.S. memo to the Japanese was submitted under the signature of Robert Thorne, the Assistant Secretary for Energy Technology who reportedly sent the memo to Schlesinger July 31 saying that the Princeton results virtually assured the scientific feasibility of fusion. Thorne was not present at the Aug. 2 meeting with the Japanese where the U.S. representative was Dr. Ben Huberman of the National Security Council.

**The Future for Fusion**

As the next article on the coming breakthroughs in fusion makes clear, the Princeton breakthrough is just the first of a lineup of critical experimental results expected from a variety of U.S. tokamaks. Turning these experiments into commercial fusion reactors will take nothing short of another Apollo Project effort. This effort is exactly what is being actively discussed now among congressional, industrial and corporate circles and the scientific community—with full recognition that both DOE policy and the present DOE chief are not capable of launching such a program.

—*Marjorie Hecht*

# *The Coming Breakthroughs In Fusion Research*

by Charles B. Stevens
& Dr. Steven Bardwell

*INTRODUCTION*

WAS THERE A BREAKTHROUGH in fusion research at Princeton? The simple answer, documented in the following series of articles, is yes.

The real significance of the astounding new results from the Princeton Large Torus experiment can be understood only in the context of the overall technical and scientific requirements for a working fusion reactor and the current research underway to fulfill those requirements. Measured against the ultimate goal of production of virtually unlimited quantities of cheap, clean energy—the unique promise of fusion energy—the results at Princeton stand out as one of a series of achieved or imminent breakthroughs toward this goal.

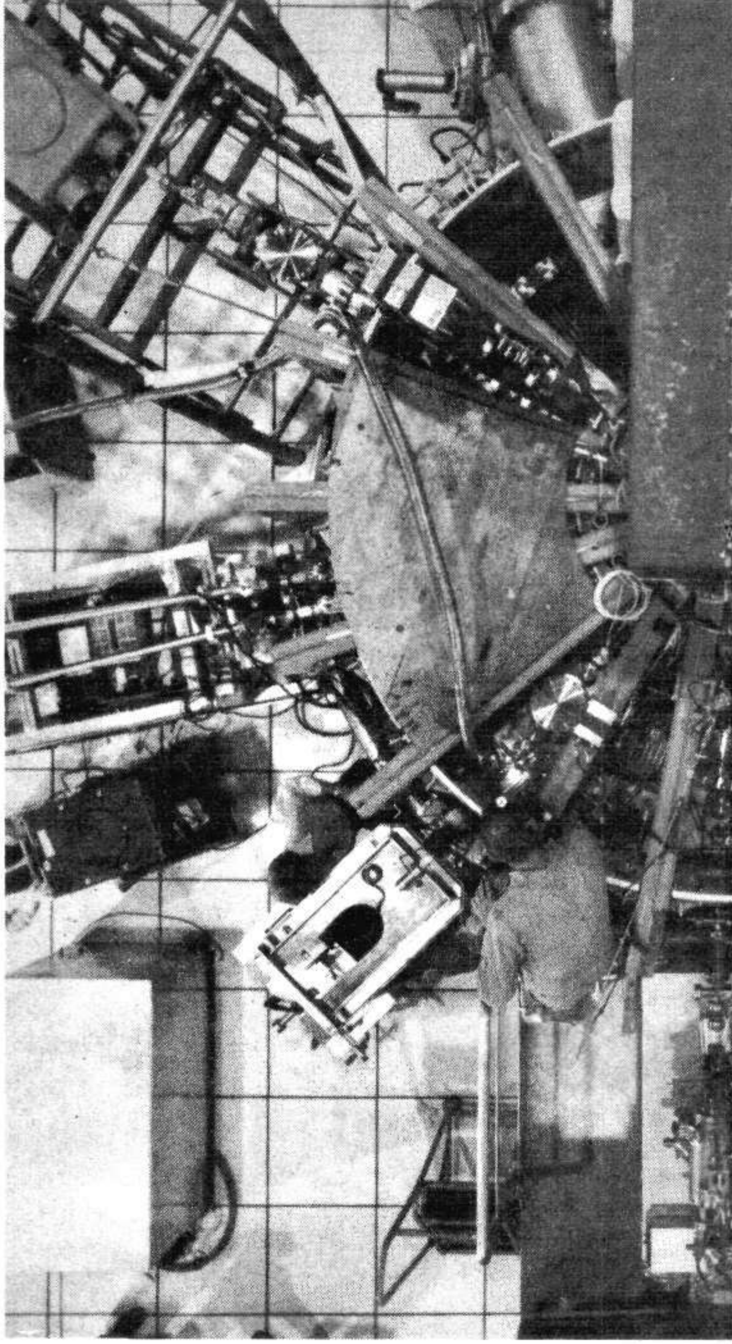
**The Requirements for Fusion Energy**

There are six essential conditions that must be met in a fusion device capable of producing commercial quantities of energy:

(1) *Temperature*. The ignition temperature of the deuterium-tritium mixture is approximately 44 million degrees Celsius (80 million Fahrenheit, or 4 keV). This temperature must be achieved and sustained in the reactor.

(2) *Density*. Fusion energy cannot be produced in commercial quantities unless there is enough fuel in the reactor to ensure a high *rate* of energy production. The basic requirement is that the density of the fuel—the amount per unit volume—must be sufficient to ensure that a given nucleus of deuterium or tritium cannot leave the plasma without hitting another nucleus.

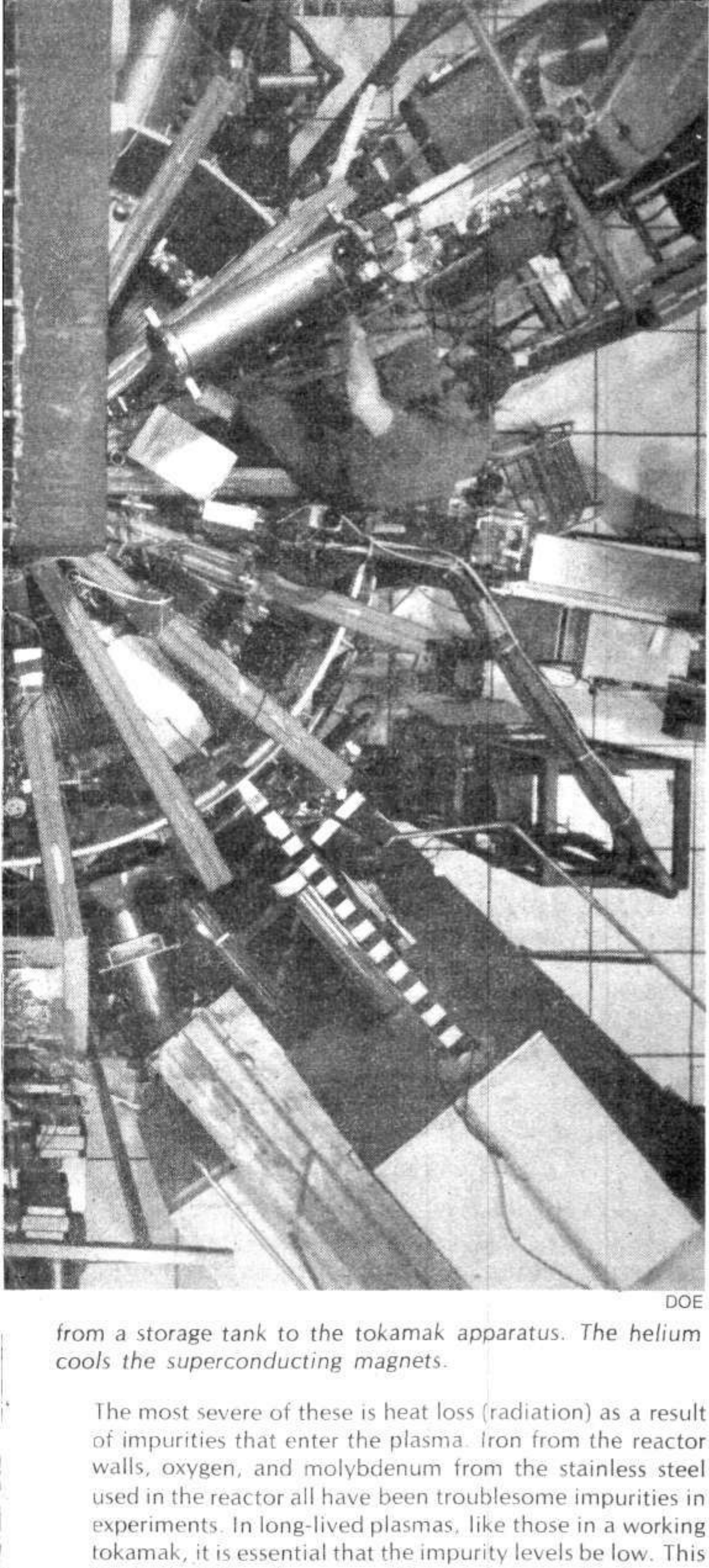
(3) *Stability*. In addition, the fuel must be contained in the reactor long enough for this energy to be produced. A rough measure of success in achieving stable confinement in provided by the *Lawson criterion*. This rule of thumb states that breakeven energy production occurs when the density multiplied by the time of confinement exceeds 30 trillion seconds-nuclei per cubic centimeter. Economical quantities of energy are produced when this density-confinement time product exceeds 300 trillion seconds-nuclei per cubic centimeter.



*The ISX-B at Oak Ridge. Researchers are transferring liquid helium, at temperatures hundreds of degrees below zero,*

This Lawson criterion shows that there are two ways of achieving the necessary stability: long confinement times (on the order of 10 seconds) and low densities, or short confinement times and high densities. The magnetic confinement approach to fusion (tokamaks) has taken the first course, and the inertial confinement approach (laser and electron beam fusion) has taken the second. For economical energy production, the tokamak will require confinement times of roughly 1 second and densities of roughly 100 trillion nuclei per cubic centimeter.

(4) *Energy loss*. In a fusion plasma state at the ignition temperature, fusion fuel has a multitude of mechanisms by which its energy can be lost before ignition takes place.



DOE

*from a storage tank to the tokamak apparatus. The helium cools the superconducting magnets.*

The most severe of these is heat loss (radiation) as a result of impurities that enter the plasma. Iron from the reactor walls, oxygen, and molybdenum from the stainless steel used in the reactor all have been troublesome impurities in experiments. In long-lived plasmas, like those in a working tokamak, it is essential that the impurity levels be low. This level is traditionally measured by the average atomic number of the nuclei making up the plasma, called $Z_{eff}$. For a successful reactor, $Z_{eff}$ must be very close to 1, the value for hydrogen.

(5) *Power density.* Power density, energy per unit area per unit time, is a measure of the overall capital efficiency of the reactor. To be economically feasible, the fusion fuel must produce a dense source of energy that is at least comparable to present-day nuclear and fossil fuel reactors.

There are two ingredients in achieving the required power density with fusion. The first is efficient use of the magnetic field in magnetic confinement devices. This is measured by a ratio, called *beta*, of the plasma energy density to the magnetic field energy density. A beta of 4 percent is the minimum sufficient for economical energy production. Second, the damage done by any fuel or reaction products, especially neutrons, hitting the reactor walls must be low enough to allow long-lived reactor vessels. This damage is proportional to the power density and is a problem in material development similar to that faced in fast flux conventional nuclear reactors.

(6) *Superconducting magnetics.* Large-scale magnetic field generation by supercooled coils is the major area of technology yet to be tackled.

Table 1 summarizes these requirements listing which fusion devices have already met the criteria or are close to breakthrough. As is clear from this table and from the documentation presented in the following articles, the coming breakthroughs taken as a whole will have sufficiently dealt with each of the ingredients in the list of six requirements for fusion energy given above.

**The Current Situation**

To summarize the current situation:

The PLT results show that we have the technology to heat a tokamak plasma to the required temperature, while the results from the Alcator show that a tokamak can be held at sufficient density for long enough times to achieve fusion. The Doublet III experiment, in the near future, will *combine these results in one machine.*

The Alcator and the ISX (soon to be expanded into the Alcator C and ISX-B) have demonstrated that the impurity problem can be solved in a high-temperature plasma.

The theoretical work at the Oak Ridge National Laboratory on tokamak operation, which, for the first time, offers a comprehensive basis for understanding the operation of tokamaks, shows that the machines now being built can overcome the beta problem. The Doublet III and ISX-B will test these predictions within the next six months to a year.

Experiments now under construction and ongoing engineering studies give confidence that existing alloys of stainless steel will be adequate for economical power production.

Several planned U.S. and Soviet experiments indicate that the technology of superconducting magnets is well on the way toward solution.

The results at Princeton are a breakthrough precisely because they are a part of the imminent solution of the remaining problems of commercial fusion energy production. That is the consensus of the fusion community, as summarized by the March 1977 testimony to Congress of Edwin Kintner, head of the U.S. Fusion Office: "Within the fusion community, fusion is no longer looked on as a question of scientific feasibility, but only of practicality and economics."

**TABLE 1**
**SUMMARY OF TOKAMAK PROGRESS**

| MACHINE OR EXPERIMENT | PROBLEM | | | | | |
|---|---|---|---|---|---|---|
| | Temperature | $n:\tau$ | $Z_{eff}$ | beta | Materials | Superconducting magnets |
| Princeton Large Torus (PLT) | ● | | | | | |
| Mass. Institute of Technology Alcator | | ● | ● | | | |
| Princeton Poloidal Divertor Experiment (PDX) | ● | ● | ● | | | |
| General Atomic Doublet III | ● | ● | | ● | | |
| Oak Ridge ISX | | ● | ● | ● | | |
| Soviet T-10M | | ● | | | ● | ● |
| Princeton Tokamak Fusion Test Reactor (TFTR) | ● | ● | | ● | ● | |

# The Basics of Fusion Power

*For the first time in man's history, it is possible to conceive of a time when there will be no technological or material obstacles to conquering the scourges of poverty, hunger, disease, and ignorance that have plagued man since his appearance on the earth. We now have sufficient scientific knowledge to guarantee that there will be no material barriers to every human being's realization of his unique, creative potential for contributing to the further progress of humanity.*

*That is what fusion energy really is. Fusion itself does not solve these problems, but it uniquely overcomes the single largest technical barrier to their solution today—energy scarcity. Fusion energy is to the world of the coming decades what fire was to primitive man and what the steam engine was to the modern age: the gateway to a new world of abundance.*

*The following brief summary of fusion technology is presented here to answer a frequent question from readers: "Just what is this fusion energy?" The real answer, however, is that it will enable all of mankind to be truly human.*

TO ACHIEVE FUSION, two nuclei of hydrogen, the basic fusion fuel, must join together. This produces one helium nucleus for every two nuclei of hydrogen, and liberates energy in the process. There is a net energy gain because the end-product nuclei weigh less than the nuclei of the input fuel. During the nuclear reaction, this mass difference is converted to energy of various forms.

The fusion process is the converse of the more familiar fission process now used in nuclear reactors, which involves the splitting up of heavy elements like uranium into lighter ones, and making use of the energy released.

**Solving the Energy Crisis**

Fusion is cheap, safe, clean, and will provide a virtually unlimited source of energy.

The sheer amount of potential energy available from fusion is mind-boggling. The basic fuel for controlled fusion is deuterium and tritium, the heavy isotopes of hydrogen. There is enough fusion fuel in the earth's oceans to provide millions of years of energy at thousands of times the present rate of consumption! A single gallon of seawater can fuel as much fusion energy as five barrels of oil can fuel conventional energy.

Second and equally important, fusion is tremendously energy dense; the high temperatures at which fusion occurs assure that fusion can produce a far greater concentration of energy than any other process. In fact, the fusion process is the most efficient converter of mass to other forms of energy that man can now technologically exploit.

Third, fusion is clean. The special form of electromagnetic energy in the fusion-energized plasma and the wide variety of energy forms available from the fusion reaction—from charged and neutral particles to various frequencies of radiation such as X-ray and ultraviolet—will make it possible to build fusion reactors with a closed cycle of material and energy flows that will have no waste and no radioactivity.

Finally, fusion opens up the possibility of a total revolution in industrial technologies through the use of plasma processing—the direct use of the hot charged gas in which fusion occurs to purify minerals out of ordinary rock. This means that any type of material—junk or waste—could be fully recycled using what is called a fusion torch, and that we could tap the entire stockpile of the earth's resources.

*Please turn to page 46*

# PLT: The First of Many Breakthroughs

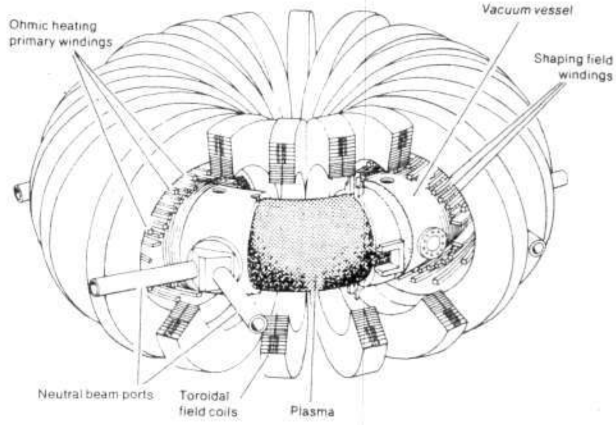
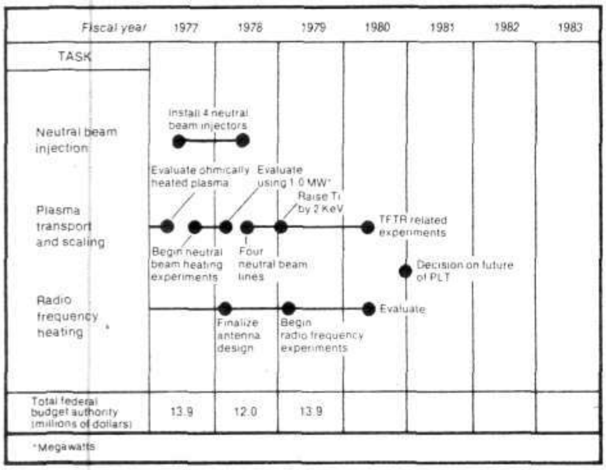



Figure 1




The fact that the Princeton Large Torus tokamak works at all, let alone that it has accomplished the most significant advance in fusion research in the last quarter century, is nothing short of an engineering and management miracle. And now that the PLT research team has brought its machine through the most difficult step of producing a stable, clean plasma at temperatures of 60 to 80 million degrees—well beyond that needed to ignite a deuterium-tritium fusion reaction—it can be confidently predicted that the Princeton team will achieve other major breakthroughs in the coming months.

Before going into detail on what these breakthroughs will be, let's review the history of the PLT.

### Tokamak History

The Princeton Large Torus was born in what many scientists believed to be the twilight of the fusion research era. Since the beginning of the Kennedy administration in the early 1960s the U.S. fusion research budget had been rapidly decreasing, and there were no significant theoretical or experimental paths to fusion on the horizon. U.S. scientists had generated fusion temperatures in a number of devices, but their fusion plasmas were only short lived and did not stay around long enough to produce net fusion energy. Furthermore, high-temperature plasmas seemed to be inherently unstable and unpredictable. In fact, if anything at all could be predicted about these beasts, it was that they would behave in a manner directly opposite to that predicted by scientific theory.

In 1968, to the astonishment of the world scientific community, researchers led by Soviet Academician Lev Artsimovich at the Kurchatov Institute in Moscow announced that they had produced a multimillion degree plasma in their donut-shaped magnetic bottle, the tokamak T-3, and that they had maintained the plasma at this temperature for more than 20-thousandths of a second. The previous record for confinement time was measured in millionths of a second.

The world scientific community did not believe the Soviet reports, and so Artsimovich invited the British to send a team of fusion scientists to the Kurchatov Institute to measure the tokamak T-3 temperature and confinement times. A delegation headed by Dr. R. Pease of England's Culham Laboratory corroborated the Soviet results, using the recently developed method of Thompson laser scattering. In fact, the British team found that the Soviet scientists had underestimated their plasma temperature; it was actually more than 5 million degrees.

The 1968 breakthrough for the T-3 was not the result of a sudden discovery. For more than a decade Artsimovich had led the tokamak team at Kurchatov Institute through a grueling and exhaustive research effort.

The general theory of the tokamak had been developed by Soviet scientists Tamm and Sakorhov in the early 1950s, and further elaborations of that original tokamak theory were carried out by physicists throughout the world, in particular by the Soviet A.A. Galeev and the American M.N. Rosenbluth.*

### How a Tokamak Works

Conceptually the tokamak is a simple device. A donut-shaped vacuum chamber is filled with hydrogen gas at a density thousands of times less than that of the atmosphere (Figure 2). Large magnetic coils circling the vacuum chamber are activated. These produce a straight, toroidal magnetic field parallel to the center line within the donut, going the long way around the torus.

In the same way that an electrical current is induced in a donut-shaped neon light to make it light up, a current is induced in the hydrogen gas with an iron core transformer. (The tokamak is a one-turn transformer.) The direction of the current flow is parallel, although in the opposite direction, to the toroidal magnetic field.

* A. A. Galeev and R. Z. Sagdeev, *Soviet Phys. JETP* 26:233 (1968); M. N. Rosenbluth, R. D. Hazeltine, and F. L. Hinton, *Phys. Fluids* 15:116 (1973).

The hydrogen gas is then ionized and heated by the process of induction and by the flow of the current. This heating process, called *ohmic* or *joule heating*, is basically the same as the process that heats a copper wire carrying an electrical current. The heating power is equal to the current squared times the electrical resistance encountered.

### Confinement

The ionized hydrogen gas (consisting of protons and electrons), now a hydrogen plasma, begins to expand toward the walls of the vacuum chamber in the same way that any gas would expand when heated. However, since the gas is ionized and, therefore, electrically charged, the plasma interacts with the magnetic field in a manner that slows down the rate at which it diffuses toward the walls of the vacuum chamber. The electrically charged protons and electrons are trapped into spiral orbits along the magnetic field lines (Figure 3). This orbiting confines the hydrogen plasma for some period of time and insulates it from losing its heat to the wall of the vacuum chamber.

The electrical current carried by the hydrogen plasma also generates a magnetic field. Called the *poloidal magnetic field,* it is perpendicular to the direction of the toroidal field and circles it. The poloidal and toroidal fields combine to form one magnetic field whose lines of force form spirals as they pass around the torus. This magnetic field geometry determines to a large extent the stability with which the plasma can be confined.

There are two possible types of instability: First, the plasma can interact with the magnetic field as a whole, that is, macroscopically, and wiggle its way to the vacuum wall where it is quickly cooled. Second, microscopic turbulence can develop. Either globs of plasma break through the confining magnetic field to the wall, or, at minimum, the plasma diffuses to the wall at a rate faster than would be expected from the standpoint of individual particles simply bouncing from one magnetic field line to the next.

To help minimize these instabilities, a third magnetic field is needed in a tokamak. A so-called *vertical magnetic field* is applied to the outside of the torus formed by the trapped plasma. This vertical field interacts with the plasma column and prevents it from moving outwardly like an expanding rubber band.

### Princeton Goes Tokamak

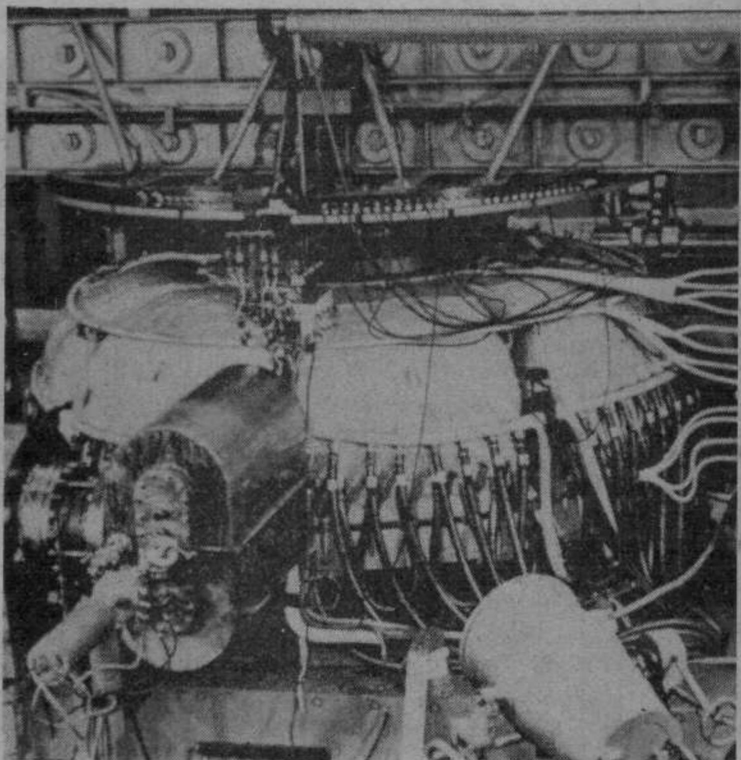
After the Soviet tokamak breakthrough was confirmed by the British in 1969, the Princeton Plasma Physics Laboratory decided to convert its large stellarator experiment over to a tokamak on a crash basis. The PPPL, Lawrence Livermore in California, Oak Ridge in Tennessee, and Los Alamos in New Mexico were the four U.S. national laboratories then working on magnetic fusion.

The stellarator is a donut-shaped magnetic bottle that is very similar to the tokamak in terms of the field geometry. The difference is that in a stellarator, the poloidal portion of the confining magnetic field is generated by external coils and not by a current induced in the plasma. This second set of external coils on a stellarator causes many difficult engineering problems, because the two sets of coils interact and can move each other around, destroying the necessary magnetic field geometry.

Since the United States abandoned the stellarator in 1969 for the tokamak, however, researchers in the Soviet Union, Japan, and West Germany have demonstrated that the originally poor performance of the stellarator was due chiefly to engineering problems. The L-2 stellarator at the Lebedev Institute in Moscow is approximately the same size as the T-3 tokamak, and has achieved equivalent results.*

Ironically, the Princeton PLT results have very significant implications for stellarators. Although the devices are not precisely the same in terms of their *macroscopic* stability criteria, the tokamak and stellarator have crucial similarities in their *microscopic* stability. For both machines, the most outstanding question has been the nature of the microscopic stability of high-temperature plasma beyond the D-T fusion ignition temperature of 44 million degrees. The PLT has answered this question with the most optimistic result; there is no instability at all.

It should be noted that stellarators have many potential advantages over tokamaks. Most important, the stellarator could lead to a steady-state reactor that continuously maintains a fusion plasma. Because it depends on an induced plasma current, the tokamak is cyclical and must be started back up over a span of time ranging from a few seconds to one hour, depending on the reactor design.



*This Soviet T-3 tokamak stunned world scientists by reaching multimillion degree temperatures in 1968.*

The converted Princeton stellarator, called the ST tokamak, generated more data in a few months than the Soviets had obtained in a year, because Princeton had access to more sophisticated and larger electrical power supplies, computers, electronics, and diagnostic systems for measuring plasmas. The ST quickly confirmed the T-3 results.

Soviet cooperation, however, was essential for this rapid success. In fact, the leader of the Soviet fusion program, Lev Artsimovich, almost singlehandedly organized for a substantial U.S. fusion program. In 1970, Artsimovich went on a national speaking tour here, detailing the tremendous progress achieved by the Soviet fusion effort. As a result, within two years of his trip, the U.S. fusion budget began to expand rapidly.

### Soviet Cooperation

During the 1970 trip, Artsimovich discussed his ideas for a high field tokamak with scientists at the Massachusetts Institute of Technology, which eventually led to the very successful MIT Alcator tokamak. At Princeton, Artsimovich discussed the need for large tokamak experiments to approach reactor conditions with temperature greater than 50 million degrees; this is how the idea of the PLT was born.

* T. K. Chu et al., *The Status of Stellarator Research in Europe*, PPPL-TM-308.

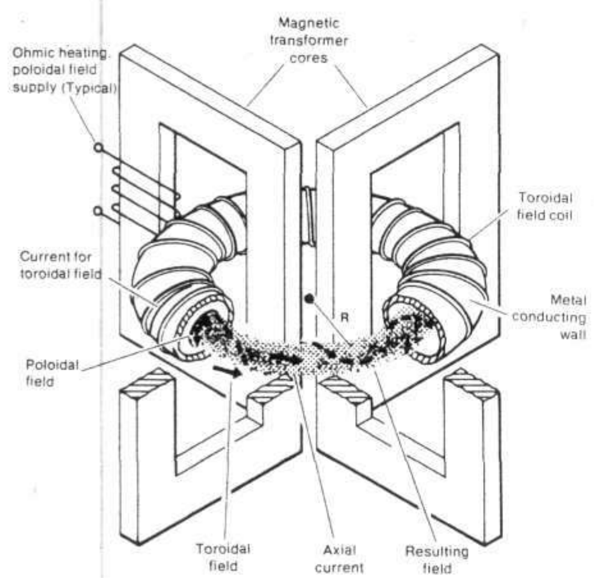
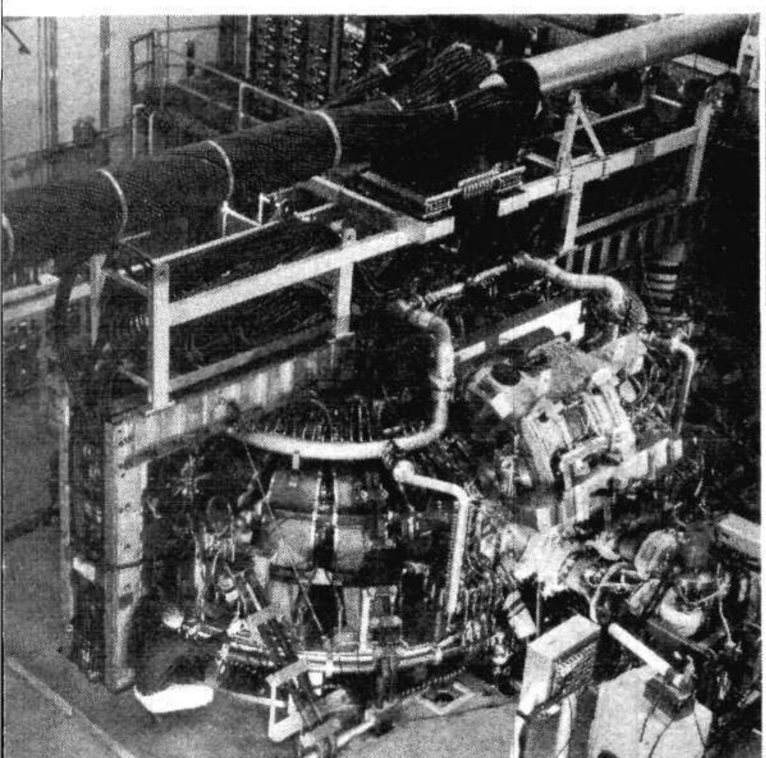



**Figure 2**
**TOKAMAK CONFINEMENT SYSTEM**

*The tokamak concept is to contain a high-temperature plasma in a donut-shaped container using a strong magnetic field created by the combination of toroidal and poloidal fields.*



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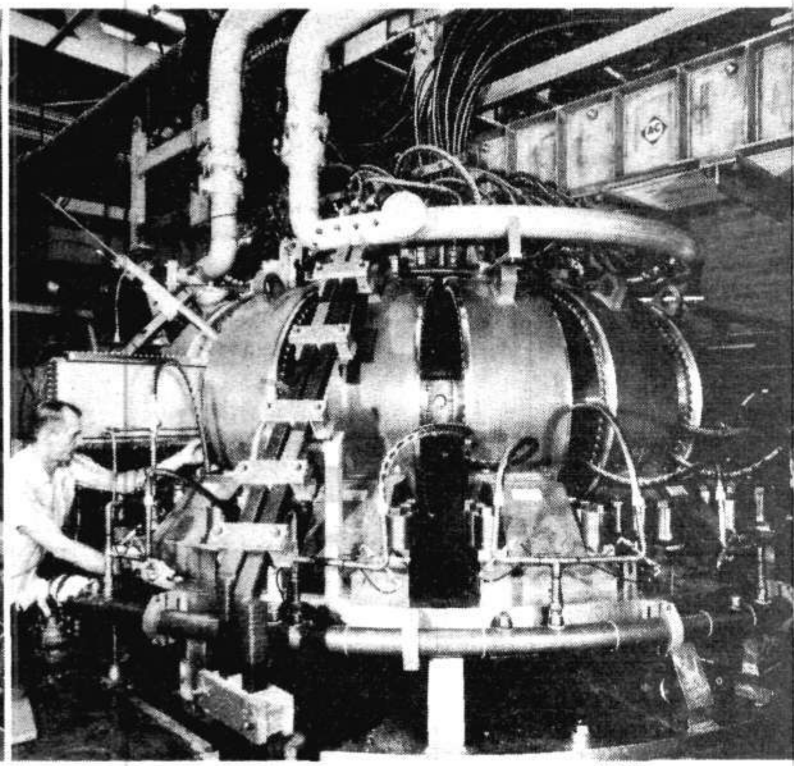

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*Soon after the T-3 results, Princeton went tokamak, converting its Model C Stellerator (l.) into the Symmetric Tokamak, or ST (r.), which quickly confirmed the T-3 results.*

Princeton scientists, however, were not given the sort of funding required for immediately embarking on this idea and they decided on an intermediate step: the Adiabatic Toroidal Compressor tokamak, known as ATC. Although the ATC was smaller than the ST and T-3 tokamaks, it turned out to be one of the most productive and successful fusion experiments ever conducted.

### Alternate Heating Methods

One major problem with the tokamak concept in its original form was that fusion temperatures could not be attained with ohmic heating alone. As noted above, the heating power of the plasma current is equal to the current squared times the electrical resistance. However, as low-density tokamak plasmas (about 10 trillion to 100 trillion atoms per cubic centimeter) approach temperatures of 30 million degrees or more, their resistance to the flow of electrical current rapidly decreases, therefore decreasing the heating power of the plasma current.

The reason for this rapid decline of electrical resistance is that the plasma becomes *collisionless* at these temperatures. Or, to be more specific, it does not have a certain kind of collision. In low-density plasmas, collisions among individual particles are a relatively minor occurrence. Much more significant is the collision of the individual plasma particles, or rather a large number of plasma particles, with the electric fields generated by the plasma as a whole. This is called a *Coulomb collision*. The frequency of Coulomb collisions is an inverse function of temperature; therefore, the frequency decreases with rising plasma temperatures. A tokamak plasma is said to be collisionless when the individual plasma particles travel around the entire distance of the torus without undergoing a Coulomb collision.

Since electrical resistance is literally the resistance to the flow of electrons, that is, collisions, as the Coulomb collision frequency declines, the electrical resistance of the plasma falls off.

In order to reach D-T fusion temperatures of 44 million degrees and more, some alternative means of heating the plasma must be used. Among the possibilities are: (1) the interaction of radio waves and microwaves with the plasma; (2) the compression of the plasma by suddenly or slowly increasing the strength of the confining magnetic fields; (3) the introduction of accelerated ions or electrons whose equivalent temperature (temperature is an average measure of the speed of a group of particles whether these particles are atoms, or separated electrons and nuclei) is billions of degrees; and (4) the pulsing of the magnetic fields at a rhythm that interacts with the plasma to heat it.

Other, more exotic methods are also possible, such as introducing globs of preheated plasmas or laser-initiated plasmas. The key criteria for any alternate heating method are that it must be both effective and efficient without unduly destabilizing the confinement of the plasma.

The Princeton ATC tokamak was designed to be built on a crash basis to test two of these alternate heating schemes, adiabatic compression and neutral beams.

*Adiabatic compression,* that is, slowly increasing the strength of the magnetic field, was a method developed at New York University's Courant Institute. The ATC successfully accomplished this, in 1972, when higher temperatures were recorded and no plasma instability developed.

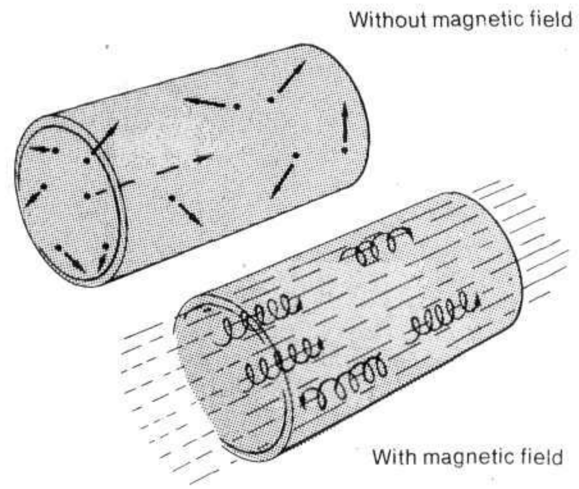



**Figure 3**
**MAGNETIC CONFINEMENT**

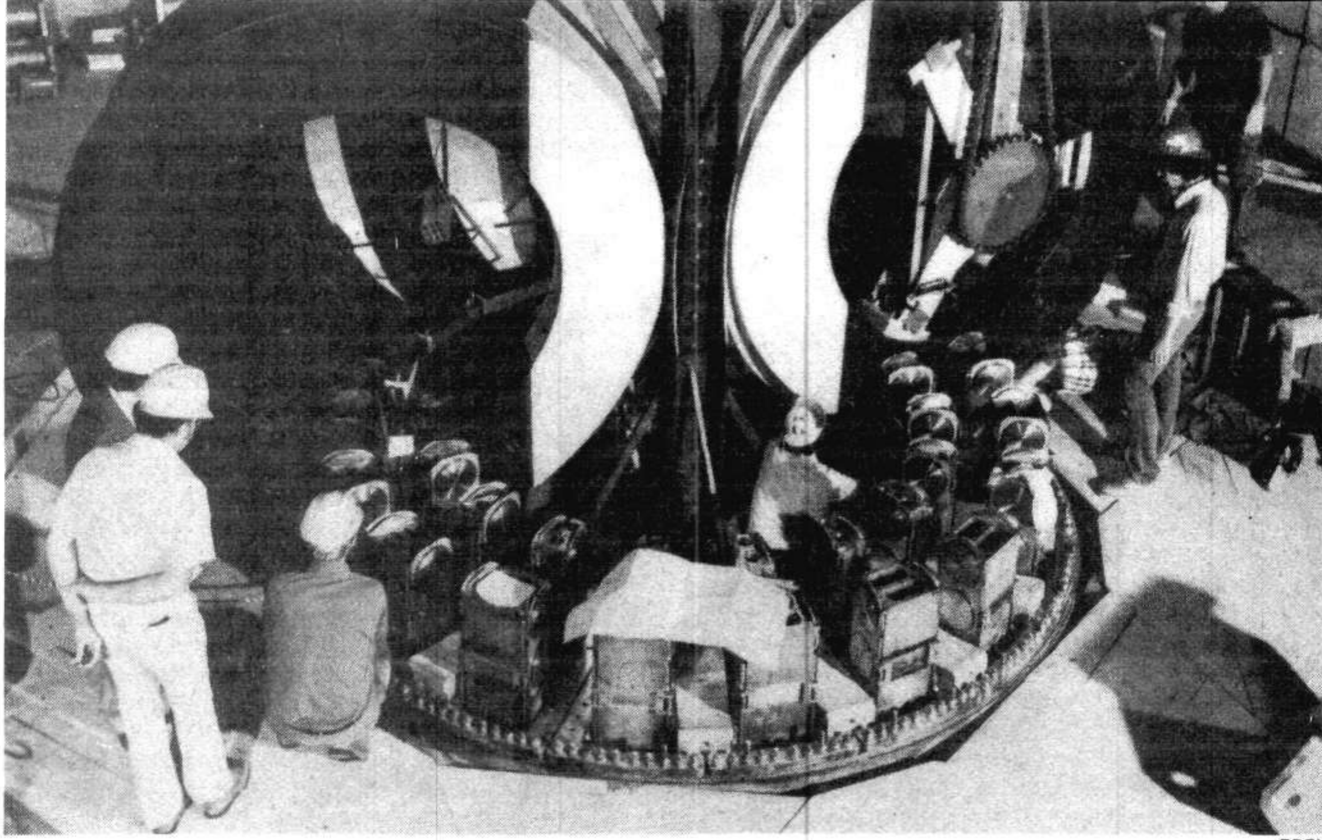
*The magnetic field forces the particles to follow spiral paths around the field lines, preventing them from striking the walls of the vessel and thus cooling the plasma and inhibiting fusion reactions.*

*Neutral beam heating*, the use of accelerated ions, was also successfully demonstrated on the ATC in 1972. The problem with introducing high-energy accelerated ions or electrons into a tokamak, is that the magnetic bottle, which is designed to trap hot ions and electrons, keeps out electrically charged ions and electrons. Only electrically neutral atoms can easily pass through the magnetic bottle to the trapped plasma.

Therefore, the way to use high-energy ion beams to heat a magnetically confined plasma is to turn them into *neutral* atoms before they encounter the magnetic bottle. This was accomplished by passing an ion beam through a gas cell. The high-energy ions pick up an electron in collisions with the low-energy gas molecules in the cell and emerge from the cell as high-energy neutral atoms.

These high-energy neutral atoms form a neutral beam that can then penetrate the magnetic bottle and collide with the plasma particles. In these collisions with the plasma particles, the neutral beam once more becomes ionized and trapped in the magnetic bottle. In this way, the injection of a high-energy neutral beam quickly heats a plasma.

In 1975, powerful neutral beam injectors were used on another kind of magnetic bottle, the magnetic mirror machine 2XIIB at Lawrence Livermore Laboratory in California to produce plasma temperatures of more than 140 million degrees.



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*Technicians working in 1975 to assemble the toroidal field coils of the PLT.*

The ATC also carried out a number of microwave heating experiments before it was retired to make room for the PDX, another major tokamak experiment at Princeton just now coming on line.

**The PLT Is Born**

After the dramatic success of the ATC in demonstrating in principle the efficacy of two different heating methods, the decision was made in 1972 to go ahead with a large tokamak experiment at Princeton. Despite a lack of funds, Princeton proceeded to build the PLT on a crash basis.

To get some idea of the problem, consider that the money spent by the entire U.S. fusion program in 1972 was less than the annual budget of PPPL today. It was not until 1973 and 1974 that Dr. Robert Hirsch, the director of the Atomic Energy Commission's Controlled Thermonuclear Fusion Division, was able to obtain significant increases in the fusion budget.

As a result, Princeton had barely enough funds for the essential long-term procurement of materials (for example, buying the large quantities of copper used in the giant magnetic field coils), let alone for thorough engineering and management planning. From an engineering standpoint alone, the PLT is as difficult and as large scale as any major space vehicle design project. Yet, instead of the hundreds of engineers that the National Aeronautics and Space Administration would put onto the job of designing a difficult project like PLT, Princeton had only a handful of engineers and graduate students. Even with large numbers of design engineering teams, it is almost inevitable that major problems will arise in a project, like the PLT, that involves the frontiers of a number of different scientific areas. Therefore it is a miracle (and a great tribute to the PPPL staff) that the PLT, built on a crash basis, works at all.

The Lawson diagram shown in Figure 4 provides a general means of gauging how close various fusion devices are to producing *net energy;* that is, producing more fusion energy than the energy put in to heat and confine the fusion plasma. For the D-T reaction, this requires temperatures greater than 44 million degrees and a so-called Lawson product greater than 30 trillion seconds-nuclei per cubic centimeter. The Lawson product consists of the time the fusion plasma is confined (that is, prevented from losing its temperature) times the density of the confined plasma in number of nuclei per cubic centimeter. In a tokamak, this product of confinement time and density would consist of a confinement time equal to three-tenths of a second and a density of 100 trillion nuclei per cubic centimeter at the requisite 44 million degree temperature.

**PLT's Immediate Future**

As shown in the figure, the PLT has already achieved a Lawson confinement time-density product of several trillion at a temperature of 60 million degrees (twice the temperature originally projected for the experiment). And this was accomplished with only two-thirds of the PLT's neutral beam heating power turned on (2 million watts of neutral beams).

Figure 5 is a flow chart of the major program elements needed to realize a tokamak power plant. The scaling of the confinement time with increasing size has been demonstrated in more than a score of different tokamak experiments throughout the world; the confinement time is shown to be proportional to the square of the radius of

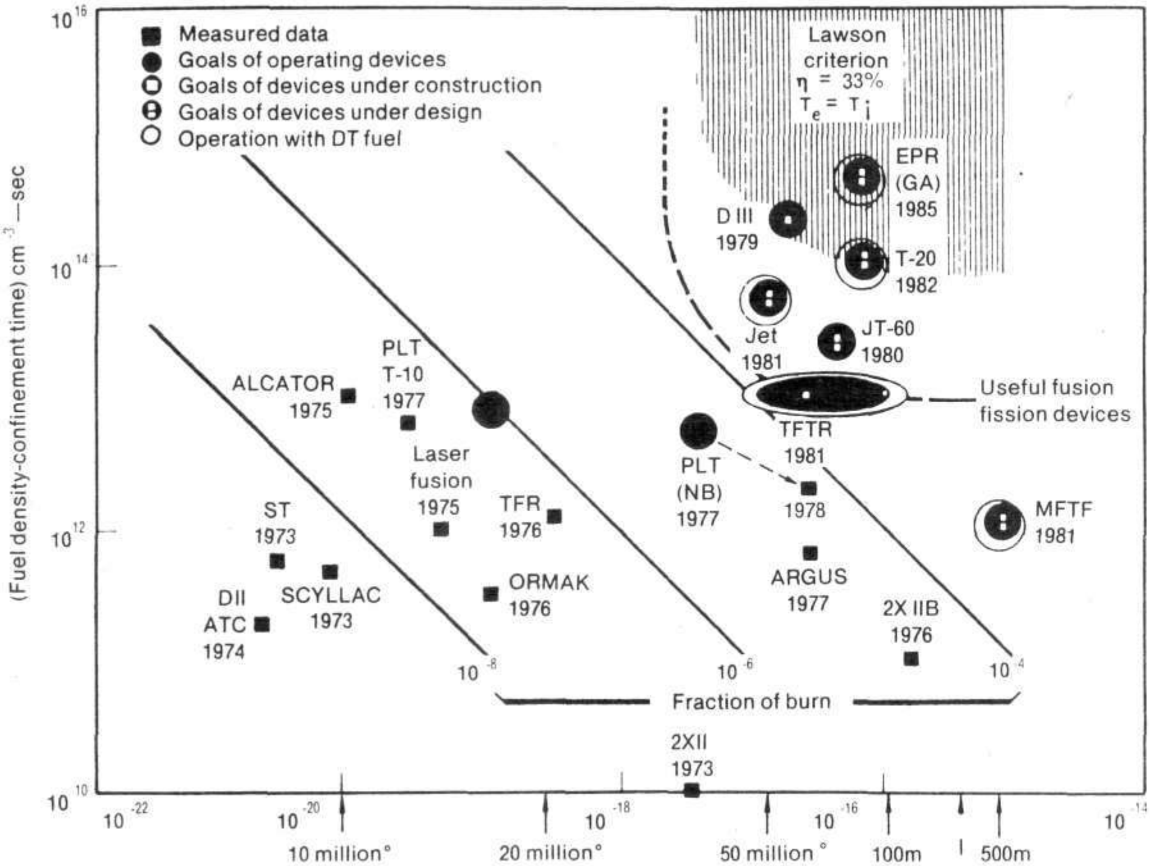



**Figure 4**
**RESEARCH PROGRESS IN FUSION POWER**

*The current state of fusion research is shown here in terms of already achieved results and projections for planned experiments under construction. Results from the various research projects are plotted logarithmically on both axes. The horizontal axis gives temperature in millions of degrees Celsius, and the vertical axis gives the density-confinement time product in number of seconds-nuclei per cubic centimeter. The hatched region in the upper right corner represents the area in which a pure fusion reactor must operate. The dashed line, also in the upper right, shows how these conditions are substantially lowered for fusion-fission hybrid reactors.*

*Below the names of the various experiments are the dates of measured results (boxes) or projected results (circles). A guide to the experiments follows: DII is the General Atomic noncircular tokamak, Doublet II, to which DIII is the followup. Doublet III, now on line, is expected to reach near-reactor conditions when neutral beams are added to the experiment in 1979. ST refers to the first U.S. tokamak, the converted Princeton ST stellerator, which duplicated the initial Soviet tokamak results. ATC was the second U.S. tokamak, also at Princeton, a small device that demonstrated the feasibility of neutral beam and plasma compression heating in tokamaks. Alcator is the Massachusetts Institute of Technology's high field, small tokamak, which, as seen, holds the record for density-confinement product. Ormak was the third U.S. tokamak to be built, and it demonstrated scaling both in terms of size and neutral beam heating. TFR, the French tokamak, also demonstrated neutral beam heating. PLT and T-10 are the large U.S. and Soviet tokamaks, respectively. PLT, the Princeton Large Torus, recently achieved temperatures of 60 to 80 million degrees with neutral beam heating. TFTR is the Princeton tokamak fusion test reactor now under construction, which will be the first tokamak to burn D-T fusion fuel (all previous experiments used only simple hydrogen). EPR and T-20 are the General Atomic and Soviet designs for Experimental Power Reactors, respectively. 2XII and 2XIIB represent the results from Livermore's open-ended mirror magnetic system. The Mirror Fusion Test Facility (MFTF) is a Livermore experiment that will demonstrate the feasibility of a number of different mirror approaches to fusion. Laser fusion refers to world results in inertial confinement. Argus was the prototype 2-beam system for the Livermore 20-beam Shiva system now in operation and projected to achieve results equal to the TFTR. Scyllac represents the results from toroidal theta-pinch research.*

the confined plasma column in a tokamak (the minor radius of the torus). The PLT conclusively demonstrated this up to and beyond fusion ignition temperatures.

Another scaling law, first observed in the MIT Alcator tokamak in 1975 and later confirmed in the Oak Ridge Ormak tokamak, is that confinement time increases with density; that is, the confinement time is proportional to density times the square of the plasma radius. This was a surprising and most optimistic discovery, since the criterion for producing net fusion energy is the Lawson product, and both elements of the product increase simultaneously.

The PLT continues to observe the same density-confinement time scaling law. Therefore, as the full 3 million watts of neutral beam heating power is turned on in the PLT, we can predict a number of dramatic strides forward.

First, the greater heating power will permit higher density plasmas to be achieved in the PLT at the 60 million degree level. This will lead to an increase in the confinement time, which, in turn, will allow the neutral beams to inject more heat energy into the plasma. The net result is that we can conservatively project the PLT will reach a Lawson product of 10 trillion seconds-nuclei per cubic centimeter at the 60 million degree temperature within the coming weeks.

### The Impurity Problem

There are basically four ways for a fusion plasma to lose its energy; that is, to be cooled below fusion temperatures:

(1) *Simple diffusion of plasma electrons and ions to the vacuum wall.* Magnetic fields slow this process down so that the hot plasma remains insulated for a sufficient duration of time to permit substantial amounts of fusion reactions to take place.

(2) *Large-scale turbulence of the plasma.* This plasma turbulence is generally caused by interactions between the plasma and the confining magnetic field, which are referred to as magnetohydrodynamic or MHD instabilities. These cause the whole plasma column to wiggle its way within a few millionths of a second to the vacuum wall where the plasma is quickly cooled.

(3) *Small-scale turbulence, which enhances particle diffusion.* These microinstabilities can be caused by a number of things, such as weak, small-scale MHD instabilities and particle-kinetic effects associated, for example, with trapped particle dynamics.

(4) *Electromagnetic radiation.* This may be caused by free electron streaming (bremsstrahlung); by simple black body radiation such as that generated by any heated body; cyclotron radiation caused by the interaction of electrons with magnetic fields; and most important, by atomic radiation generated through the ionization of neutral atoms or through the further ionization of partially ionized heavy elements.

These partially ionized heavy elements consist chiefly of oxygen, tungsten, and iron, which emerge from the wall of the vacuum chamber and flow into the confined plasma. Although the impurities constitute only a small percentage of the nuclei of the plasma, they can be the major source of the plasma's energy loss through the generation of electromagnetic radiation, because they have a much greater nuclear electrical charge than the hydrogen.

The PLT achieved minimal impurity levels by applying various cleansing routines, like preheating the vacuum wall and expunging the loose heavy elements before discharges. But, as the MIT Alcator first demonstrated, completely pure hydrogen plasma discharges can be achieved at higher plasma densities, and purity levels increase with increasing density. Therefore, the confinement time and temperature can be predicted to increase even more as the PLT reaches higher densities.

### Temperature Scaling

The most significant result of the PLT breakthrough to 60-million-degree temperature levels is that confinement time does *not* decrease with increasing temperature in the fusion range. The most optimistic previous expectation for tokamak plasmas in this temperature range was for slight decreases in the confinement time with increasing temperature, because of the development of microscopic plasma instabilities in the collisionless regime. However, none of these theoretically predicted potential instabilities has been observed in the PLT, and confinement time does not decrease. In fact, it is quite possible that the confinement time could increase dramatically with increasing temperatures.

In quantitative terms, the achieved quality of confinement in the PLT at fusion temperatures is a "hundred times better than what is minimally needed for fusion reactors," according to Dr. Melvin Gottlieb, the director of PPPL.

Classical plasma physics theory, which is based on the simple model of individual plasma particles trapped to follow spiral orbits along magnetic field lines, predicts that nonlinear effects, like the Ware effect,* could develop in a tokamak at high temperatures. In the Ware effect, also known as the Ware pinch, a large portion of the confined plasma is predicted to "pinch" toward the center of the plasma; that is, in a direction opposite to outward plasma diffusion through the magnetic field to the vacuum chamber wall. This means that if the Ware effect develops, the confinement time could increase dramatically.

Indications of a possible Ware pinch were reported by Ron Parker, head of the MIT Alcator research team, at the U.S. Plasma Physics Meeting of the American Physical Society in November 1977 in Atlanta.

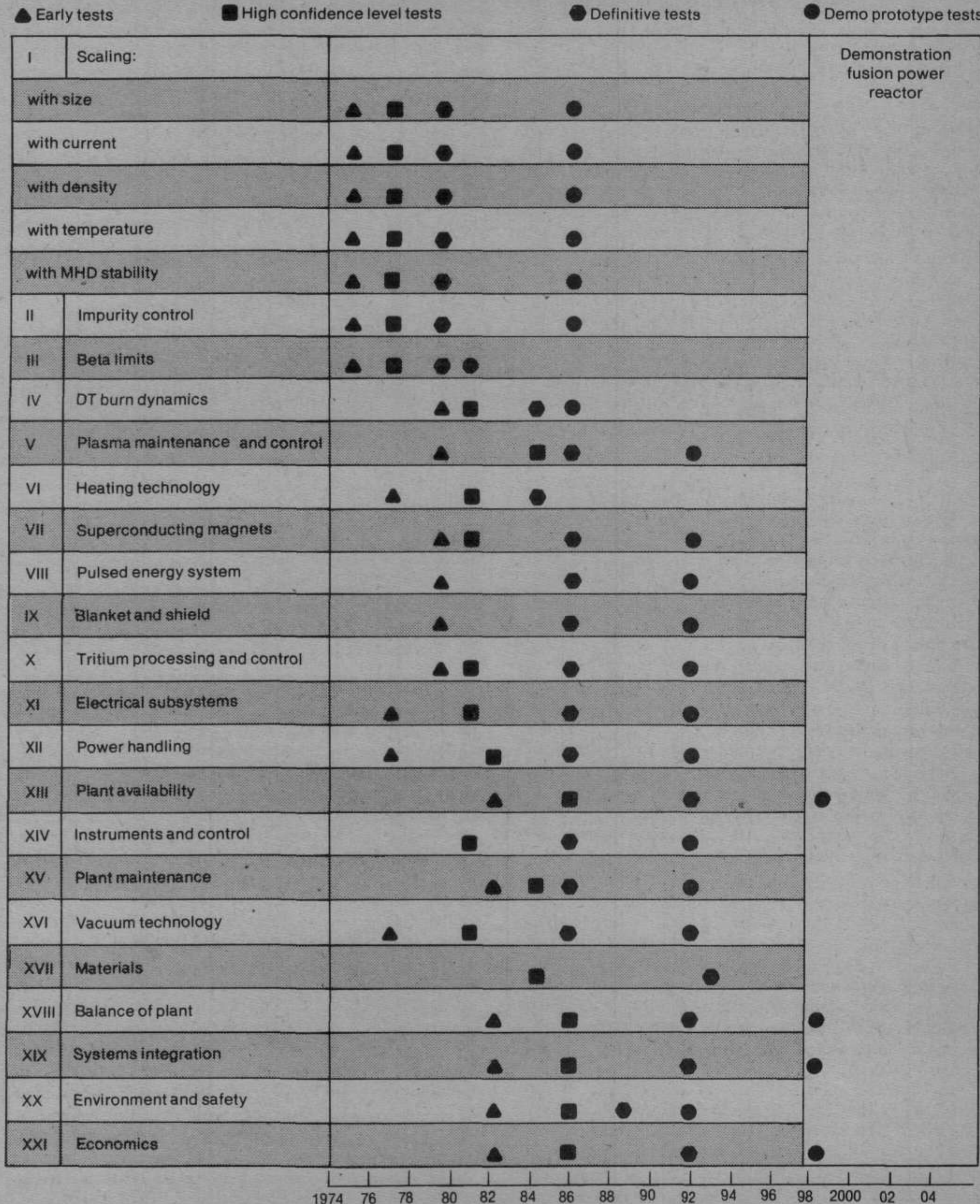
### Bootstrap Electrical Current

Another potential effect that classical theory predicts is *bootstrap electrical current*, which is thought to be caused by the frictional forces between trapped and untrapped plasma particles in a collisionless regime.** As noted in the discussion on the advantages of the stellarator, the tokamak cannot run continuously because a plasma current must be induced from some external source to

* A. A. Ware, *Phys. Rev. Letters* 25:916 (1970); A. A. Galeev, *Soviet Phys. JETP* 32:752 (1971).

** R.A.E. Bolton et al., in *Plasma Physics and Controlled Nuclear Fusion Research*, Vol. 3, p. 79 (Vienna: IAEA, 1972).

Figure 5
MAJOR PROGRAM ELEMENTS FLOW CHART
FOR THE TOKAMAK



maintain the poloidal magnetic field component. If this bootstrap current occurs in a stable, significant way, the tokamak could be run continuously using the external induction as a means of startup.

The bootstrap current depends upon the fact that the *trapped particle effect* develops in a collisionless regime, where plasma particles traverse the entire distance around the tokamak without undergoing a collision, on a spiral orbit on one magnetic field line. As the plasma particles travel along the spiral-shaped magnetic field lines following spiral orbits, however, there is an increase of the magnetic field strength toward the inner part of the torus. This leads to some plasma particles being turned around and "reflected" back in the opposite direction. (This is the principle of operation of the magnetic mirror bottle.)

As a result, a significant number of the plasma particles do not travel around the full distance of the torus in the collisionless regime, but are trapped into banana-shaped paths inscribed by their spiral orbits (Figure 6). It is the frictional forces between the trapped and untrapped plasma particles that are predicted to cause the bootstrap electrical current to arise. It is also predicted that intense neutral beams could provide the "seed" current for the onset of this bootstrap current.

### Two-Component Tokamaks

The Princeton Tokamak Fusion Test Reactor, scheduled to begin operation in 1981, was originally named the Two-Component Tokamak (with the neutral beam and the background plasma as the two components). Basically, the two-component idea is that significant amounts of fusion energy can be generated without reaching fusion ignition conditions where the fusion reactions release more energy within the fusion plasma than that being lost. This is accomplished by the collisions of nuclei injected by the neutral beams and the hot plasma, at overall plasma temperatures below the fusion ignition temperature—a sort of *wetwood burner.**

Although the overall energy gain in a two-component system is limited to less than 5 (energy gains of 10 and more are desirable for economical reactors), this is more than sufficient for operation of economical *hybrid fusion-fission tokamak reactors.*

The PLT has already demonstrated the conditions needed for running a two-component fusion-fission hybrid.

### Electromagnetic Wave Heating

A number of alternative heating systems have been demonstrated in principle utilizing radiowave and microwave-frequency electromagnetic waves. Although these have not been tested on a large scale, many successful experiments have been conducted on the Soviet tokamak TM-3 using wave heating. The Alcator reports some interesting recent results, and the Princeton ST tokamak, before it was torn down to make room for the PLT, also conducted experiments along this line.

*Figure 5 shows the U.S. Energy Research and Development Administration's time estimates, from their 1976 study, for solving various problems along the way to a demonstration tokamak reactor. The assumed funding is Logic III.*

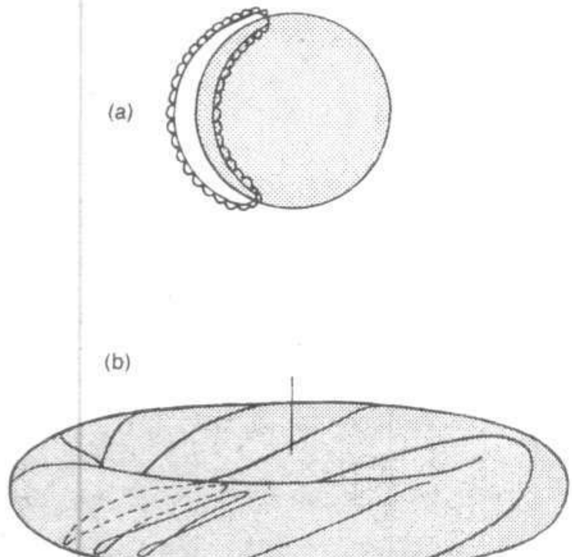



**Figure 6**
**TRAPPED AND CIRCULATING PARTICLES**

*This banana-shaped orbit, shown in a projection of the cross section of the torus in (a), characterizes a trapped and collisionless plasma particle (a nucleus or electron) in the helical magnetic field of a tokamak. The particle has triple motion: the gyration in a spiral along the magnetic field line, the banana orbiting, and the drift across the magnetic field lines.*

The potential progress that the PLT could achieve with wave heating in the coming months may be judged by the fact that the device has only 3 million watts of neutral beam injectors, but more than 4.5 million watts of radio frequency wave apparatus. If this heating method proves to be effective, even higher temperatures than those achieved with neutral beams could be attained. Furthermore, if both the wave and neutral beam systems are used simultaneously, the PLT could reach very high temperatures indeed.

### Plasma Beta

The *plasma beta* is a measure of how effectively the magnetic fields confine fusion plasmas. Specifically, beta is the ratio of the plasma gas pressure (usually given as proportional to the density times the temperature) to the

* J. M. Dawson, H. P. Furth, and F. H. Tenney, *Phys. Rev. Letters* 26:1156 (1971).

strength of the confining magnetic field (which is proportional to the square of the magnetic field). The plasma beta generally is given as a percentage with a ratio of 1 being 100 percent, the most effective use of the magnetic fields.

The beta is an important quantity, because a major cost of a tokamak power plant will be the coils that generate the magnetic field, and a low beta would lead to uneconomical systems.

Tokamaks generally have been low-beta systems, achieving plasma betas of less than 1 percent, compared to the betas of 6 to 10 percent needed for economical reactor designs. The reason is that previous tokamaks, which depended chiefly on ohmic heating, were limited because of the macroscopic instabilities that occurred when the ratio of the plasma current to the main toroidal magnetic field exceeded a value determined by the geometry of the particular tokamak—its size and the fatness of the donut. With the successful use of neutral beam heaters to replace the ohmic heating, the beta limits of a tokamak can be explored.

A specific method using neutral beams to achieve reactor level betas and better is discussed below in the section on the Grad-Hogan theory. The PLT will demonstrate the efficacy of this theory and could completely resolve the beta problem within the coming months.

### The Near-Term Forecast for the PLT

The Princeton PLT is in a position to resolve all the major scientific questions of tokamak reactors—scaling, impurity control, beta, and heating—in the coming months and in addition to open up two other important paths for fusion development: two-component tokamak hybrid fusion-fission breeders and advanced pure deuterium reactors.

PLT has already secured the essential scientific base for developing two-component hybrids.* As the projected results unfold in the coming months, this base will be vastly expanded, improving the prospects for extremely economical two-component hybrid designs.

The other route, which had been the subject only of speculation prior to the recent PLT breakthroughs, is the use of tokamaks to attain the extremely high temperatures (300 million to 1 billion degrees) needed for advanced fusion fuel reactors like pure deuterium-deuterium (D-D) systems. The unexpected stability of the high-temperature, collisionless regime in the PLT gives every indication that it is possible to attain the high-temperature, stable operation needed for the D-D reaction.

PLT breakthroughs in the coming months could secure this new route to fusion. Furthermore, this development would overcome major technological barriers of the D-T fusion reactor systems: the need to breed tritium in the fusion reactor and the materials problems caused by the breakdown of the vacuum wall by the high energy D-T neutrons (D-D reactions produce fewer neutrons and at a lower energy than D-T reactions).

The PLT was able to attain a maximum toroidal magnetic field strength of only 35,000 gauss instead of the original projection of 50,000 gauss, because of the engineering problems caused by the lack of funds when the tokamak was designed. Next year, the PLT will be upgraded and reworked to be able to attain this higher field rating. This will permit the plasma current to be raised from the present 400,000 amp level to more than 1 million amps.

**Figure 7**
**RELATIONSHIP AMONG MAJOR TOKAMAK SYSTEMS PROGRAMS AND CRITICAL RESEARCH AREAS**

| RESEARCH AREA | PROGRAM: PLT | PDX | ISX | Doublet IIa | Doublet III | Alcator A | Alcator C | TFTR |
|---|---|---|---|---|---|---|---|---|
| Transport and scaling | ● | ● | ● | | ● | ● | ● | ● |
| Heating | ● | ● | ● | ● | ● | ● | ● | ● |
| Beta optimization | | ● | ● | ● | ● | | | |
| Impurity control | | ● | ● | | | | | |
| Fueling | ● | ● | ● | | ● | ● | | |
| Alpha effects | | | | | | | | ● |

At the same time, the neutral beam heating capability will be more than tripled, and the wave heating power will be doubled. This upgrading will permit the PLT to resolve fully any questions that might remain on the Grad-Hogan theory for attaining high beta tokamak operation.

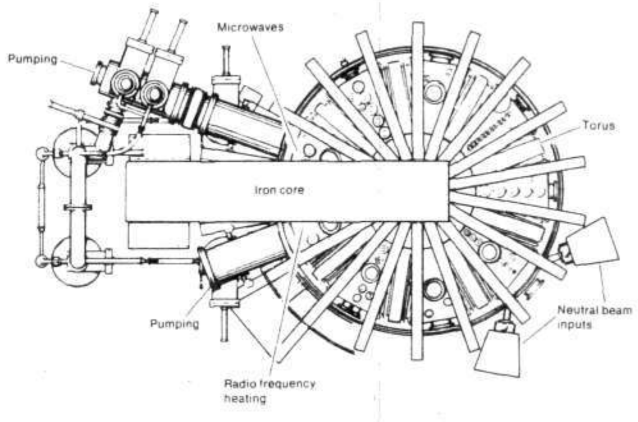
In addition, experiments on the upgraded PLT will address the last remaining significant question for demonstrating the scientific base for minimal tokamak reactor systems: What effect, if any, will the high-energy fusion product helium nuclei have on the stability of the plasma? At present, the general scientific view throughout the world is that the fusion products will have little effect on the stability of fusion plasmas, although there is a remote possibility that some deleterious effects may show up. The PLT will use a number of beam-plasma experiments to replicate the effect of having these helium nuclei in its plasma. It is expected that the PLT will resolve the question in principle in 1980, and the TFTR will completely resolve it in 1982 with full D-T operation.

The critical research areas now being explored by the various tokamak experiments are summarized in Figure 7.

Although the chart indicates that the PLT will not completely resolve questions of beta optimization, impurity control, and Alpha effects—which the PLT was not designed to do—the creative PPPL scientists may be able to explore the essential aspects of these questions by making full use of the experimental capabilities of their versatile tokamak.

* D. L. Jassby and H. H. Towner, *Optimization of Plasma Profiles for Ignited Low-Beta Toroidal Plasma*, PPPL-1360 (June 1977).

# The Oak Ridge ISX-B: Solving the Beta Problem



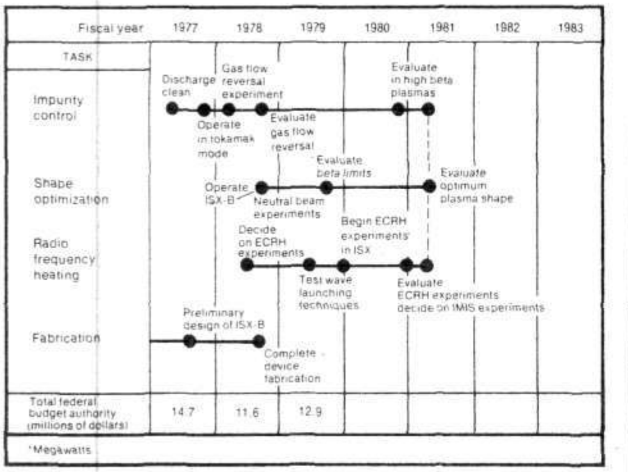




Figure 8

Although the fusion team of the Oak Ridge National Laboratory is in the backseat in terms of public acknowledgement of the Princeton results, it should probably be in the driver's seat. Oak Ridge was the first to develop neutral beam injectors in a significant form, and the injectors used on the PLT were hand-delivered from Oak Ridge. Moreover, these devices are every bit as complex and costly as the main experimental tokamak.

Neutral beam injectors are what has put the United States in the lead in fusion research today. Until recently, in fact, neutral beam construction was described by many foreign scientists as a "black art," since no other country could match the success of Oak Ridge and Livermore in constructing these devices.

In addition to supplying Princeton with neutral beams for the PLT, Oak Ridge has a significant tokamak experiment coming on line, the ISX-B, which stands for the Impurities Studies Experiment with neutral beam heating. In the weeks ahead, this device could secure the single, remaining major scientific question needed for successful tokamak reactor design—efficient plasma betas. (Plasma beta is a measure of the efficiency with which the magnetic fields confine a plasma. Tokamaks now operate with betas of less than 1 percent, while a beta of at least 6 is needed for the most economical reactor designs.

## The Ormak

First, some history. Oak Ridge quickly followed Princeton's lead into tokamak research in the early 1970s. At about the same time that the Princeton ATC came on line, Oak Ridge brought on line the Ormak tokamak. This machine demonstrated that the plasma confinement time increases with the square of the plasma radius. Later, the Ormak demonstrated that significant temperatures of more than 20 million degrees could be produced with neutral beam injectors.

There were plans to upgrade the Ormak for extremely high-power neutral beam heating last year. But when cuts in the federal fusion buget completely cut off Ormak funds, Oak Ridge supplied neutral beams to Princeton and the PLT became the first tokamak to reach fusion ignition temperatures.

As Ormak was torn down, another tokamak experiment was brought on line at Oak Ridge, the ISX, or Impurities Studies Experiment. The ISX is a medium-size tokamak, about the same size as Ormak and half the size of the PLT in terms of plasma radius. Volumetrically it is only a fraction of the PLT size, with a modest-size magnetic field around 18,000 gauss, about half that of the PLT.

Originally the ISX was designed to achieve modest goals: to carry out experiments on controlling the influx of nonhydrogen elements (impurities) into the confined plasma; to test various methods of fueling tokamaks for reactor design; to examine what plasma betas might be attained in a tokamak using various means.

Despite such apparent modesty, the ISX has already demonstrated the most important qualities needed for realizing tokamak fusion power plants—mature scientific and engineering capabilities. Unlike any previous fusion experiment, the ISX was able to go into full operation within days of its completed construction last year. In addition, its operation was virtually perfect. The ISX demonstrated successfully several means of cleansing a plasma of impurities including a new idea that uses a gas blanket and pellet injection for fueling a tokamak power plant.

Key comparisons between ISX and Ormak are shown in Table 2. As noted in the table, the plasma confinement time was increased by 170 percent simply because of the increased purity of the ISX plasma. This is reflected in the radiation measurements shown, and it correlates with impurity levels.

Table 2
ORMAK COMPARED TO THE ISX

| ITEM | ORMAK | ISX |
|---|---|---|
| Minor radius | 23 centimeters | 26 centimeters |
| Limiter material | Tungsten | Stainless steel |
| Longest energy-confinement time with ohmic heating alone | 10 milliseconds | 27 milliseconds |
| Radiation loss normalized to ohmic power | | |
| Radiometer | 50-80% | 25-40% |
| Spectroscopy | 38.7% | 11.8% |
| Hydrogen | | 3.6% |
| Carbon | 0.2% | 2.3% |
| Oxygen | 16.8% | 5.5% |
| Iron | 0.3% | 0.5% |
| Tungsten | 21.4% | |

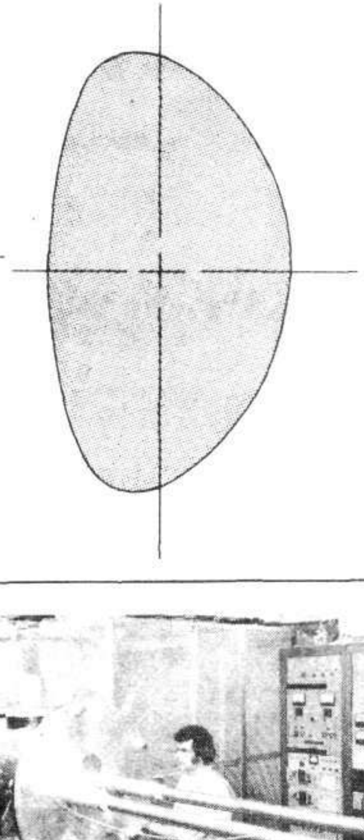
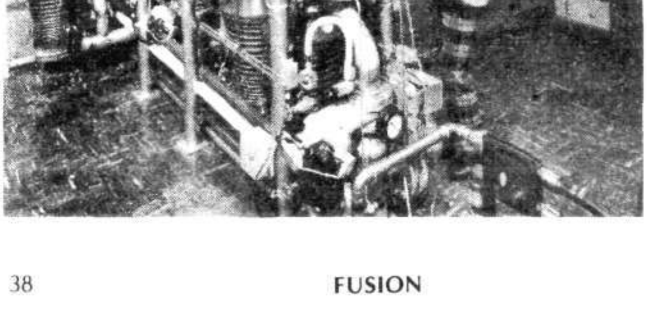


**Figure 9**
**ISX-B**
**CROSS SECTION**

*The D-shaped cross-section of the ISX is designed to permit the ratio of the plasma current to the main toroidal magnetic field to increase significantly while maintaining macroscopic plasma stability.*



This summer the ISX experiment was rebuilt. The reborn ISX, the ISX-B, has just now come on line with 1.8 million watts of neutral beam heating; this wattage equals the heating power used by the much larger PLT to achieve plasma temperatures of 60 million degrees.

The ISX-B is actually two experiments. The first is to see if theoretical predictions of using changes in tokamak geometry to increase the plasma beta can work. Instead of having a circular cross-section, as do conventional tokamaks like the PLT, the ISX has an oval D-shaped cross-section (Figure 9). This should permit the ratio of the plasma current to the main toroidal magnetic field to be increased significantly while maintaining macroscopic plasma stability. In this way, plasma betas up to the minimum needed for tokamak reactors will be achieved.

This is only the beginning. In the coming months, the ISX-B simultaneously will achieve very high plasma temperatures with neutral beam injectors and high plasma betas, up to the 10 percent range. This will be accomplished by the application of the Grad-Hogan theory (discussed in the last section of this report) and the flux-conserving tokamak theory developed chiefly at Oak Ridge.

### Flux Conservation

In brief, the flux conservation theory holds that if the tokamak plasma can be heated fast enough in the right way, the magnetic lines of force will be "frozen" into geometrical surfaces (the flux surface) in the tokamak plasma. In this way, a macroscopically stable plasma-magnetic field configuration is maintained while the plasma is at high betas.

The Grad-Hogan theory provides powerful mathematical and physical insights into how this flux conservation works, giving a roadmap of how the plasma must be maintained in terms of temperature and density distribution and how fast the heating is to be accomplished.

### Near-Term and Long-Term Forecast

Given the PLT success and the previous performance of the Oak Ridge fusion team, it is likely that in the months to come, ISX-B will go well beyond resolving the beta question. The ISX-B will approach the temperatures reached in the PLT, either this fall or later next year when more neutral beam heating power is added. At the same time, the higher beta operation and the higher level plasma currents it can achieve will permit the ISX-B to proceed to higher densities and confinement times. In this way, the ISX-B not only will resolve the beta question but also will reinforce the scientific base that the PLT has established for tokamak reactor design.

*A neutral beam injection system in its developmental stage at the Oak Ridge National Laboratory in 1977. Hal Haselton, who headed the injection project, is shown working with a beam line.*
ORNL

# The MIT Alcator C: Small Size, High Power

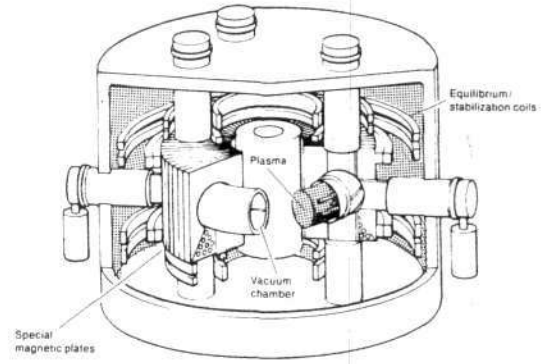
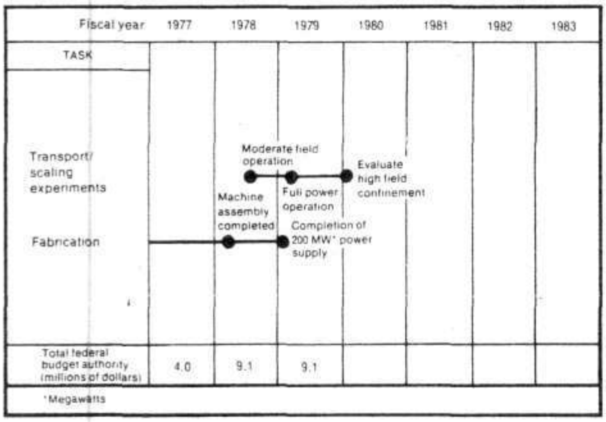



Figure 10




Although it encountered many problems with its initial startup, the Massachusetts Institute of Technology Alcator tokamak, which is 100 times smaller than the Princeton PLT, has generated the greatest surge of advances ever recorded in tokamak research.

To the Alcator's credit are:

(1) the highest Lawson product ever attained in magnetic confinement, 30 trillion seconds-nuclei per cubic centimeter at a temperature of 10 million degrees;

(2) completely pure operation without the influx of heavy elements from the vacuum chamber wall (this was previously believed to be the most difficult problem facing tokamaks);

(3) demonstration that confinement time increases with increasing plasma density;

(4) breaking through the density barrier for tokamak operation, attaining densities of 100 trillion nuclei per cubic centimeter and thereby demonstrating the possibility of new types of tokamak fusion reactor plasma regimes—the high-density regime;

(5) qualitative performance correlating with the most optimistic theory for tokamaks, so-called neoclassical theory, even demonstrating the predicted type of distribution in space for heavy element impurities purposely injected into the hydrogen plasma; and

(6) the exploration of tokamak plasma physics over an unprecedented range of three orders of magnitude.

The Alcator experiment was initially conceived as a token program for university participation in the expanding fusion program of the early 1970s. By 1975, when Dr. Edwin Kintner was brought in to head up the U.S. magnetic fusion effort by Dr. Robert Hirsch, director of the Controlled Thermonuclear Fusion Division, the high field Alcator was attaining groundbreaking progress.

In 1976, Edwin Kintner made the decision to fully back the MIT Alcator team. Kintner decided to go full steam ahead with high-density tokamaks. Bypassing the small, incremental program to a slightly larger Alcator B, he gave the okay for the Alcator C, more than twice the size of Alcator A with a toroidal field capability of 150,000 gauss, compared to Alcator A's 100,000 gauss.

The original Alcator team, led by Ronald Parker, was dynamic and creative, but operated on a shoestring, with a large portion of its funding coming from such diverse sources as South Africa, the Soviet Union, and Holland. The most costly element for the Alcator C, the power supply, was obtained from New York City's Consolidated Edison Co. This consisted of an obsolete, gigantic flywheel from the East Side of Manhattan.

More recently, the Alcator group obtained 8 million watts of microwave generators used in the Alaska-based early warning system, which the North American Air Defense Command was scrapping for new equipment.

The microwave system gives the MIT team more than a total of 12 million watts of wave heating capability to apply to the Alcator C—double the power available to the much larger Princeton PLT.

### Near-Term and Long-Term Forecast

The Alcator C is already in operation, and full power operation will begin in spring 1979. By fall 1979, Alcator C is confidently projected to attain a Lawson product of 100 trillion seconds-nuclei per cubic centimeter, with a temperature of 20 to 30 million degrees. This Lawson product is in the range necessary for pure fusion reactor operation.

In reality, Alcator C will far exceed the conservative official prediction. And once the wave heating capability is hooked up in mid-1979, the Alcator C most likely will hit temperatures equal to (or better than) those attained in PLT.

Even before the Alcator C reaches such breakthrough temperatures, there is a strong possibility that the tokamak could demonstrate a new idea on how to reach fusion temperatures using only ohmic heating. Bruno Coppi, the scientific originator of the Alcator, has developed several stratagems for using *plasma instabilities* to obtain higher temperatures in low-density discharges. These would drive up the density and ignite fusion reactions that were sufficient to maintain and increase the temperature.

The original Alcator breakthroughs dramatically changed the entire scientific basis for the design of tokamak fusion reactors. All current tokamak reactor studies are using higher densities and smaller sizes. This has permitted the Wisconsin University fusion engineering group, to take one example, to produce the NUWMAK, a small tokamak power reactor design with a capital cost in the same range as current nuclear fission light water power plants.

And MIT's engineering design group, working with the Princeton group, has developed a number of new designs.*

The use of neutral beam heating on the Alcator C at first glance might seem to be precluded by the small size and high-density operation of the device. The neutral beam could not penetrate the high-density plasma to the center, given the current energy levels of neutral beams—40 to 80 thousand volts. Also, the machine is too small to trap the high-energy neutral atoms once they become ionized.

Despite these limitations, original thinking at Princeton came up with a new approach. If the toroidal magnetic field in an Alcator-type system is purposely distorted, the neutral beam can be made to penetrate the plasma and become trapped when it is ionized. This will permit a high density, small tokamak like the Alcator either to reach fusion temperatures or to operate in the two-component beam-plasma mode.

Although the MIT group did not have the funds for trying this on the Alcator C, because of the Carter administration fusion budget cuts, there are plans for neutral beam testing in 1980, if the money can be turned up.

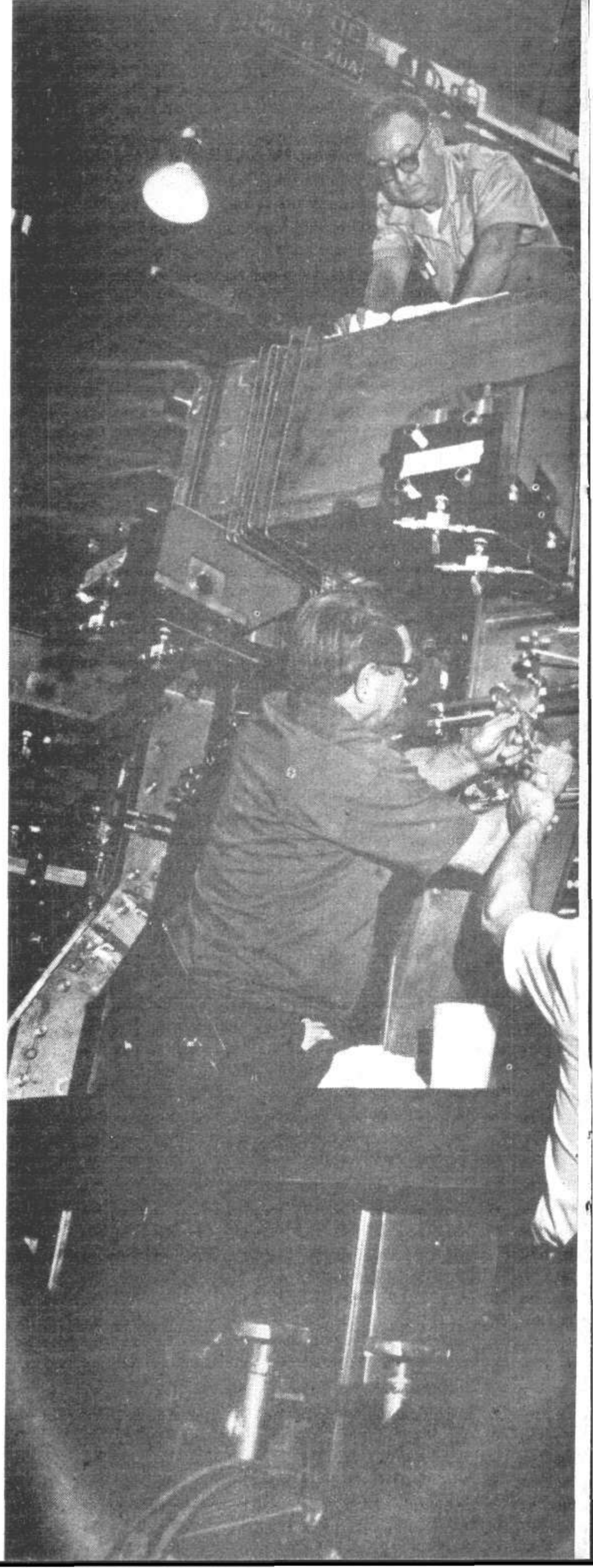
Meanwhile, the West Germans have begun to collaborate with the MIT group to work out plans for MIT participation in a West German program of high-density tokamak research. Detailed designs for a D-T high-density tokamak will be completed by December 1978, and this prototype fusion reactor core could be built in the next three to four years.

Some of the new ideas being explored for use in this joint MIT-West German effort include a neutral beam heating system combined with adiabatic compression (slowly increasing the strength of the magnetic field).

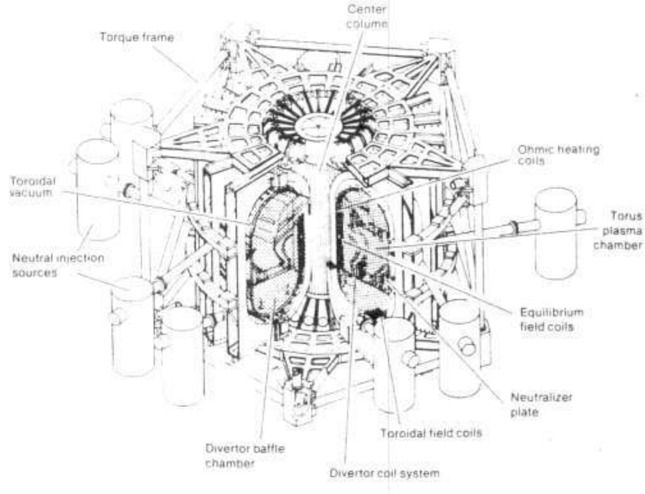
### Summary

The Alcator team is known for its accomplishments in breaking through scientific barriers. In producing the most significant general fusion advances prior to the PLT, the MIT group was actually concentrating on basic plasma physics research, however, and any fusion advances were a by-product. Now with a major increase in physical and personnel resources, the Alcator team confidently can be predicted to continue its past practice and come up with scores of unexpected breakthroughs. An inkling of what can be expected was indicated recently by initial, successful results with wave heating on the Alcator A.

* MIT Plasma Fusion Center Research Report. RR-78-2 (March 1978).



# The Princeton PDX: World's Largest Tokamak



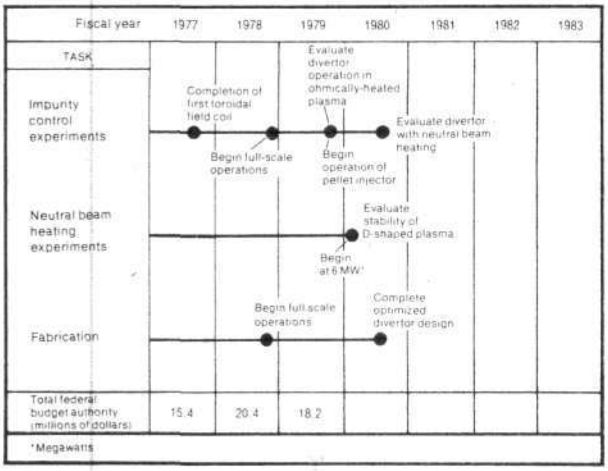
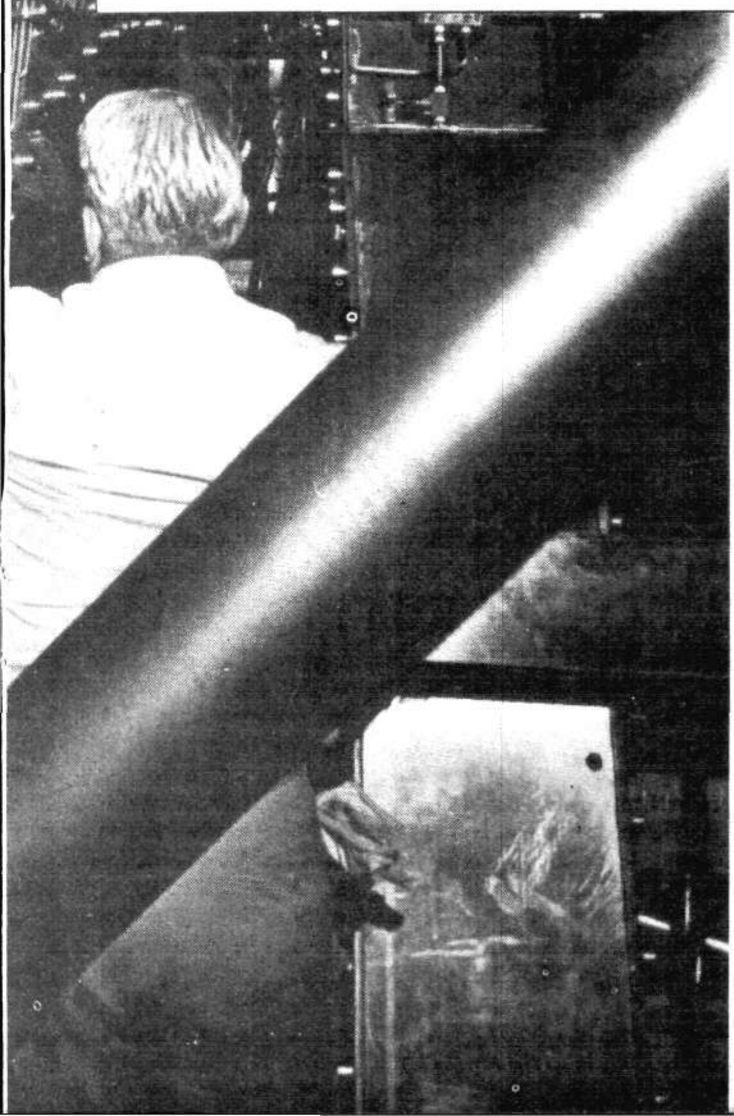




Figure 11

Standing next door to the now-famous PLT is the world's largest tokamak, the Princeton PDX, which will begin operation in the fall. The PDX, or Poloidal Divertor Experiment, initially may perform with only modest results and may be quickly overtaken by its equally large brother at General Atomic in San Diego, the Doublet III. However, in late 1979 when the PDX is upgraded with neutral beams and reworked for full-scale operation, it will quickly demonstrate its full powers for establishing the technological base for tokamak power reactors.

The PDX tokamak was conceived at Princeton in the early 1970s to deal with what was then considered the most serious problem of tokamak power reactors, the influx of heavy-element impurities into the hydrogen plasma. One solution had been developed in the 1950s for use on the Princeton-designed stellarator, another type of donut-shaped magnetic trap (described in the PLT section). Termed the *magnetic divertor system*, this solution consisted of forming the outermost shell of magnetic field lines so that it had a hole in it instead of a closed surface. Because the magnetic field lines would then lead outside of the torus proper, the plasma and the nonhydrogen elements in this outer surface would be diverted out of the magnetic trap.

The PDX was designed to test a number of different magnetic divertor geometries for the extraction of impurities and eventually for the extraction of the fusion-produced helium from the tokamak bottle.



*Technicians completing work on the Princeton PDX, which will begin operation this fall.*
Photo by Ulanowsky

In almost all present-day magnetic fusion experiments electromagnetic radiation is a major source—up to 50 percent—of the rapid cooling and hence energy loss of confined plasmas. And this, in turn, is due to the presence of even minute quantities of heavy-element impurities, which dramatically affect the overall energy flow of confined plasmas. In fact, until the last few years, most magnetic fusion experiments were more *atomic* physics experiments than plasma experiments because of these impurities.

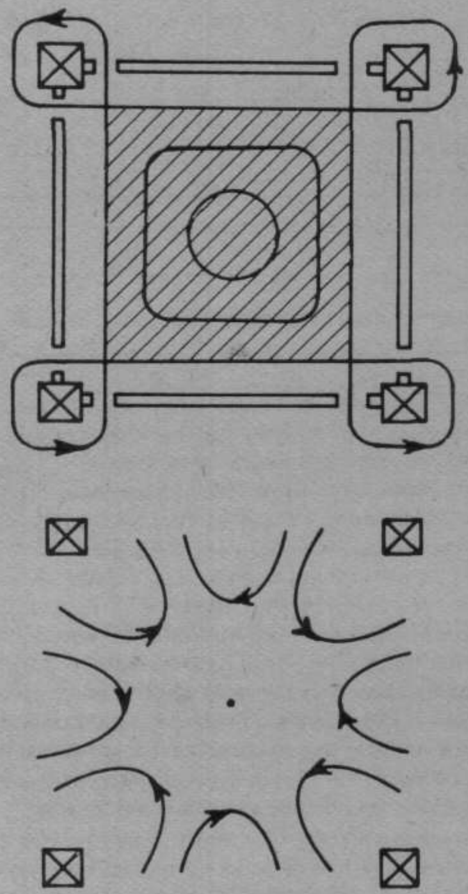


**Figure 12**
**PDX DIVERTOR CONFIGURATION**

*The concept of the divertor is to make the outermost magnetic field lines in the tokamak with a "hole," so that impurities in the plasma can be diverted out of the magnetic trap.*

*In all the various divertor configurations, the plasma column has a noncircular cross-section. The one shown here is rectangular, and is produced by the superposition of quadropole and octopole fields on the tokamak discharge. The PDX will experiment with several divertor geometries in its first year and then be reworked to operate without divertors.*

The effect of impurities on this radiation cooling of fusion plasmas is measured in terms of the Z effective or $Z_{eff}$, the effective ionic charge of the plasmas. The rate at which a plasma radiates away electromagnetic energy is proportional to the square of the $Z_{eff}$.

Z for any particular atomic element is equal to the number of protons it has in its nucleus, which is also the atomic number of an element. When an atom is stripped of all of its electrons it has a positive electrical charge proportional to its Z. For a completely ionized hydrogen plasma (hydrogen has a Z of 1) the effective Z of the plasma is 1.

However, if we just add one completely ionized iron atom for every 500 hydrogen atoms in this hydrogen plasma, the rate at which the plasma radiates would more than double. This is because iron has a Z of 26 and the square of 26 is 676. The effective Z of the overall plasma thus increases from 1 to almost 2.

Since the success of the MIT Alcator and Oak Ridge ISX in developing methods of surface preparation for the vacuum chamber wall to prevent the influx of heavy elements into the hydrogen plasma, the PDX divertor experiments are no longer so crucial. However, tokamak power reactors still may need divertors for long-pulse operation, for extraction of fusion-generated helium nuclei, and, possibly, for plasma control. Divertors also could be used for direct conversion of fusion plasma energy either through MHD channels or particle-collecting plates.

### Near-Term and Long-Term Forecast

Over the next year PDX will give a virtuoso performance, exploring a large number of different divertor geometries and demonstrating the high degree of maturation of tokamak plasma physics in the last decade.

One of the divertor configurations the PDX will explore is shown in Figure 12. A number of these configurations will demonstrate how to maintain a plasma purity with an effective Z approaching 1 over long periods of time. The PDX will also look at how impurities diffuse in plasmas—whether they tend to gather in the center of the plasma as predicted by neoclassical theory, or whether they are forced to the surface of the plasma.

In the various PDX divertor configurations, the plasma column has a noncircular cross-section. As discussed in some detail in the section on Doublet III, this is important for maximizing the plasma beta (the efficiencies with which magnetic fields are used to confine hot plasmas) and maintaining control over plasmas.

In late 1979 when the PDX is reworked for full-scale operation without divertors and a noncircular cross section, PDX should quickly take the lead over the PLT in exploring the physics of tokamak reactor-grade fusion plasmas.

In the beginning of 1980, the PDX will be fitted with the PLT's neutral beam heating systems. Given the PLT breakthroughs already achieved, it can be confidently predicted that the PDX will approach the full conditions of a tokamak reactor.

# Doublet III: The Gamble to Go All the Way

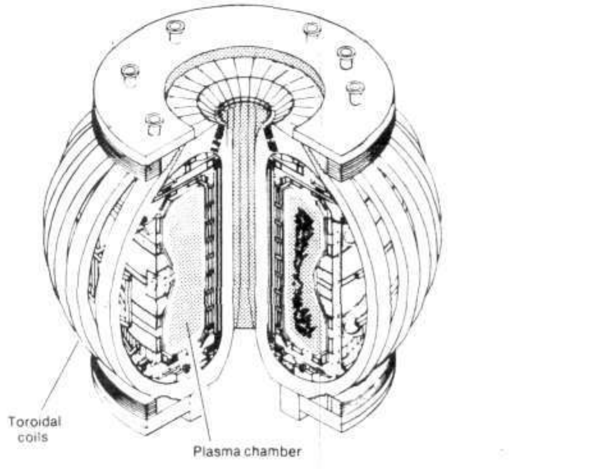
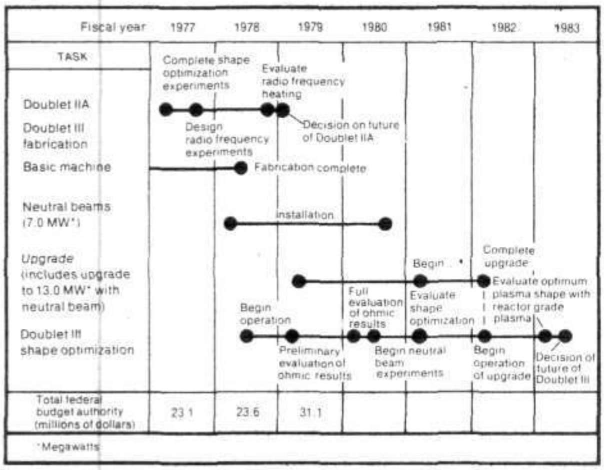



Figure 13




The General Atomic Doublet III tokamak is projected in the near future to obtain plasma parameters well beyond those needed for power reactor operation (see Figure 4 in the PLT section). In addition (and not shown in Figure 4), Doublet III also will obtain power densities well beyond those needed for economic tokamak power plants. This means that in one experiment, fusion scientists will virtually complete the physical exploration of what is needed to make this type of tokamak power plant.

The Doublet III tokamak in San Diego, California is at the forefront of fusion research not only in a scientific sense but also from an economic and political standpoint. Doublet III is the most significant fusion experiment undertaken by a private corporation in the world. The company, General Atomic, is also a leader in the development of advanced fission reactors like the gas-cooled high temperature fission reactor. And the director of the General Atomic fusion lab, Dr. Tihiro Ohkawa, is a principal architect of the rapidly growing Japanese fusion program.

General Atomic began a very modest tokamak research effort in the early 1970s. After their approach to tokamaks showed some initial success, Robert Hirsch, director of the ERDA Magnetic Fusion Division, decided to make General Atomic a major component of the U.S. fusion effort. In 1974, Hirsch took the bold step of getting the government to back the major Doublet III tokamak experiment.

Although the official target date set by Energy Secretary Schlesinger for the first U.S. tokamak fusion power plant is the year 2005, General Atomic's Dr. Ohkawa stated in 1977, "we project the next transition to a working reactor in about 10 years."* Given the recent General Atomic successes with their small-scale tokamak experiments and the dramatic advance of the Princeton PLT, there is every reason to believe that this very aggressive, private company can maintain this schedule.

The conventional tokamak geometry can be fully described by the major radius, R, of the torus and the minor radius, r, which is also the radius of the plasma column confined into the donut shape (see Figure 2 in the PLT section). In this circular geometry it is found both experimentally and theoretically that the ratio of the main toroidal magnetic field, $B_t$, to the poloidal magnetic field, $B_p$, which is generated by and directly proportional to the plasma current, I, must be greater than 2.5 R/r.

### The Beta Parameter

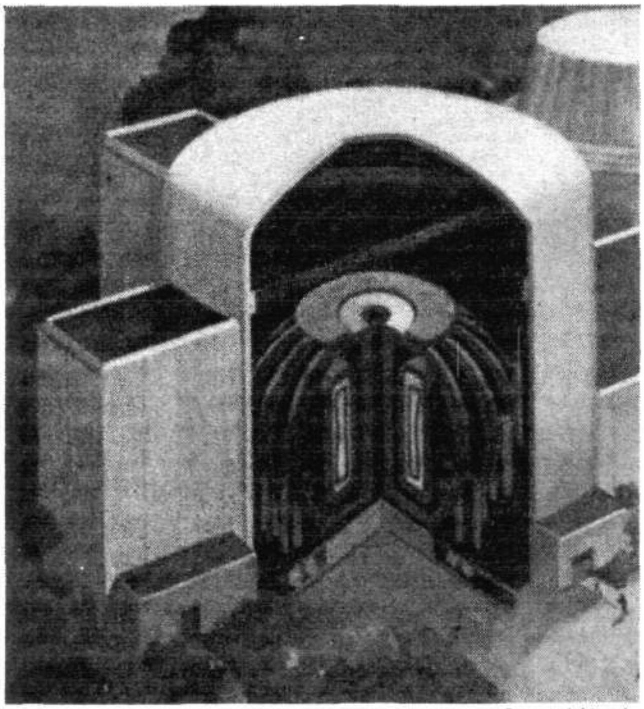
In addition, the key plasma parameter, beta, is limited to being less than r/6R. This is important in determining the Doublet approach as discussed below. Beta is a measure of how efficiently a magnetic field confines a hot plasma. Specifically it measures the energy density of the plasma relative to the energy density of the magnetic field confining it and is generally given as a percentage.

Experimental tokamaks currently operate with plasma betas of 1 percent and less, while a minimum beta of 4 percent is necessary for a power reactor, and betas of 5 to 20 percent are necessary for economical fusion power plants.

High betas are needed both to have efficient use of the magnetic fields and to have high power densities for minimizing the size of power plants. The power density of a magnetic fusion plant is a direct function of the beta. And, since a large part of the capital and operating costs of a tokamak fusion power plant is directly tied to the size and strength of the coils that generate the toroidal magnetic field, a high beta means that this aspect of the plant will be cost efficient.

Now, given the restrictions stated above for circular tokamaks, it can be seen that both the beta and the plasma

* *General Atomic Calendar*. Vol. 9, no. 1 (Jan.-Feb. 1977).



General Atomic

*Artist's drawing of the Doublet tokamak fusion power reactor. General Atomic's Doublet III began operation this month.*

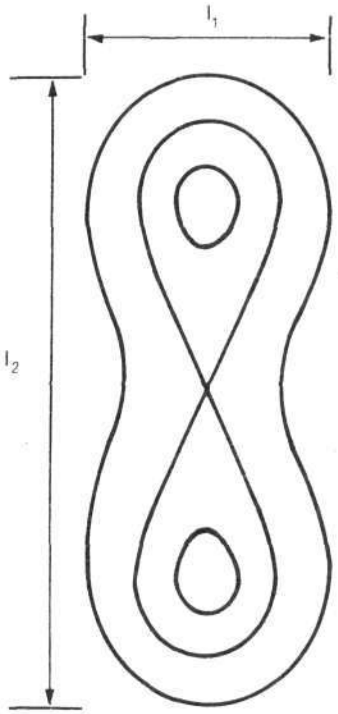



**Figure 14**
**THE DOUBLET CROSS SECTION**

*This figure 8 tokamak configuration is expected to be the most stable of the noncircular tokamaks and to produce an increased beta limit.*

electrical current (which is also a describable quantity to increase because the plasma is heated by the current in direct proportion to the size of the current it carries) can be increased by maximizing the ratio of the minor radius, r, to the major radius, R. For circular cross-section tokamaks the ratio of r/R is limited to a maximum ranging from .2 to .33. This is because of the engineering considerations in terms of the mechanical support for the main toroidal magnetic field coil, and it means that the maximum beta, from the standpoint of this limit, is about .05 or on a percentage scale, 5 percent. This is just barely what is necessary to make a tokamak power reactor with sufficient power density to be economical.

The Doublet III, the PDX, and the ISX-B are exploring an approach to going beyond this beta limit that is based on changing the geometry of the tokamak to a noncircular shape.* (Another approach to exceeding this 5 percent limit in circular cross-section tokamaks is the recently developed concept of flux conservation, discussed in the Grad-Hogan Theory section of this report.)

Figure 14 here shows the change for the Doublet III, and Figure 11 in the PDX section and Figure 8 in the ISX-B section show the changed geometry of those machines.

The noncircular shape affects the beta limit, r/6R, in the following way: If the tokamak cross-section (Figure 14) is noncircular, the beta limit, according to MHD theory, is changed from r/6R to more like $(l_1^2 + l_2^2)/6Rl_1$. Now if $l_1$, the height of the cross section, is about equal to R and much greater than $l_2$, the cross-section width, then the beta limit is increased toward 1/6.

As discussed in the section on Grad-Hogan theory, it is difficult to make this type of change in geometry macroscopically stable. The Doublet-type of cross-section—a shape in which the height of the plasma column is equal to 2.7 meters, almost twice the size of the major radius of the device, 1.4 meters—appears to be the most stable, both from initial experiments and theoretical work.

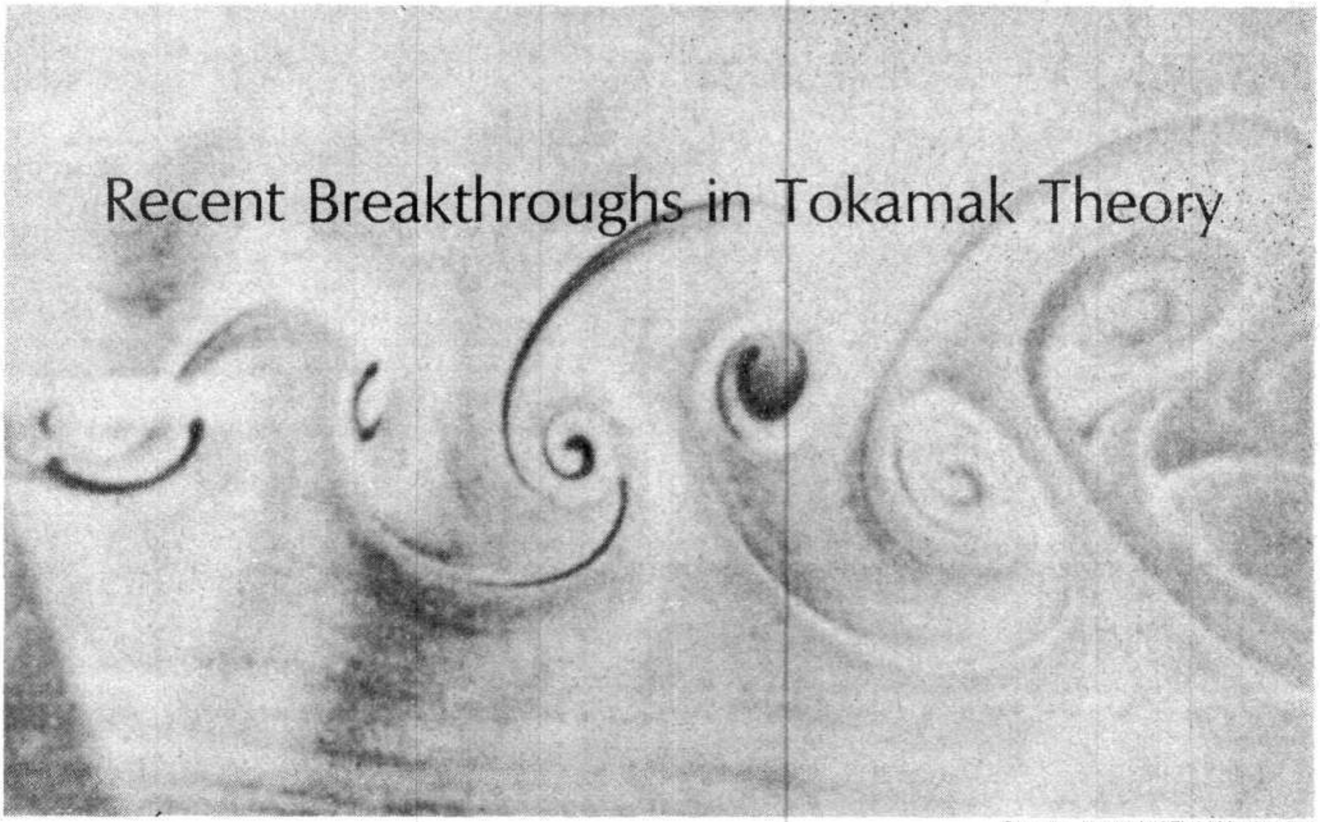
**Short-Term and Long-Term Forecast**

Because it represents a bold thrust into unproven ground in tokamak experiments, the Doublet III is not absolutely assured of success, as is now the case for upgrades on the PLT and the TFTR. However, it is highly likely that Doublet III will succeed. Using ohmic heating alone, it will achieve Lawson confinement products well beyond what is needed for breakeven—100 trillion seconds-nuclei per cubic centimeter with temperatures of 10 to 30 million degrees. This will provide the proof in principle for the efficacy of this very economical approach to tokamak fusion reactors.

With experimental success expected in late 1978 and early 1979, Doublet III will be upgraded with substantial neutral beam heating in 1979-1980. This will permit the tokamak to reach temperatures in the range of 50 to 100 million degrees and more, with Lawson products in the range of several hundred trillion.

* J. P. Freidberg and W. Grossman, *Phys. Fluids* 18:1494 (1975); D. Dobrott and M. S. Chu, *Phys. Fluids* 16:1371 (1973); U.S. Atomic Energy Commission, *Status and Objectives of Tokamak Systems for Fusion*, Wash-1295.

# Recent Breakthroughs in Tokamak Theory



Source: *Journal of Fluid Mechanics*

One of the most important theoretical studies in fusion-related physics was published recently by the Oak Ridge National Laboratory, reporting on work by H. Grad of New York University's Courant Institute and J. Hogan, formerly of the Courant Institute and now at Oak Ridge.* This Oak Ridge report provides convincing evidence, for the first time, that the tremendously successful experimental program in tokamak reactor development (the mainstay of the world's fusion work for the last 10 years) has a theoretical basis that can now be understood. Although the Grad-Hogan theory of tokamak dynamics is by no means the end of the story, it does provide the first consistently successful dynamic theory of tokamak operation as well as guidelines for construction for future experiments and reactor designs.**

The basic conclusions of the Oak Ridge report are as follows:

(1) There is a theory capable of describing the main interrelations and scaling laws that affect the operating characteristics of current tokamaks. These theoretical insights allow reliable prediction of the basic parameters of temperature, density, magnetic field geometry, and energy density.

(2) The application of this theoretical framework to currently operating tokamaks and immediately projected experiments leads to optimistic conclusions regarding the performance of these machines.

(3) When this Grad-Hogan theory is used to project the characteristics of future tokamaks, both laboratory scale and prototype reactors, there is the unambiguous conclusion that these tokamaks lead to an economically viable system for energy production. The critical questions of plasma beta and power density, which ultimately determine the practicality of the tokamak system, can be answered affirmatively. These optimistic conclusions, which heretofore could be reached only on the basis of extrapolation from current experiments, now have a substantial theoretical basis.

### The Grad-Hogan Results

The Oak Ridge report is the outcome of almost a decade of work of a group around Grad at the Courant Institute that has been attacking the same basic problem of the rigorous implications of the classical equations of magnetohydrodynamics, MHD. These equations have been known for more than 100 years, well before Maxwell's time, and because of their appearance in substantially the same form in both a conducting fluid and a nonconducting fluid that supports vorticity, there is a large body of theoretical work attempting to describe their implications.

The basic and universally used results in the field were derived by Helmholtz in 1858. Helmholtz proved that

* J. Hogan, *The Accessibility of High-Beta Tokamak States*, ORNL Report TM-6049 (1978).

**For a history and comparison of past projections of tokamak operation and the actual performance of the experiments once they were built, see A. M. Sleeper, *Predicted Plasma Parameters for PLT*, ERDA (Sept. 1975). This paper documents Grad's claim that there has yet to be a plasma machine that operates on principles that were understood before the machine was operating.

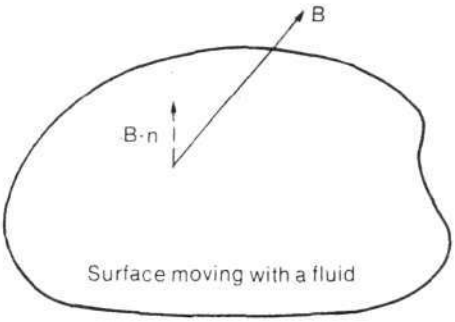



**Figure 15**
**THE HELMHOLTZ THEOREM**

*Helmholtz showed that a fluid under certain conditions conserves a quantity called* flux *[the integral of the perpendicular component (B·n) of a given field across a surface moving with the fluid]. In a classical fluid, the conserved flux is of vorticity; in a plasma, it is the magnetic field. Thus, the topology of the given field cannot change—lines cannot reconnect, islands cannot form or disappear. This theorem does not hold if there is dissipation (viscosity or electrical resistance) in the fluid.*

continuum systems had a geometrical character fundamentally different from the usual equations in physics; they describe a system whose global properties are intimately related to singularities in the system.*

Helmholtz drew on a developing body of geometrical ideas by Riemann to derive the single most pervasive and important theorem in continuum mechanics: the conservation of vortex lines in a fluid, or equivalently, the conservation of magnetic flux in a conducting fluid. The immediate implication of both statements of Helmholtz's theorem is that the topology of the magnetic field (or vortex lines) cannot change unless there is dissipation (either electrical resistance or viscosity) in the continuum.

This theorem is a very powerful statement about the relation between singularities—induced by any changes in topology in the field lines, for example—and the global properties of the system, namely the conservation or nonconservation of energy. Helmholtz showed that for a fluid that conserves energy, the topology of the field lines is also preserved (see Figure 15).

Perhaps the most striking thing about most modern attempts to apply these ideas and the general theory of MHD to the question of the behavior of a plasma in a tokamak is that the equations have been attacked from the standpoint of making them mathematically solvable rather than physically applicable. As Grad says, "We note that

# Basics of Fusion

*Continued from page 26*

Scientists discovered in the 1930s that the energy given off by the sun and the stars had the same origin—the fusion of nuclei of lighter elements. However, major scientific and technological problems had to be solved before the fusion reaction could be reproduced in the laboratory. First, it requires a huge amount of energy to achieve a controlled fusion reaction. Second is the problem of confining the fusion fuel at the necessary temperature and density long enough to get a sustained fusion reaction going. After years of experimental research, the Princeton results and other breakthroughs expected in the next 12 months demonstrate that the problems can be solved in the immediate future.

### How Fusion Works

Fusion occurs only at a high temperature—tens of millions of degrees Celsius—because only at such temperatures and the associated high velocities of the nuclei can the natural repulsion of the positively charged nuclei be overcome. At these temperatures, the negatively charged electrons that are normally bound to the nuclei are stripped from the atoms, and matter becomes a highly charged gas called a plasma.

In the case of the sun, the necessary confinement of the fusion plasma at sufficient density for a sufficient length of time is achieved by the tremendous inward pressure of gravity. In the laboratory, there are two basic approaches to confining the plasma, inertial confinement and magnetic confinement (the method used by the tokamak device at Princeton).

In inertial confinement, the fusion fuel plasma is confined by its own inertia; in other words, it is made to give up its energy so quickly that it does not have time to fly apart. Examples of inertial confinement are the destructive release of fusion energy in the hydrogen bomb, where the fusion fuel is ignited explosively by the detonation of a fission bomb, and controlled thermonuclear research with laser, and electron and ion beam fusion.

In laser and beam fusion, the intense concentration of laser light or electron beams is focused on a small pellet of fusion fuel to ignite the pellet in a tiny, controlled explosion. In the second method, magnetic confinement, the charged plasma is trapped through its interaction with a magnetic field and is used in a variety of devices, including the most researched tokamak.

The first generation of commercial fusion reactors will use deuterium-tritium fuels, and the main energy release will come in the form of high-energy neutrons. These neutrons can be used to produce heat and run conventional generators for electricity, or they can be used to initiate chemical reactions, producing artificial fuels and valuable chemicals, as described above.

Later generations of fusion reactors will use deuterium-deuterium or even hydrogen-boron fuel, which will produce charged particles exclusively. These reactors will be able to produce electric energy directly from the plasma, eliminating the costly steam-turbine method.

### The Tokamak

The tokamak fusion machine was developed in the Soviet Union in the 1960s and represented a major break-the misleading simplicity of the standard Pfirsch-Schluter and neoclassical formulations is based not on arguments of physical validity but solely on criteria for mathematical solvability."**

The most pernicious consequence of this nonrigorous approach to MHD theory has been the generation of a large number of conceptual insights that are either misleading or false. Over the past decade, the work of the Grad group has challenged these intuitive assumptions in a series of papers. These papers, whose particularly important conclusions are summarized below, all involve the interplay of three critical ideas:

(1) Local and global phenomena in a continuum system are interdetermined. Helmholtz's theorem, rigorously understood, is a model for this *interdetermination*.

(2) Such interdetermination implies that the quality of the singularities in a system is of global consequence. Specifically, the temporal and evolutionary properties of the system depend *on* and, *in turn*, shape the kinds of singularities in the system.

(3) Given this evolutionary quality that pervades both the singularities and the global (topological) properties of the system, the geometry of that system is as much a dynamical entity as the usual dynamical variables describing the plasma. Among other things, this means that the geometry of the system evolves as a part of the overall evolution of the plasma and cannot be assumed to be given beforehand or somehow determined from "outside" the plasma.

### Time Scales

In the Grad group's rigorous reexamination of the MHD equations, their most important observations concerned the time scales in the system of equations. A careful examination of the MHD equations shows that these equations describe phenomena on several, interacting time scales. Unless these phenomena can be untangled, the equations cannot be solved either analytically or on a computer. The usual approach to these equations, however, selects the relevant time scale on the basis of mathematical convenience rather than on the basis of physical reality.

The basis for the Grad-Hogan theory began with the uncovering of an appropriate adiabatic time scale in the

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* H. von Helmholtz, *Journal fur die Reine und Angewandte Mathematik*, Vol. 55 (1858). An English translation, "On Integrals of the Hydrodynamic Equations That Correspond to Vortex Motion," appeared in the *International Journal of Fusion Energy*, Vol. 1, nos. 3-4 (Winter 1978).

**H. Grad, P. N. Hu, D. C. Stevens, and E. Turkel, in *Plasma Physics and Controlled Nuclear Fusion Research*, Vol. 2, p. 355 (IAEA: Vienna, 1977).

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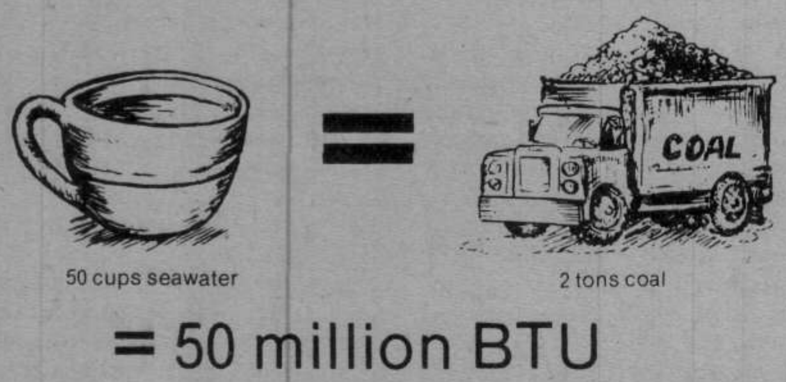
through in fusion development. It is a donut-shaped device in which the plasma is kept confined inside the donut by two magnetic fields. One field is produced by powerful electromagnets surrounding the donut, the other field by currents produced in the plasma itself. The combination of the two fields, one around the donut and the other running through it, creates the remarkable stability of the hot plasma.

#### PLT

The Princeton Large Torus, known as the PLT, is the largest tokamak in the world, but it is still a relatively small device, 3 meters in diameter. The PLT has now come closer than any other tokamak to the conditions required for a commercial fusion reactor. An increase of only a factor of about 10 in the length of confinement time, something easily achievable with larger devices, will bring the tokamak into the regime necessary for pure fusion generators.

Even more immediate, a tokamak just a little different from the PLT could form the core of a fusion-fission hybrid reactor, in which fusion neutrons would be used to breed more fission fuel for other reactors.

It should be emphasized that achieving fusion power reactors in the 1980s is not just a problem of making more engineering breakthroughs for the tokamak and other devices. Basic research work in alternative lines of approach to fusion is absolutely necessary. Some of these approaches, which use the self-organizing character of plasma—its tendency to greater order and increased energy density—may lead to more advanced and cheaper forms of fusion power than the tokamak.




**ABUNDANT ENERGY FROM SEA WATER**

*One out of every 6,500 molecules of seawater is heavy water, which provides the deuterium for fusion fuel. As can be seen from the comparison here, seawater can provide us with virtually unlimited energy.*

MHD system, a time scale of phenomena that can safely abstract from the very short times that govern the specific motion of the plasma. Instead the time scale concerns the motions of the plasma that are on a global scale, always governed by a dynamic pressure equilibrium. This adiabatic state assumes specifically that the central features of a tokamak-type plasma are determined in the large scales by the fact that the plasma always will exist in balance with the magnetic field; the plasma will evolve always subject to this balancing of the magnetic and plasma pressures, slowly passing through a sequence of approximately static equilibria.*

This problem of adiabatic evolution, although interesting in itself, turned out to intersect the traditional conceptual approach to plasma dynamics, whose main underpinning is Helmholtz's theorem: the study of diffusion in a plasma—the phenomenon of spreading of either fields or matter through a plasma. When either of these phenomena is formulated in a rigorous way, the resulting equations are nonstandard; that is, they involve a strange interdetermination of local conditions of continuity and global geometric constraints. The specific problem of the Grad-Hogan theory then revolved around inventing methods of solving this bizarre equation.

The clearest indication of the fact that this equation is not merely a mathematical curiosity is that the flow velocity of the plasma is determined by these equations in a totally different way from the other field and plasma variables. The velocity field does not get advanced in time by the differential equation; it is determined only after the differential equation is solved for the magnetic field and geometrical configuration.

The technique Grad's group discovered for solving the equation took advantage of this feature of the mathematics; the equation can be suitably averaged over a previously determined magnetic field geometry. Using the averaged equation, which is now standard, they could now solve for the magnetic fields and plasma variables. With this description of the plasma, the resulting geometrical configuration of the fields can be calculated, and this geometrical calculation can be used as the starting point for a recalculation (at the next time interval) of the averages needed to begin again.

This method of "flux surface averaging" contains two critical elements. First, the geometry of the magnetic field lines (actually the flux surface created by this field) becomes a dynamical entity in its own right; *it*, rather than the determined velocity field of the plasma, is the primary feature of the plasma. Second, since the geometry has

* H. Grad, P. N. Hu, and D. C. Stevens, *Proc. Natl. Acad. Sci. U.S.*, Vol. 72, no. 10 (1975).

# Where International Fusion Research Stands

Fusion research and development for peaceful purposes has been an area of extensive international cooperation since the 1950s and the Atoms for Peace program of President Dwight Eisenhower. Today this international effort provides the fusion effort with a breadth and depth of research that no single country has as yet undertaken.

Current estimates are that approximately 3,500 scientific man years are spent annually in fusion research. Of these, the Soviet Union accounts for 2,000, the United States for approximately 1,000 and the remainder is divided approximately equally between the European and Japanese efforts. U.S. research is less than one-third of the world's total fusion effort.

In many ways, the Soviet effort has been the flagship of the world fusion research program, most notably in the Soviet discovery and promotion of the tokamak—now the main contender for economical energy production by fusion. The Europeans have specialized in scientific research at such outstanding laboratories as Garching and Juelich in West Germany, Frascati in Italy, and the TFR tokamak establishment in France. The Japanese began fusion research only recently, but they have rapidly increased their investment in the past several years. Business magazines in Japan are confidently predicting that Japan will be a net energy exporter by the year 2000 because of its commercialization of fusion.

In all of these countries there are a series of large tokamaks and inertial confinement experiments now coming on line that promise results as favorable as the series of U.S. experiments. The Japanese and Europeans are in the process of designing experiments roughly parallel to the Princeton TFTR. In Europe, the JET, or Joint European Torus, and in Japan the JT-60 will test ignition and materials problems. The European effort now has a high-density tokamak at Frascati, which in August achieved temperatures of 20 million degrees at densities 10 times those of the lower field PLT.

### The Soviet Program

Without doubt, the most aggressive and engineering-oriented fusion program in the world today is that of the Soviet Union. For at least 10 years, the Soviets have recognized the potential of fusion energy as a programmatic necessity and have geared their research effort toward the medium-term realization of fusion. They project that a fusion-fission hybrid will be breeding fuel in the Soviet Union before the end of 1990, and that this hybrid source of fusion energy will be supplying significant quantities of energy for the Soviet Union by the year 2000.

As several Soviet engineering studies have noted, a hybrid reactor is

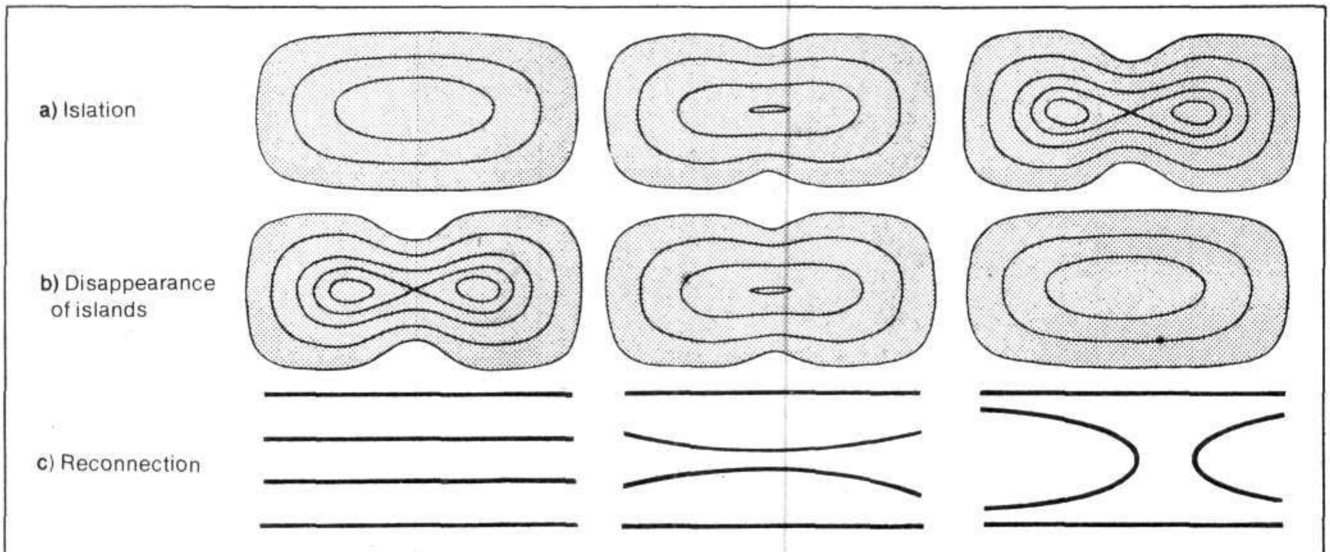



**Figure 16**
**THE THREE STANDARD TYPES OF NONCONSERVATION OF TOPOLOGY**

*There are three usual ways in which the magnetic field (or vorticity) might change its topology. The formation of islands or loops where none existed before (islation), the disappearance of these islands, and the connection of two lines, forming a so-called X-point.*

absolutely necessary for rapid growth rates of energy consumption. As these studies noted, the rapid growth of conventional nuclear energy production will quickly exhaust naturally available fissionable isotopes, and the growth rates of fuel supplied by conventional breeder reactors are insufficient to sustain increases in energy consumption that are greater than 8 to 10 percent per year. In the context of Soviet projection of energy growth rates of 15 to 20 percent per year, the hybrid reactor is essential.

As a result of this practical necessity, the Soviet program has devoted a much larger amount of its resources to the engineering aspects of fusion. (The program is as a whole larger and so they devote more manpower to all aspects, but the most salient difference is in the engineering area, where the U.S. program is relatively weak.)

The Soviets are building a tokamak machine the size of the PLT, which will operate with superconducting magnetic coils. This machine, the T-10M, is a rebuilt version of the successful conventional tokamak, the T-10 and should be operational in the next 12 to 18 months. The T-10M is predicted to exceed scientific breakeven in temperature and Lawson criteria, and to provide data on a number of heating mechanisms in a large tokamak plasma. However, its most important contribution will be to the first serious work on the problems of construction, maintenance, and control of large superconducting magnets in the complex configurations required for fusion devices.

The Soviets are also in the design stages of a large, ignition-type device, the T-20. This machine is expected to resemble the Princeton TFTR, but it is designed to allow the insertion of four different types of blanket modules—replaceable sections of the tokamak walls. Using actual fusion environments, these modules will test the problems associated with breeding tritium for the fusion fuel and the heavy nuclei blankets for a hybrid reactor. As presently designed, the T-20 will be a prototype hybrid reactor producing measurable amounts of fissionable material from fertile isotopes. In addition, the blankets will test various heat-exchange mechanisms (by liquid metal lithium, helium, and liquid salts) and temperature differentials (up to 650 degrees Celsius).

Most indicative of the innovative and groundbreaking breadth of the Soviet program is the electron-beam experiment conducted by fusion scientist Leonid Rudakov. The most heavily funded single experiment in the Soviet Union, the Angara experiment is now set to be scaled up to a 48 electron beam system, the Angara 5. Angara 5 is projected to produce breakeven by the time of its completion in 1980 or 1981. The Rudakov experiment also has been the source of a number of new and important theoretical insights into the nature of very high energy interactions in a plasma. (For details see *Fusion*, Dec.-Jan. 1977-1978.)

The Soviets also have an innovative laser fusion program, which last fall achieved the highest yet compressions of a fuel pellet, reaching a Lawson product of more than 100 trillion at temperatures of .5 keV. These results were achieved with relatively low power lasers on targets much larger than those used in the U.S. program. (See *Fusion*, August 1978 for a review of the Soviet and American approaches to laser fusion.)

this independent character and is not specified in some *a priori* way, it can change. This method of flux averaging makes it possible to study changes in the topology of magnetic field lines, the formation of magnetic islands, the disappearance of these islands, the reconnection of magnetic lines at an X-point (see Figure 16).

The Grad-Hogan theory then provides a method for studying the evolution of a magnetized plasma in terms of the long-time behavior of the plasma and its fields, without building up this long-time dynamics out of the rapid variations that most theories use to "construct" the long-time stability or instability properties of the plasma. By using the dynamically determined geometrical average of the magnetic field as the primary variable in the temporal changes of the plasma, it becomes possible to describe the plasma behavior directly in terms of its global behavior.

Knowing this global behavior then makes it possible to go back and calculate the velocity of the plasma and then derive the "classically" interesting quantities relating to plasma diffusion and the invariants described by Helmholtz's theorem. When this is done in the classical cases, the conclusions Grad and his group have been able to deduce from their study of the actual consequences of the MHD equations have contradicted the standard and long-accepted deductions that have guided plasma physics.

### The Entropy Question

*The traditional understanding of the Helmholtz theorem* is taken to imply that without energy nonconservation, there can be no change in magnetic field topology. Since energy dissipation is equivalent to increases in entropy and magnetic field topology changes are usually evidence of the formation either of intense self-generated magnetic fields or of complex self-subsisting structures in the plasma, the more profound result is that self-generated structure in a plasma can occur only as a result of increases in entropy in the plasma. On an intuitive level, Helmholtz's theorem provided reassurance that so-called self-ordering phenomena could not occur without an exchange of entropy, which, in the end, would doom the plasma to increased disorder in spite of the disturbing tendency toward self-concentration of energy and spontaneous formation of complex structure.

The Grad-Hogan theory shows that it is not so simple! In a recent paper* Grad has shown that the Helmholtz theorem does *not* show that magnetic line reconnection or plasma diffusion across field lines (the two halves of the usual conservation laws deduced from Helmholtz's theorem) occur only in the presence of dissipation. As *Helmholtz seems to have noticed himself, the critical* assumption of a simple continuity in the field must be made to deduce Helmholtz's theorem from the equations.** That is, if suitable types of singularities exist in the system, then the magnetic field topology can change even without dissipation. In fact, Grad's adiabatic formalism generates such singularities, and he is able to explicitly exhibit a solution that shows mass flow and magnetic line reconnection without dissipation.

Grad's results actually show two interconnected points. First, even when there is magnetic field line reconnection in the at least implicit presence of dissipation—a problem still poorly understood both experimentally and theoretically—the reconnection depends on the dissipation in a very strange way. As he notes: "The significance [of this kind of reconnection] is that it reverses [the usual notion of] cause and effect; instead of resistivity producing a certain rate of flow across a separatrix [the singular magnetic field lines], the rate of flow is determined by external, global boundary conditions and other constraints, and the resistivity and thickness of the layer adjust to produce the required reconnection rate." In other words, the resistivity does not really cause the reconnection; the global constraints that make reconnection possible "cause" the dissipation!

Moreover, even this intimate connection between dissipation and changes in topology is not necessary. As Grad notes in his recent paper: "There is a large class of problems in which there is no net entropy increase, even with mixing of plasma and magnetic flux (e.g., tearing), or splitting of one region into two (e.g., Doublet)....These phenomena, exhibiting nonconservation of magnetic field topology, are shown to occur in an ideal, nondissipative fluid, thereby violating beliefs, theorems, and calculations of over a century (including the mathematically equivalent questions involving vortex lines in an ideal fluid)."

Grad shows that the usual results do hold in the presence of the usual kind of singularity admitted in a plasma, but that the quality of this singularity changes. It is the result of adiabatic considerations, he shows, that the global constraints on the plasma flow change dramatically with the change in the temporal qualities ascribed to the singularity.

### Revolutionary Conclusions

The conclusions of the Grad-Hogan theory in the realm of tokamak physics have been no less revolutionary. In providing the first satisfying explanation of a number of so-called anomalous results of tokamak experiments and in providing the first satisfying dynamic theory of tokamak operation, Grad and Hogan also burst a number of time-honored presumptions in the main line of tokamak theory.

First, the Grad-Hogan work shows that impurities have played a critical role in the operation of almost all tokamaks to date (with the exception of the Massachusetts Institute of Technology's Alcator). In case after case, the Grad-Hogan theory is able to explain effects that had remained mysterious for several years by explicating the critical role that energy radiation by impurities plays in *determining the heating and energy balance within the* plasma. Hogan goes as far as to say that tokamaks to date have been dominated by *atomic* physics rather than by plasma physics. (In other words, the ionization properties of heavy impurity ions have been the critical effects in these tokamaks.)

In fact, the Grad-Hogan model shows that in cases like that of adiabatic compressional heating, the presence of impurities can result in a situation in which the further heating of the plasma results in poorer energy deposition and stability.

Second, this same theory gives the very optimistic conclusion that for tokamaks in which the impurity problem has been solved (for example, the PLT), present heating schemes should work very well. The model predicts efficient energy deposition and heating for these machines. More important, it predicts increasing density and stability at higher temperatures.

This means that the results that have already been experimentally demonstrated in the Alcator can also be expected in the larger, lower density machines like the PDX and Doublet III.

Third, the most exciting result of the Grad-Hogan theory, specifically as developed by Hogan in the Oak Ridge report, is the favorable prognosis for solving the beta problem. Hogan showed not only that high beta tokamaks are possible—a point that the antifusion critics repeatedly questioned—but that the present design of low-field tokamaks heated by neutral beams can achieve betas on the order of 5 percent. These results are even more optimistic in the case of the noncircular cross-section machines like the Doublet III and the PDX.

As Hogan summarized the conclusions of the report: "The calculations lead us to expect that high beta states in tokamaks should be accessible if present trends in confinement scaling continue."

The key to the success of the Grad-Hogan theory as applied to tokamaks is its unique ability to account for changes in the magnetic field topology as the plasma is heated and compressed. In his report, Hogan assembled a set of microscopic equations describing the operation of the neutral beam, impurity ions, and the like, all connected by the Grad-Hogan equations for the magnetic geometry. The critical ingredient in modeling the overall behavior of the plasma was the Grad-Hogan "force-balance" condition—the nonstandard equation that allows adiabatic changes in equilibrium. "The solution of the equilibrium, or force-balance, equation is a necessity for consideration either of high beta injection or of major radius compression, because the most important variables are the characteristics of the magnetic geometry," Hogan wrote.

In a certain sense, this theoretical work is the most basic and far-reaching breakthrough that the tokamak program has yet achieved. In conjunction with the experimental results, it provides confident projections for the design of future experiments and their extrapolation to commercial-size reactor construction.

*Charles B. Stevens, well known internationally as a fusion reporter, is the director of fusion engineering studies for the FEF. Steven Bardwell, associate editor of* Fusion, *is the FEF director of plasma research.*

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* H. Grad, "Reconnection of Magnetic Lines in an Ideal Fluid," private communication, 1978.

**H. von Helmholtz, "On Integrals," *International Journal of Fusion Energy*, Vol. 1, nos. 3-4, pp. 43-44 (Winter 1978).

# *The Fusion Budget*

## Funding a U.S. Policy For Energy Growth

*To get the nation back on the track as a world leader for growth and development requires nothing short of an Apollo Project centered around fusion research. The Fusion Energy Foundation has proposed a total fusion budget of $6 billion for fiscal year 1980, with a $220 million supplemental budget for fiscal year 1979. The bulk of the proposed budget is focused on tokamak research; $1.5 billion is allocated for alternate magnetic fusion systems, and $1.5 billion for inertial confinement research.*

*Presented here are the details of the proposed budget and an FEF memorandum on energy policy, circulated on Capitol Hill after the Princeton breakthrough was announced.*

### How the Figures Were Arrived At

*The figures in the tables on page 53 are based on past FEF studies, updated for 1980 dollars, and on the actual fusion funding in the past two years. The primary source for the magnetic confinement program is the detailed Energy Research and Development Administration study,* Fusion Power by Magnetic Confinement: Program Plan, *Vol. 1-4, ERDA 76/110 (July 1976).*

*The budget figures given here for magnetic confinement (A) were arrived at by taking the most advanced ERDA plan in this study, Logic V, and adding to the Logic V 1980 budget those funds suggested by Logic V, but not actually appropriated for experimental and engineering facilities in 1978 and 1979.*

*Inertial confinement program studies are just now being completed and are not available to the public. The projections for this program (B) were made using previous outlines of program plans presented by the DOE Laser Office, the Lawrence Livermore Laser Division Annual Report (1976), and consultations with research scientists.*

*The funding for 10 basic research centers (C) represents a target figure to be authorized but not spent until the scientific manpower is built up to support a full research program that will back up the mainline fusion efforts.*

# Memorandum To the U.S. Congress

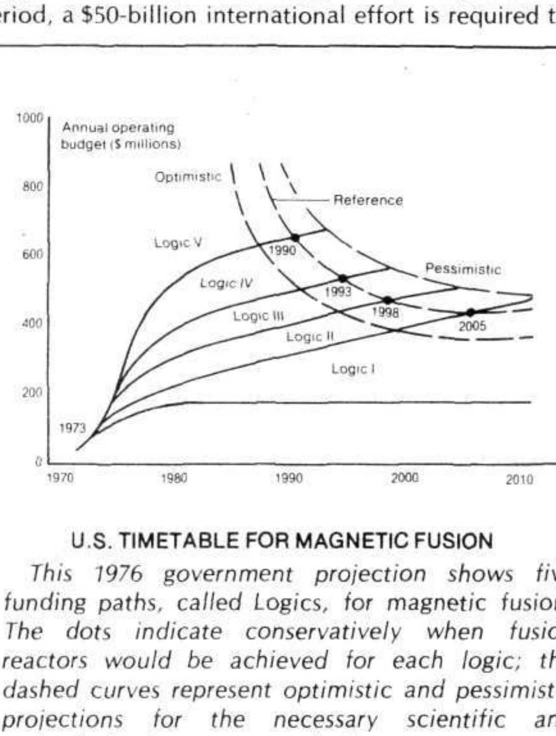
### [1] Energy Policy

United States energy policy is at a crossroads of the most serious consequences for the health of the dollar, our national economy, and industrial strength. This crisis has direct repercussions on the potential for development in the rest of the world.

The advanced industrial nations stated in the Bonn summit communique released July 17 that nuclear energy has an "indispensable role" to play in meeting the world's energy needs. That economic summit made an international commitment to mobilize the advanced technology of the industrial nations to develop the industry and agriculture of the developing sector for the prosperity of the entire world economy.

In the spirit of the Bonn agreements, the advanced sector, led by the United States, has the opportunity to begin the massive building of cities centered around nuplexes—nuclear-based agroindustrial complexes—at the same time that a vigorous international program in reserach and development is conducted on the frontiers of science.

The foremost need in such a research and development program is the upgrading of the current U.S. fusion program which, as seen in the recent results obtained with the Princeton Large Torus tokamak reactor, maintains a leading place in world fusion research. Over the 1980-1990 period, a $50-billion international effort is required to ensure that the world's population will have an inexhaustible source of power into the next century. This commitment to solving the remaining scientific, engineering, and materials problems in fusion and to designing commercial-scale electric-power reactors must be spearheaded by the United States.




**U.S. TIMETABLE FOR MAGNETIC FUSION**

*This 1976 government projection shows five funding paths, called Logics, for magnetic fusion. The dots indicate conservatively when fusion reactors would be achieved for each logic; the dashed curves represent optimistic and pessimistic projections for the necessary scientific and technological progress required.*

### [2] Acceleration of the Fusion Program

In light of the important results announced by Princeton University from the Princeton Large Torus, the Fusion Energy Foundation recommends that Congress greatly expand and accelerate the national effort to develop commercial, controlled thermonuclear fusion.

Over the next 6 to 12 months a number of experiments both in magnetically confined and inertially confined fusion will be producing important results that are expected to solve most of the remaining scientific questions and some of the materials and engineering problems on the road toward developing commercial reactors. As the Princeton results indicate, the scientific questions are being solved. The necessary next step is to accelerate basic system design and materials development.

It has long been recognized in the scientific community and by the predecessor to the Department of Energy, the Energy Research and Development Administration, that the rate at which scientific and engineering progress can be made in the fusion program depends directly on adequate levels of funding. Yet the U.S. program is presently on the lowest and slowest of the five funding timetables develeoped by ERDA (see figure). In order to ensure the most rapid progress toward large-scale introduction of virtually unlimited fusion energy, the Fusion Energy Foundation urges Congress to take the following steps:

(a) Increase the fiscal year 1979 budget allocation by supplemental appropriation to the level required to maintain the construction schedule of the next generation of large-scale magnetic and inertial experiments, and begin full engineering backup for test reactors.

(b) Upgrade the fiscal year 1980 budget level as a transition to an Apollo-style fusion program.

(c) Convene a panel of leading scientists, engineers, and industrial experts that would make recommendations to Congress on the organization, structure, and funding of an accelerated fusion program to begin in fiscal year 1981. This effort would draw on the already proven expertise of the National Aeronautics and Space Administration.

### [3] International Collaboration

The United States is in the process of responding to offers for international cooperation in fusion research made by Prime Minister Takeo Fukuda of Japan and Soviet Academician E. P. Velikhov. The offer by Prime Minister Fukuda has the potential to significantly upgrade the U.S. fusion program by a large infusion of additional funding.

The foundation strongly recommends that an appropriate congressional committee, such as the science subcommittee of the Senate Commerce Committee, hold hearings to determine the proper response from the United States to both the Fukuda and Velikhov proposals.

# The Fusion Budget

## PROPOSED SUPPLEMENTAL BUDGET FOR FISCAL YEAR 1979

| ITEM | AMOUNT[†] |
|---|---|
| Operating expenses | 100 |
| Engineering upgrading | 100 |
| Development of alternate concepts in fusion | 20 |
| TOTAL SUPPLEMENTAL BUDGET | $220 |

## PROPOSED BUDGET FOR FISCAL YEAR 1980—MAXIMUM EFFECTIVE EFFORT

### A. MAGNETIC CONFINEMENT FUSION PROGRAM

| PROJECT | AMOUNT |
|---|---|
| **Tokamaks—Procurement, Construction and Engineering (PACE)** | |
| Princeton TFTR and upgrade | 80 |
| Prototype Experimental Power Reactor or Ignition Test Reactor | 260 |
| Experimental Power Reactor | 390 |
| **Engineering Facilities PACE*** | |
| High Flux Neutron Source | 170 |
| Heating Technology Test Facility | 20 |
| Tritium R&D Facility | 30 |
| Blanket and Shield Facilities | 30 |
| Rotating Target Neutron Source | 2 |
| Intense Neutron Source | 25 |
| Plasma Maintenance and Control Facilities | 10 |
| Vacuum Technology Testing Facilities | 10 |
| Superconducting Magnet Test Facilities | 20 |
| Engineering Test Facilities | 60 |
| **Alternate Concepts PACE** | |
| Large Mirror Experiment (Livermore) | 80 |
| Large Staged Scyllac | 50 |
| Linear Theta Pinch | 50 |
| Elmo Bumpy Torus | 50 |
| Liner | 50 |
| High Density Tokamak | 10 |
| Stellarator | 50 |
| *Others* | 100 |
| TOTAL PACE | 1,547 |
| TOTAL OPERATIONS** | 800 |
| TOTAL EQUIPMENT*** | 80 |
| TOTAL MAGNETIC CONFINEMENT PROGRAM | 2,427 |

### B. INERTIAL CONFINEMENT FUSION PROGRAM

| | |
|---|---|
| **Major projects—Construction** | |
| Three 10 kilojoule glass laser systems | 180 |
| Three E-beam 100 terawatt (or better) facilities | 120 |
| Two 100 kilojoule glass laser systems | 300 |
| Two ion-beam systems | 200 |
| TOTAL CONSTRUCTION | 800 |
| **Major Areas of Study—Operations** | |
| Ion beams | 100 |
| New lasers | 120 |
| Pellet Design | 48 |
| Pellet experiments | 48 |
| Diagnostics | 24 |
| Reactor Systems | 24 |
| TOTAL OPERATIONS | 364 |
| **Equipment** | |
| Ion beam | 100 |
| Laser | 180 |
| E-beam | 60 |
| TOTAL EQUIPMENT | 340 |
| TOTAL INERTIAL CONFINEMENT PROGRAM | 1,504 |

### C. BASIC RESEARCH PROGRAM

| | |
|---|---|
| (includes establishment of 10 national fundamental research centers) | 2,000 |
| **GRAND TOTAL 1980 fusion budget** | **$5,931 million** |

Footnotes

*Includes new projects only.
**Includes all existing projects.
***Includes support services.
† *in millions of dollars.*


# The World Reaction to

*A front-page article in the Washington-based newsletter,* Energy Daily, *broke the Princeton story July 31, reporting "persistent reports of a major breakthrough in the U.S. program in magnetic fusion." The next coverage occurred Aug. 12, with articles in the* Miami Herald, *the* Chicago Tribune, *and the* Baltimore Evening Sun. *Major international coverage began the next day after CBS television and radio aired an interview on the Aug. 12 evening news with Stephen Dean, director of the DOE division of magnetic confinement systems, who called the Princeton results the "biggest thing that has ever happened in fusion research."*

*Selected excerpts from the world press are presented here in chronological order. Note that the coverage breaks down into two groups, reporters who see the tremendous possibilities of fusion and reporters who, witting or not, follow the Schlesinger line.*

**Atlanta Journal, Atlanta Constitution**
*"Atomic Breakthrough Made, Could Mean Cheap Energy,"*
*Aug. 13:*

"For the first time in history, the actual conditions of fusion have been produced in a fusion reactor in scale model," said Stephen Dean, director of the department's Magnetic Confinement Systems Division. "This is the biggest thing that has ever happened in fusion research," he said.

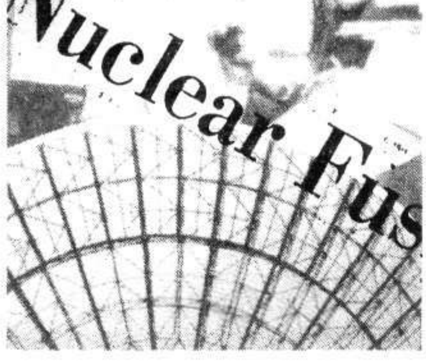
"Experiments at Princeton University that began three weeks ago and are now in progress are the most significant developments in the 27 years of the fusion program," Dean said. "It has laid to rest the question of whether fusion is feasible from a scientific point of view. There is now a scientific basis for embarking on engineering developments of fusion reactors."

**Star Ledger**
*Newark,*
*"Princeton Reports Breakthrough in Creating Cheap, Clean Energy,"*
*by Tim O'Brien,*
*Aug. 13:*

"This significant achievement establishes the foundation for fusion as an energy source," said Dr. Morris Levitt, executive director of the New York-based Fusion Energy Foundation (FEF), adding "Now it's up to the United States to make the same kind of commitment to fusion as it did with the Manhattan Project."

"The breakthrough...eliminates the final scientific hurdle to the production of a pollution-free and virtually unlimited supply of power," according to FEF's director of plasma physics, Dr. Steven Bardwell. "What remains now are technological and engineering breakthroughs in order to produce a prototype fusion reactor and ultimately commercial production of electricity through fusion."

Bardwell said most scientists worldwide believed the prototype fusion reactor could be built by 1990, and commercial production of energy through fusion is possible by the turn of the century. "This undercuts solar energy and of course oil and coal because fusion represents an unlimited efficient clean source of energy. The energy scarcity's over," said Bardwell.



# the Princeton Breakthrough

**Le Figaro**
*Paris,*
*"Considerable Progress in the Study of Thermonuclear Fusion,"*
*by Aurore Molinero,*
*Aug. 15:*

The current raging battle in the United States between pro- and antinuclear forces was marked by a turning point at the Bonn summit meeting with the famous little phrase of President Carter, "the indispensable development of nuclear energy." It is in this political context that one must situate the earth-shattering announcement by leaders in the U.S. fusion program, undoubtedly made to influence political decisions.

**Le Monde**
*Paris,*
*"Record Temperature Has Been Obtained by Princeton Laboratory,"*
*by Maurice Arvonny,*
*Aug. 15:*

A good twenty years of work is still required. The statements reported by UPI should thus be seen in the light of the ferocious struggle for grant money in which the American laboratories are involved, a struggle which drives them to trumpet *urbi et orbi* the least success....

Nevertheless, the step from 26 million to 60 million degrees is noteworthy. "Breakeven" requires temperatures of 50 to 100 million degrees, and the American test shows that these temperatures can be obtained in a tokamak.

**La Repubblica**
*Rome,*
*Aug. 15:*

It has laid to rest the question of the realizability of fusion from the scientific point of view. Now there is the scientific basis to develop the technology.


**The Washington Post**
*"The Fusion Experiments,"*
*editorial,*
*Aug. 16:*

One thing the government must now reconsider is whether the secrecy wrapped around the laser approach to fusion can be reduced. It is the lack of secrecy and the large amount of international cooperation on the (magnetic) bottle approach that have brought success to the work at Princeton. The configuration of the machines in use there is Russian in origin.. Somewhere in this maze of science is a solution to the energy problem. That should encourage the government to be generous in its support of a variety of research programs aimed at the development of a source of clean and unlimited energy.

**Christian Science Monitor**
*"DOE: Fusion Power Still Decades Off,"*
*by Robert C. Cowen,*
*Aug. 16:*

Scientists at Princeton University who are working toward harnessing nuclear fusion to make electric power have indeed had a noteworthy laboratory success. But it is not the "breakthrough" or "major milestone" that was reported over the weekend.

Public affairs officers for the U.S. Department of Energy, which supports that research, says the DOE was both puzzled and embarrassed at what it considers an unauthorized and overblown announcement of the Princeton work....

[DOE public affairs director Jim] Bishop emphasized that, while the Princeton work is a major scientific achievement, it probably won't shorten the time scale or the cost of fusion power development.

**The Baltimore Sun**
*"Fusion's Unlimited Promise,"*
*editorial,*
*Aug. 16:*

Scientists believe judicious increases in the federal fusion budget could hasten fusion's development. Yet the Carter administration has actually cut the modest budget. The promise is for *unlimited* energy, enough to make not only the Texaco find seem paltry but even to render the Arab petroleum reserves of minor importance. With the success of the Princeton experiment, the promise is significantly nearer fulfillment. It is time for the administration to review its attitude toward the fusion energy budget.

**Le Matin**
*Paris,*
*by Henri Laurent,*
*Aug. 16:*

The tokamak results from Princeton prove that thermonuclear fusion is possible....Professor Bardwell...of the American Fusion Energy Foundation, goes even further. He has explained to *Matin* that in his opinion, the industrial application will occur before the year 2000. This is only, according to him, a question of investment: it is necessary to devote $1 billion a year....

**Tass**
*Moscow,*
*"Soviet Physicists Congratulate American Colleagues on Their Success,"*
*Aug. 17:*

Soviet physicist Academician Boris Kadomtsev said that his colleagues of Princeton University had scored a major success in taming thermonuclear fusion. . . .

**Star Ledger**
*Newark,*
*"U.S. Lab Takes Step Toward Taming Fusion,"*
*by Tim O'Brien,*
*Aug. 20:*

If all goes as planned, in a relatively short time the world will have an unlimited, clean, cheap source of energy, and there will be no energy crisis. . . .

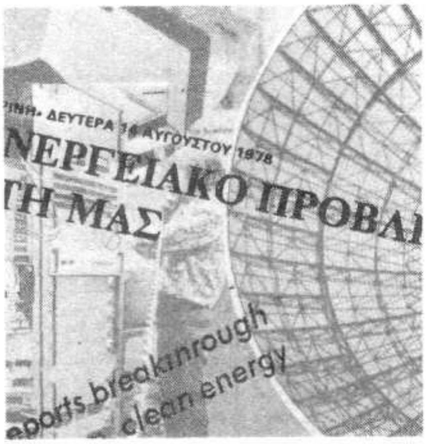
[The head of the Princeton program, Dr. Melvin Gottlieb, said in an interview]: "This is not the end of the energy crisis. Anyone who says that is irresponsible. . . ." Gottlieb, 61, praised the DOE for "not overemphasizing" the 60 million degree milestone. "Breakthrough is not a scientific term," he said.

Others at Princeton, though, expressed disappointment at how the announcement was handled. "It was a major, worldwide development and the DOE certainly went out of its way to play it down," said one Princeton official.

**Pittsburgh Press**
*"Weekly Sizeup"*
*Aug. 20:*

Energy Secretary James R. Schlesinger sizzles over handling of Princeton University research team's giant step in nuclear fusion. They achieved temperature of 60 million degrees centigrade in an experiment funded by Schlesinger's shop. But they announced it on their own.

If good energy news is to be announced, Schlesinger let them know, it will be announced by the Carter administration—with Schlesinger having the key role in telling the public.




**The Washington Post**
*"Taming Fusion's Fury,"*
*by Thomas O'Toole,*
*Aug. 20:*

An enduring irony of the Princeton achievement of last month is that it does nothing to speed up the U.S. program to develop fusion as an energy source. . . .

The politics that followed the Princeton achievement are curious and deserve at least a mention. When the Department of Energy was notified of the 60-million-degree milestone, a mixed reaction ensued. The fusion people were ecstatic, drafting what the federal government calls an "early warning memorandum" for cabinet and agency heads to explain what had happened. Curiously, the memo never reached the White House, presumably the place such memos are aimed at.

There was discussion inside the Energy Department about whether to hold a press conference to announce the achievement. Top management did not want a press conference. They worried that Congress might demand an increase in the fusion budget request, anathema in this year of a forecast balanced budget.

There's another reason Energy Department sources say top management looked askance at the fusion achievement. Energy Secretary James R. Schlesinger believes in the "economics of scarcity," meaning he preaches energy economy because all our fuels are in scarce supply.

Fusion? All fusion does is tell the world that we have all the energy we'll ever need.

**O Globo**
*Brazil,*
*"Nuclear Fusion: Brazil Will Not Have to Import Uranium,"*
*by Edgardo Costa Reis,*
*Aug. 20:*

Nuclear programs like those of Brazil "are now more than justified" in virtue of the recent advances in nuclear fusion technology, said Dr. Charles Stevens, researcher of the Fusion Energy Foundation. . . .

**Pravda**
*Soviet Union,*
*Aug 20:*

. . . It would be incorrect to think that the advocates of "cold war" were taking the upper hand everywhere. News of an entirely different type is also being reported these days. . . . Scientists at Princeton University have achieved a major success in the area of thermonuclear fusion. They succeeded in obtaining a temperature of 60 million degrees C in an experimental tokamak reactor. This was accomplished thanks to cooperation with Soviet scientists. . . .

Our party and the Soviet government, realistically evaluating the international situation in all its complexity, consistently follow the policy of detente, which does not depend on any conjunctural fluctuations. Comrade L.I. Brezhnev has said, "The vital interests of workers of all countries require that everything good accomplished internationally not be permitted to be erased, and that there be forward movement toward truly firm peace for all peoples."

**Newsday**
*New York,*
*"Fusion: Hope for Energy Freedom,"*
*by Robert Reno,*
*Aug. 20:*

The benefits of such a discovery and its application would be staggering:

*The dollar overnight would become once again the strongest currency on earth.

*The forces of inflation—which today draws much of its strength from steadily rising energy prices—would be dealt a mortal blow. . . .

*Oil would cease to be one of the principal sources of international tension, environmental pollution and excessive profit. It would henceforth be used to make such things as chemicals, fertilizers and even animal feeds....

Unfortunately, the fusion people are not at the point where they can go ahead right now. The temperatures achieved at Princeton are only one step....

Fusion ultimately may solve the world's energy problems for the next several thousand years. That won't matter much, however, if between now and the year 2000 we have energy shortages that bring on worldwide economic depression, political upheaval, and international tensions so severe that we blow ourselves up fighting over what little oil is left.

# The Reaction in Congress

*The congressional reaction to the Princeton breakthrough was one of excitement, with many congressmen using the tokamak results as a positive way to pressure the White House and the DOE to move into a program of real research and development. Some statements from the Congressional Record follow.*

**Representative Charles Rangel, [New York Democrat, member of Black Congressional Caucus], Aug. 16:**

Miraculously, this timetable [the 20 to 30-year timetable cited by the *Washington Post*] coincides with most estimates of when we'll reach the end of the world's oil supplies. The implications of this advancement are tremendous. The solution to the world's energy problem is before us. We must seize the initiative and pursue it. This breakthrough compels us to redirect our energy and funnel further funds and attention to highly promising and vitally important nuclear fusion research.


**Representative Olin Teague [Texas Democrat, Chairman, House Science and Technology Committee], Aug. 16:**

This nation is eager for victories on the energy front and demonstrating advanced technology to tap renewable resources is mandatory if we are to show other nations that we are serious about energy supply....

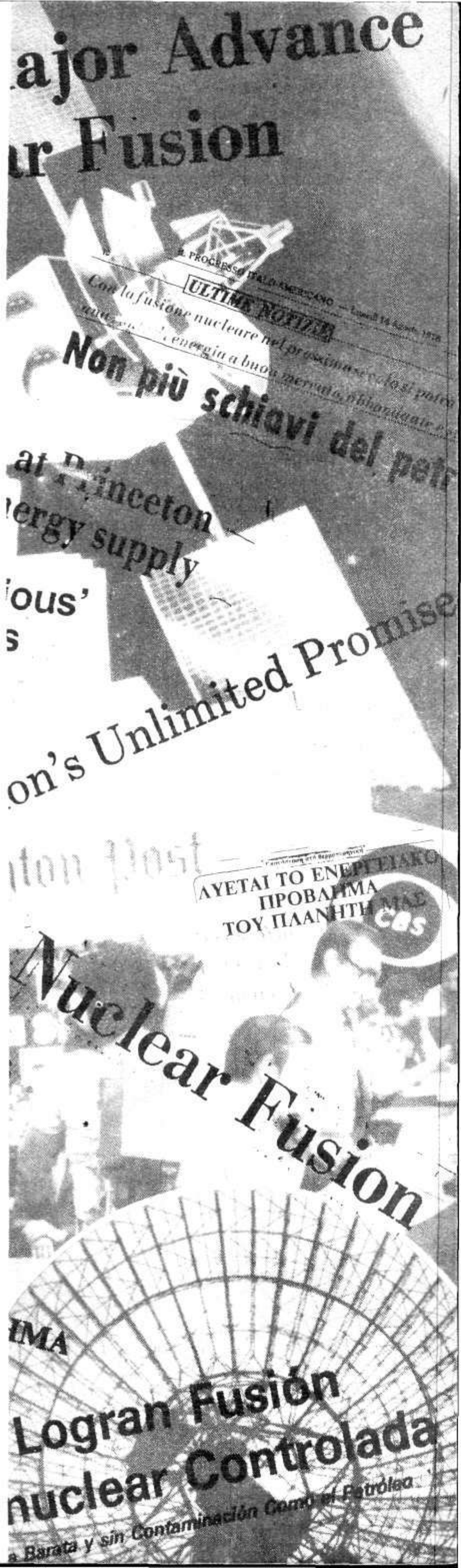
The stakes are too high for this nation to take a timid approach to magnetic fusion. We must move aggressively on this option and this committee expects the Department of Energy to reap the fruits of this latest advancement.

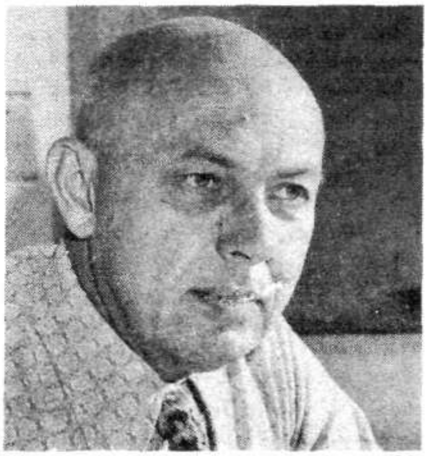
**Representative Carl Pursell [Michigan Republican], Aug. 17:**

Fusion is America's future energy supply. Recent developments in our national fusion research program have given this potentially vast new source of energy the widespread public attention it deserves.... The real question is not so much if we can do it, but when and how.... I suggest to my colleagues that the time is right to push ahead with an intensive national commitment to develop fusion and other alternate energy sources....

Fusion power can lead the way to a secure, inexhaustible energy supply, not just for America but for all the world's people. We should pursue it with all the vigor of our successful space program.

I would ask the membership to look carefully at HR12922 [a bill for a limited supplemental appropriation] which I've introduced as a blueprint for a space program-type effort to accelerate the development of fusion and other alternate energy sources.





Kintner DOE

# The Artsimovich Memorial Lecture

## *Exploring Fusion Energy for*

*Edwin E. Kintner, the director of the Office of Fusion Energy in the U.S. Department of Energy, delivered the first Artsimovich Memorial Lecture at the Aug. 23 Seventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research in Innsbruck, Austria. We are pleased to reprint his speech here.*

* * *

LEV ANDREEVICH ARTSIMOVICH said in 1970, "There can be no doubt that our descendants will learn to exploit the energy of fusion for peaceful purposes even before its use becomes necessary for the preservation of human civilization."

It is a high honor to have been asked to deliver this first Artsimovich Memorial Lecture. I approach the task with deep humility. It is a difficult assignment for me because I did not know Academician Artsimovich personally. However, I will do my best to convey to you the character of the man and his contribution to the great enterprise to which we are all so deeply committed.

My personal knowledge of Artsimovich began during a visit of the Joint Fusion Power Coordinating Committee to the Soviet Union in the summer of 1976. On our first quiet day in Moscow, Mel Gottlieb [director of Princeton University's Plasma Physics Laboratory] insisted that we find Artsimovich's grave. It seemed strange to me to visit the grave of a man who had been buried for several years, with all of Moscow to visit, but the rest of the group agreed that was an appropriate thing to do, so we found our way to the Novodivichi Monastery where so many of Russia's great and near great are buried.

As a result of and following that visit I learned much more of the life and works of Lev Andreevich Artsimovich. He was born in Moscow, the son of a university professor, a graduate of the state university in Minsk, head of a major department at the Kurchatov Institute, and recipient of the Lenin Prize in 1958. From 1950 until near the time of his death five years ago, Artsimovich was in charge of the Soviet program in controlled thermonuclear research.

But those simple biographical facts are familiar to most of you. They do not explain the special respect in which Artsimovich is held throughout the world of science. That level of respect could be earned only by an outstanding personage—a man of unusual qualities in a number of different directions. He was, of course, a brilliant scientist with a remarkable grasp on both the philosophical and material aspects of science as a whole. That grasp was supported by an instinct for the central point in any scientific problem, by a critical sense of technical rightness, and by skepticism tempered with hope and enthusiasm.

Brilliance as a scientist does not alone explain Artsimovich's special influence on the history of fusion. There had to be other important characteristics to explain his contribution to controlled thermonuclear fusion.

First, he was unusually human in the way he related to his fellow men, even when the relations involved sharp technical criticism; and human in the humor and wit he exhibited in his interpretation of his work. I believe the ability to be truly witty, the ability to recognize humor in the most serious of endeavors, is the mark not only of a great mind, but of a great personality. I would like to quote several of Artsimovich's humorous comments. The first is one experimentalist view of theoreticians:

> Our relationships as experimentalists with theoretical physicists should be like those with a beautiful woman—we should accept with gratitude any favors she offers, but we should not expect too much nor believe all that is said.

The second quotation describes the conservatism of some scientific bodies:

> If one proposed to the Royal Society a two-wheeled vehicle for personal transportation, they would immediately conclude that it was impossible because it is clearly and absolutely unstable.

The third comment summarizes the great difficulties of fusion:

> Confining a fusion plasma is like riding a one-wheeled bicycle.

# Peaceful Purposes

But Artsimovich felt there could be rewards from fusion more than the generation of useful energy:

Every housewife should have her own "pinch."

Finally, he stated his own view of why scientific endeavors deserved governmental support:

Science is a way to pursue one's sense of inquiry at the expense of the state.

Those of you who knew him will remember many more wise and witty remarks.

So what did this man, a brilliant mind with unusual intellectual honesty, sharp wit, and forceful personality, achieve?

Although Artsimovich did not conceive the tokamak idea, he quickly perceived its possibilities, nurtured the concept from its infancy, recognized and clearly enunciated the fundamental principles which made its potential for plasma confinement so great, demonstrated that potential in his own laboratory, and then convinced the rest of the world. Now, worldwide, the tokamak is clearly the leading experimental device for confining plasmas.

We in the United States owe him a special debt of gratitude for convincing our fusion community that the tokamak was superior to the concepts on which we were then working. Even after the exciting results reported at the Novosibirsk meeting in 1968, the United States did not appreciate the significance of Soviet tokamak work. It was Artsimovich's lectures at the Massachusetts Institute of Technology in the spring of 1969 following the British Thomson scattering experiments at Kurchatov that changed all that dramatically.

The MIT lectures are classic in the purity of the basic insights of the physical principles involved and the clarity of the presentation. Of course, there was great reluctance in Great Britain and the United States to accept as valid tokamak advances after so many disappointments with other ways of confining plasmas, but the lectures at MIT lead quickly to the ST at Princeton and the Ormak at Oak Ridge and thence to a diversion of the mainline of the U.S.

APN

*Artsimovich*

program away from stellarators toward tokamaks. Dave Rose, Bob Hirsch and several others are quite proud of the five dollars won in a bet with a distinguished bearded American that the British Thomson scattering experiments would show that the Soviet claims were correct, and that as a consequence the United States would convert its mainline research to tokamaks.

From that decision have come the remarkable developments which have taken place in the U.S. program, both in its growth and in its scientific achievements in confinement of plasmas.

Those of us in the program now very often forget how rapidly progress has been made. At the time of the reporting of the fundamental promise of the tokamak principle in Novosibirsk in 1968, the best parameters which had been achieved were an $n\tau$ of 350 billion and an ion temperature of 300 eV.* In the decade since that time, $n\tau$ has been improved by a factor of almost 100, and temperature by a factor of more than 10.

* The Lawson product for determining the energy output of a fusion system is designated by $n\tau$, where $n$ is the density of the fusion plasma in nuclei per cubic centimeter and $\tau$ is the confinement time in seconds. For breakeven, an $n\tau$ of 30 trillion seconds-nuclei per cubic centimeter is needed. An eV is an electron volt and is a measure of temperature; 1 eV is equal to approximately 11,000 degrees Celsius.

The rapid progress of the past decade is continuing. In recent experiments, Princeton has achieved significantly higher temperatures than heretofore, earlier than expected and in stronger form than expected. These results provide increased confidence that the scientific feasibility of fusion will be completely demonstrated in the Tokamak Fusion Test Reactor. They have provided essential scientific information which confirms that our thinking of magnetic fusion is correct. We believe them to be of great significance not only to the U.S. fusion effort, but to the world fusion community. You will hear of them in detail in the next paper. I am sure Academician Artsimovich would have been highly gratified by this further confirmation of the validity of his work.

So the Artsimovich contribution was not simply to select a confinement scheme and demonstrate its possibilities, but to point the direction—based on sound understanding and judgment of the natural phenomena involved—which fusion research has so successfully followed, not only in the Soviet Union but worldwide.

Another result of the significant influence of Professor Artsimovich is in the uniquely international relationships which fusion represents. Artsimovich's personal leadership was fundamental in advancing the cause of international scientific collaboration. He believed about science as a whole, and especially for fusion, that close collaboration on a world scale was vital to success. He stated this viewpoint so strongly and so well in a paper he presented 20 years ago at the Second Geneva Conference that I would like to quote it:

> A most important factor in ensuring success in these investigations is the continuation and further development of the international cooperation initiated by our conference. The solution of the problem of thermonuclear fusion will require a maximum concentration of intellectual effort and the mobilization of very appreciable material facilities and complex apparatus.
>
> This problem seems to have been created especially for the purpose of developing close cooperation between the scientists and engineers of various countries, working according to a common plan, and continuously exchanging the results of their calculations, experiments, and engineering developments.
>
> The combining of efforts on an international scale in the field of controlled fusion reaction investigation will undoubtedly shorten the time needed for us to arrive at our ultimate goal.

Artsimovich's thoughts about the need for international cooperation in fusion were reciprocated by scientists in other nations who recognized the great future importance of fusion and its freedom from military or proprietary implications. The United States and Great Britain had been working together under the Libby-Cockcroft agreements for several years and the United States opened all its work and results in [the] Second Geneva [Conference] in 1958.

Where has this mutual recognition of the need to work together in developing fusion for the benefit of all mankind led? This conference is, itself, an important example of the distance fusion has traveled under the leadership of the International Atomic Energy Agency (IAEA) toward full, open scientific cooperation on a world scale. There are other examples. The close collaboration under the bilateral agreement between the United States and the Soviet Union provides upwards of 100 man-weeks of scientific exchange each way each year, with many workshops and conferences. This collaboration between the United States and the Soviet Union has contributed much to the progress being made in the United States, and I hope and believe the same can be said for its benefits to the Soviet program.

**International Collaboration**

There is a strong and growing collaboration through the International Energy Agency agreements for work on plasma-surface interactions on Textor at Julich, the Large Coil Project at Oak Ridge National Laboratory, and on projects for fusion materials research facilities at Los Alamos Scientific Laboratory in New Mexico, and Hanford Engineering Development Laboratory in Hanford, Washington.

The United States and Japan are presently discussing ways to strengthen the relationships for fusion development between our two nations.

Furthermore, there are proposals through both the International Fusion Research Council (IFRC) and the International Energy Agency (IEA) channels for closer working relationships in planning programs and projects so as to eliminate duplication, share facilities, and assign responsibility for solving specific fusion problems. One such proposal—that by Academician Velikhov, Artsimovich's successor as leader of the Soviet program, in Vienna in June of this year—that the next large fusion device should be built on an international basis, is being vigorously discussed. I expect that concrete actions resulting from that proposal will commence shortly. . . .

These unprecedented initiatives stem, I believe, from a growing consensus, beginning with attitudes and principles for international collaboration expressed by Artsimovich, that fusion offers a unique opportunity for cooperation between nations on a problem whose solution is vital to the survival of the entire race on this planet. There are no military and no immediate proprietary or commercial threats in fusion. Therefore, if we are able to work together toward solving this problem in a mutually beneficial, synergistic way, we may establish precedents for solving important future problems which are inevitable for the world's population riding a limited sphere through space, a sphere which contains increasingly limited resources, and on which war with thermonuclear weaponry is unacceptable as a basis for deciding the distribution of those resources.

The nations of the world are now spending a total of approximately $1 billion per year equivalent on research in controlled thermonuclear fusion. Even that is not enough considering the massive implications and similarly massive problems of developing fusion to practicality as the

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*A Soviet delegation meeting in 1975 with staff of the Electric Power Research Institute to discuss fusion-fission programs.*

ultimate energy resource. So we must carry forward with our efforts to gain maximum possible progress by making our cooperation and collaboration increasingly effective.

In this connection it may be interesting to note that the U.S. Department of Energy has been reviewing the prospects and status of the U.S. fusion program for almost a year. The review included as a major element an analysis of the balance and pace of the program by a group of eight respected scientists. I am glad to report my expectation that, on the basis of that extensive review, the momentum and breadth of the U.S. program will be maintained. That expectation should be a matter of encouragement and satisfaction to all of you.

Finally, I would like to speak on a thought first proposed by Artsimovich which seems especially pertinent to our circumstances and for the individuals and programs whose leadership is represented so well in this auditorium. Artsimovich wrote in 1970 that there were three main reasons for mastering controlled nuclear fusion: first, it would provide access to practically inexhaustible energy sources; second, it did not require formation of great quantities of radioactive by-products; and finally—a philosophical reason—success in developing fusion for the practical benefit of all mankind would reestablish the self-confidence of scientists in themselves and in science....

In the United States, and I sense to some degree in the rest of the world, science has lost its own internal confidence and the confidence of the lay public in it. The assumed certainty that it is "good" to penetrate the dark corners of nature with the illumination of the human mind is being questioned. Science is held responsible for the doubts that it has raised about the existence and nature of God, as explained by medieval man, with all the moral questions those doubts raise. Science is blamed for the development of weapons which can end civilization in seconds. Science is charged with providing the modern industrial processes which contaminate the environment and allow the population to increase to the point that life is not as full as many wish. Science is feared when it begins to experiment with the more fundamental aspects of genetics.

And so, in many places, there is a turning of the back on science and scientists, at least in those areas which might be oriented toward further development of modern applied technology. Some scientists have accepted this value judgment. Many of the most brilliant have turned from working on or supporting any subject, including fusion, which might have direct, practical results.

Perhaps it is precisely in this context that we should examine and try to learn from the life and contribution of Lev Andreevich Artsimovich. If we in the fusion community can build on the great beginning which has been made and carry forward with the development of fusion—hopefully, optimistically, enthusiastically working together toward providing unlimited energy, the fundamental energy of the universe, in a controlled, environmentally benign manner—we can once more believe in ourselves and in science as the noblest, most constructive activity to which the mind of man can be turned. We may help reestablish that no one need fear shining the bright searchlight of the human mind on the many remaining dark corners of our understanding of the universe around us.

We have made great progress in that direction. We are on the threshold of accelerating our pace. We are not yet at "the beginning of the end," but we may be "at the end of the beginning" of the most difficult technological development man has ever attempted. We can and should proceed from this point with confidence—the confidence Artsimovich expressed in the quotation with which I began, "Nevertheless, there can be no doubt that our descendants will learn to exploit the energy of fusion for peaceful purposes."

# Electric Power from Laser Fusion

## by Dr. Michael Monsler

THE LASER FUSION PROGRAM is one of the most exciting, promising, and fast-paced energy programs in the world today. From our current vantage point, it appears that fusion power can provide a virtually inexhaustible supply of energy in an economically competitive and environmentally acceptable manner.

In the near term, the laser fusion program is primarily a physics research effort to understand how mother nature works. We are providing valuable information on the technical feasibility of obtaining net energy gain from inertially confined fusion, in order to allow rational decision making on development programs for our energy future. In the longer term, our goal is to dramatically increase the energy supply by substituting the technological capabilities of the United States and other advanced countries for the nonrenewable natural resources that the world is currently burning up at an alarming rate.

Converting fusion energy into electricity is fundamentally different from burning oil or coal because of the nature of the fuel. A typical 1,000-megawatt electric power plant today consumes a great deal of fuel, both in physical terms and in terms of cost (see table). A coal plant uses about 190 trains of coal per year, of 200 cars each, while an oil-fired plant may consume 10 million barrels (10 supertankers) of oil per year. Fission fuel is more compact; a nuclear plant may consume only a railroad car of fuel per year, but the total fuel cycle costs may be $45 million.

**ANNUAL FUEL REQUIREMENTS FOR A 1,000 MW* ELECTRIC POWER PLANT****

| ENERGY DEVICE | AMOUNT | |
|---|---|---|
| Coal | 2,100,000 tons | 191 trains (110 cars each) |
| Oil | 10,000,000 barrels | 10 supertankers ($10^6$ bbl each) |
| Fission | 30 tons $UO^2$ | 1 rail car load |
| Fusion | 0.6 tons | 1 half-ton pickup truck |

*Megawatts   **Working at 75 % capacity

In contrast, once fusion is shown to be feasible, the deuterium fuel required would fill only one pickup truck. Furthermore, deuterium, an isotope of hydrogen, is obtainable from sea water in a very inexpensive process. To dramatize the energy value of deuterium, consider that about 1 out of every 6,000 water molecules has deuterium in place of hydrogen. In the fusion process 1 gallon of water can provide the energy equivalent of 850 gallons of gasoline. Although it will require a great deal of technology development to tap this resource, the incentives are high, for there is no shortage of water on earth.

How does this fusion fuel work? In the first fusion reactors, we plan on fusing atoms of deuterium and tritium, a second isotope of hydrogen that can be bred entirely within the fusion chamber. Fusing deuterium and tritium (D-T) requires temperatures of nearly 100 million degrees, and results in a helium atom and a neutron, which carry off the energy released (Figure 1). The helium atom and neutron are slowed down in a thick blanket, furnishing heat at a desired temperature. We can then produce electricity through a conventional steam cycle; the fusion heat source simply replaces the coal-fired boiler.

### What Is Laser Fusion?

Picture a small pellet of solidified deuterium-tritium, perhaps one-quarter inch in diameter, and imagine focusing laser beams on all sides of the pellet. The absorbed laser light vaporizes the solid material and causes the heated gas to stream off at extremely high velocities during the laser pulse, which lasts a billionth of a second. This escaping gas provides an equal and opposite reaction force, directed inward, which acts very much like the thrust of a rocket engine. The inward force crushes the pellet up to 10,000 times the density of ordinary matter, bringing the temperature up to the required 100 million degrees, and fusing the atoms, as shown in Figure 1.

The key is to fuse the central material and obtain the energy release from the nuclear reaction before it has time to fly apart. To use scientific terms: the pellet is confined by its own inertia; it reacts faster than it can disassemble. All the hot material, including the neutrons and X-rays, are then absorbed in the blanket of the reactor chamber. A working reactor would repeat this fusion about once a second, cresting a pulsed energy source, similar to an internal combustion engine, that would provide steady output power.

Lawrence Livermore Laboratory is pursuing a three-pronged program in inertial confinement fusion. First, the largest part of the program is devoted to building large neodymium-glass laser facilities and performing laser-target interaction physics experiments using these powerful

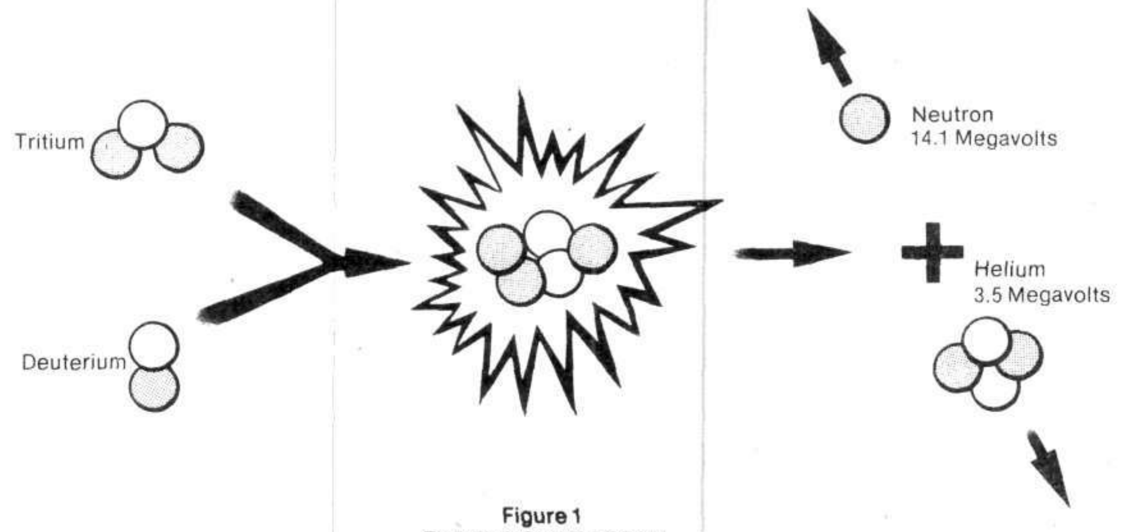



**Figure 1**
**THE FUSION PROCESS**

*In the deuterium-tritium fusion process shown here, a deuterium nucleus (which consists of one neutron and one proton) fuses with a tritium nucleus (which consists of one proton and two neutrons). The deuterium is a form of hydrogen found naturally in water, and the tritium is another isotope of hydrogen formed in nuclear reactions. The two protons and two neutrons combine to form a stable helium nucleus, with the extra free neutron flying off with four-fifths of the released energy in the form of kinetic energy. (The stable helium atom carries the remaining one-fifth.) This kinetic, or "moving" energy can then be easily converted to heat or electricity. The energy needed to start the deuterium-tritium reaction is 10 keV, while the energy produced is 17,600 keV.*

lasers. Second, we are investigating new and different drivers that will be more suitable for the power plants of the future: advanced, short wavelength lasers and ion beams. Third, we are studying reactor concepts to convert fusion energy into electrical energy.

Figure 2 shows the achievements of the Livermore program since 1974, as well as our plans through the mid-1980s. The vertical axis shows pellet gain, the ratio of energy output to the laser energy input to the pellet. The horizontal axis shows the year.

In 1974 we went to Congress with a proposal to build a series of lasers that we named Janus, Cyclops, Argus, and so forth. We told Congress that computer simulations showed that we could obtain the kind of performance shown in the figure if we could build lasers of greater and greater energy per pulse. This is because the energy gain improves as the energy input to the pellet is increased. So even though in 1974 we had obtained only a billionth of the energy out that we put in, we had confidence that we could surpass breakeven with the larger and larger lasers we had planned.

As you can see from Figure 2, if we continue to get the support required to build the Nova facility, we should demonstrate the scientific feasibility of inertial fusion in the mid-1980s. This success depends not only on laser development, which is very visible, but on the incredibly sophisticated capabilities in computer simulation and diagnostic instrumentation, which the U.S. national laboratories have been developing since the 1940s for the design and testing of nuclear weapons. This transfer of knowledge and technology from the weapons program has been very valuable.

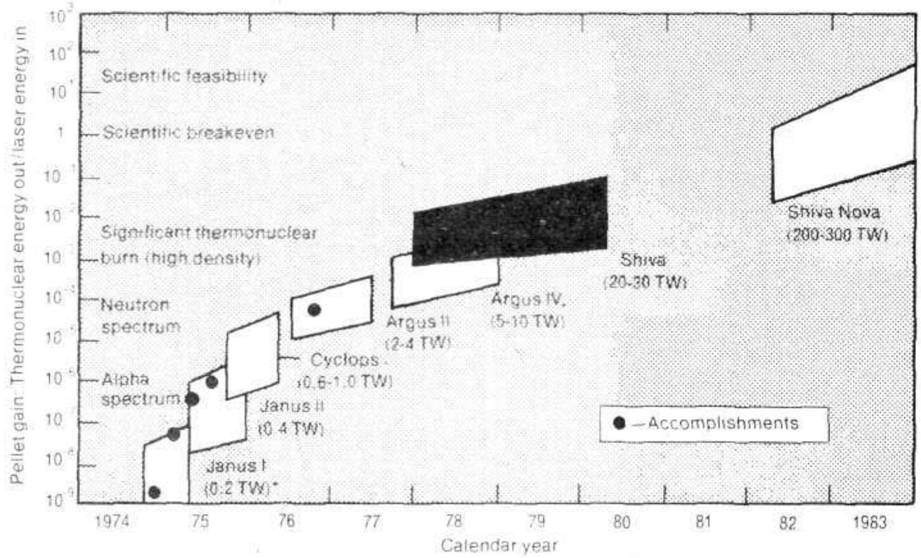
The experimental results actually achieved are shown in the dots of Figure 2, culminating in the Argus II result, which corresponds to about $3 \times 10^9$ billion neutrons output. (Argus IV was proposed but never built.)

Shiva just began operation at the end of 1977, and target experimentation is scheduled to begin very soon. It is the world's most powerful laser, capable of delivering 27 terawatts (that's 27 trillion watts) of power per pulse. The largest laser facility, Nova should break ground within a year if the funding becomes available.

As Figure 2 shows, the program is clearly marching toward the goal of a scientific feasibility demonstration.

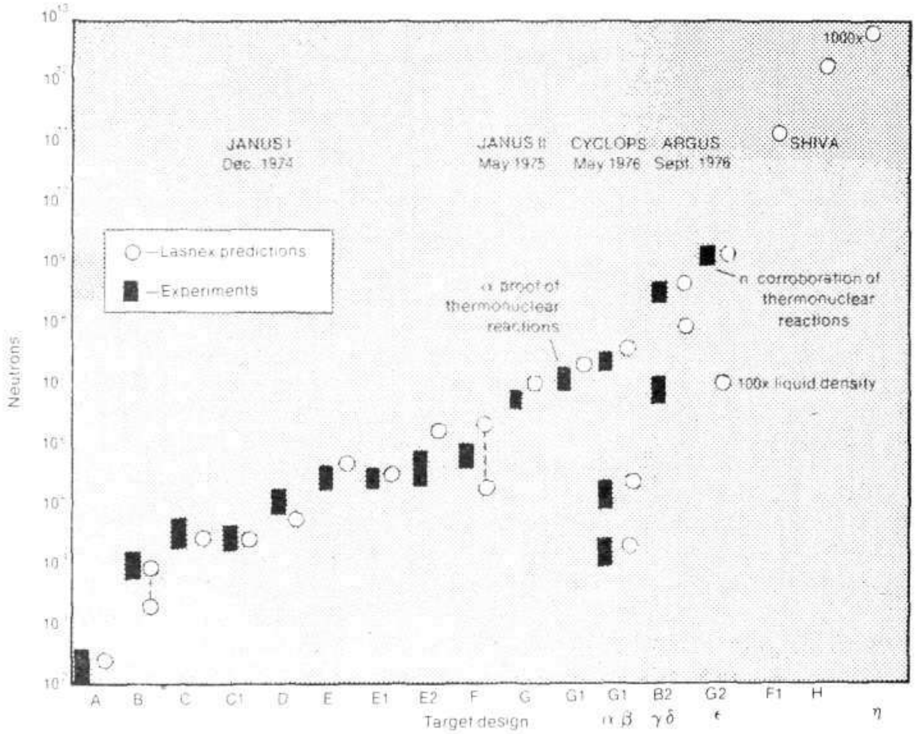
Figure 3 is complicated but most important. It compares Livermore's experimental results (boxes) to the results predicted by the physicists using computer simulations for different target designs (dots). The vertical axis shows the number of neutrons per shot—from 100 to 1 billion. There is a large variety of target designs, indicated by different letters on the horizontal axis. LASNEX is the name of the computer code used to test the effect of different assumptions included in the theory (indicated by the dotted line). After a target is designed, it is fabricated within given tolerances on size, surface finish, shell thickness, and so forth. Months later we inactivate it with the laser, and the experimental results of this are shown. Over a range of 7 orders of magnitude, (7 factors of 10), we have come within a factor of 2 or 3 of the computer predictions—an extraordinary predictive capability. The latest results are shown

Figure 2
LASER FUSION ENERGY YIELD PROJECTIONS




The dots designate the achievements of the Lawrence Livermore program since 1974, and the boxed areas indicate the program goals through the 1980s. The Shiva-Nova laser, now under construction, is expected to reach scientific breakeven and feasibility in the mid-1980s.

Figure 3
NEUTRON YIELDS VERSUS THE COMPUTER PREDICTIONS




The Livermore experimental results (designated by boxes) have consistently kept pace with the LASNEX computer predictions for different target designs (designated by circles). The vertical axis shows the number of neutrons produced per laser shot, from 100 to 1 billion.

in the upper right corner of Figure 3, a few billion neutrons per shot. To demonstrate scientific feasibility, we must obtain about $10^{19}$ per shot.

### Hitting the Target

Let's first look at the target and then discuss the target chamber and lasers in more detail. As can be seen in Figure 4, which shows a target on the head of a pin, the target obviously represents a very small area onto which we must focus. Furthermore, the target must be irradiated uniformly. If the laser beams are off center it is difficult to achieve the spherically symmetric implosions required to compress the material in the core, cause nuclear reactions, and thus yield output energy.

The surface finish of the pellet is good to 100 to 200 angstroms (about 50 atoms), a factor that also favors symmetry of implosion. Reactor pellets will be much larger, perhaps a quarter of an inch in diameter. The extreme small size of the experimental target demonstrates that in many respects we are doing the most difficult experiments now, because we are so limited in laser power.

The target chamber of the Shiva laser, about a meter in diameter, is shown in Figure 5. The 20 laser beams, 20 centimeters diameter each, enter the chamber from two sides in two clusters of 10. The remainder of the space around the chamber is fairly bristling with diagnostic instruments of all kinds, to measure the types and energies of the particles and X-rays that are emitted. By measuring the magnitude of the energies and the spread of energies, we can determine the maximum temperatures and pressures achieved. This information improves our modeling and predictive capabilities, and teaches us just how intricate and devious mother nature is.

Figure 6 shows a portion of the laser amplifier chains for Shiva. The white metal space frame is constructed of 6-inch square steel members and serves as the optical bench on which we hang mirrors, amplifiers, and other optical components. Kept at more or less 1 degree Fahrenheit, the structure has exceptional dimensional stability over the entire barn-sized building—aside from the time periods during occasional earthquakes.

First, the energy is stored in large capacitors located in the basement under the space frame. This energy is then brought into the amplifiers, which convert electrical energy into light energy in a way that is precisely controlled by the light input.

Figure 7 shows an amplifier opened up to expose the neodymium glass disks surrounded by flashlamps. The electrical energy from the capacitors excites the flashlamps (very similar to a camera flash) and the ultraviolet light from the flash is absorbed in the special glass disks, which have a small percentage of neodymium atoms. The neodymium atoms store the energy sufficiently long so that when the input laser pulse sweeps through the glass disks, it stimulates the neodymium atoms to emit the stored energy in light of the same frequency and in the same direction as the incoming light. In this way the light pulse stays highly directional while growing in energy. Thus, the laser gets its name: Light Amplification by Stimulated Emission of Radiation.

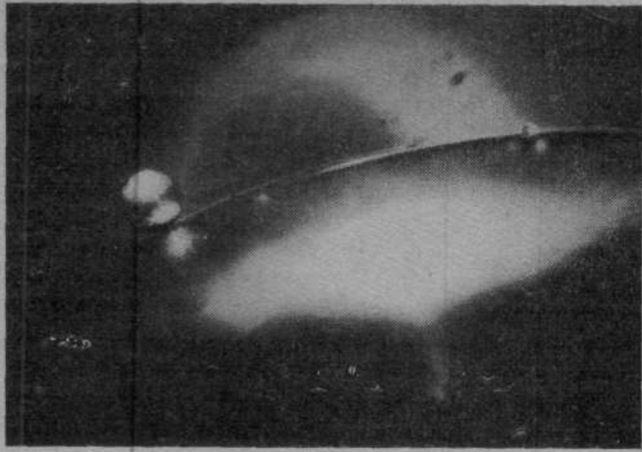
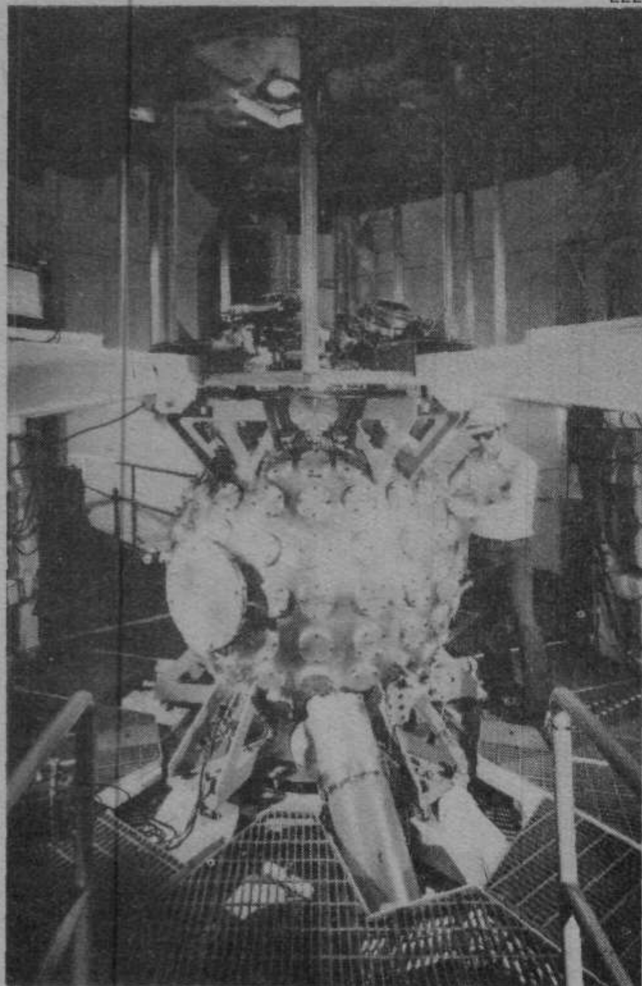
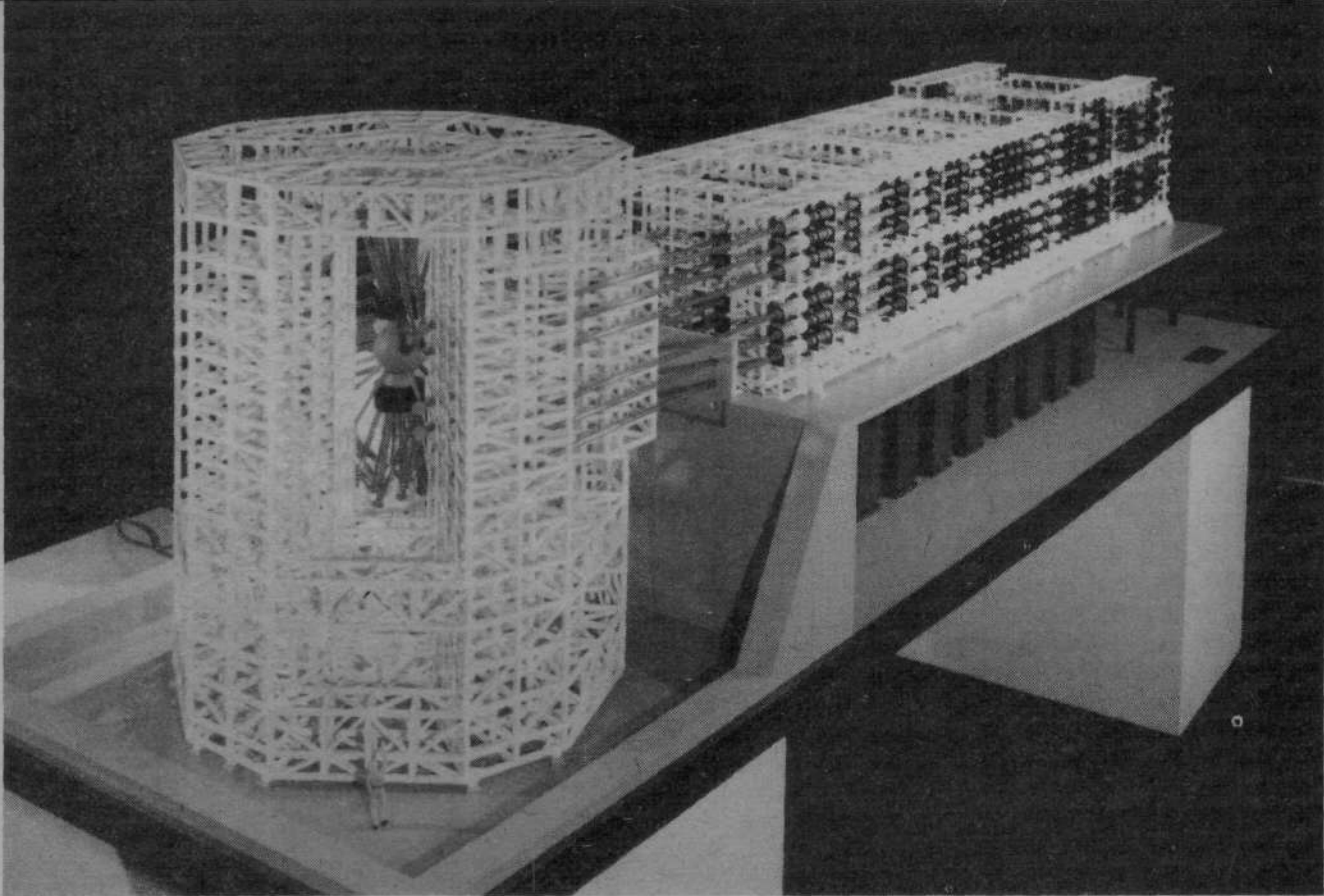


Figure 4 LLL

*Above: A model of the laser fusion pellet, shown dwarfed by the head of a pin. Below: The Shiva target chamber, which is about 1 meter in diameter. The 20 laser beams enter the chamber in two clusters of 10 from each side. The portholes you see here are now filled with various diagnostic equipment.*

Figure 5 LLL





LLL

**Figure 6**

*Model of the white-metal structural framework for the Shiva laser system, showing some of the laser amplifier chains and the target chamber.*

Starting from a tiny pulse of light, we continue to add energy in this manner by cascading the amplifiers in series. We also split the light into many beams with half-transparent mirrors and then amplify the pulses in many parallel chains. Shiva, for example, has 20 laser chains.

The power level reachable today is in the tens of terawatts, for a pulse duration of a billionth of a second or less. (One hundred terawatts is equivalent to the power consumed by a million times a million 100-watt light bulbs.) It is currently within the state of the art to align all these beams under computer control and have all the laser pulses arrive at the target sufficiently simultaneously. This means controlling the length of the light path to about one-tenth of a quarter of an inch over the length of a football field.

### Achieving Scientific Feasibility

Soon Livermore will break ground for an even larger laser called Nova, twice the size of Shiva, but 10 times more powerful. By using improved laser glass in the amplifiers, more amplifiers per chain, and twice as many chains, we can increase the laser power 10-fold in a building only twice the size. This will be accomplished in a two-phase operation, which will cause only minor interruptions in the ongoing experimental work. Nova is the facility on which we hope to attain scientific feasibility; that is, obtain not only breakeven, but more than 20 times the energy out than we put in.

The neodymium glass laser systems just described may not be optimum for a power plant because they have two limitations. First, they are too inefficient; and second, they have a very limited capability to be repetitively pulsed. We are working on advanced lasers that do not have these drawbacks. Nevertheless, these glass lasers continue to be the most cost-effective way to do scientific feasibility experiments to convince the world that inertial fusion works and that it deserves funding for technology development.

How much do these experimental facilities cost? The Shiva facility is a 30-terawatt system costing $25 million (not including operational costs) and is about a 100-man-year effort. The 10 times more powerful Nova system, which will come into operation in two phases in 1982 and 1984, will be about a 500-man-year effort and cost about $195 million over a six-year construction period. Although this may sound costly, it is a rather inexpensive source of information critically needed to assess the spending of future energy development funds which may range in the hundreds of billions of dollars.

I want to emphasize that we do not have to use lasers for inertial confinement fusion. Some researchers advocate ion beams and electron beams to beam the energy onto a target from a distance. However, those who favor the ion beam and other approaches are also looking for the success of the Livermore laser fusion program to demonstrate the fusion physics, since most physicists will agree that

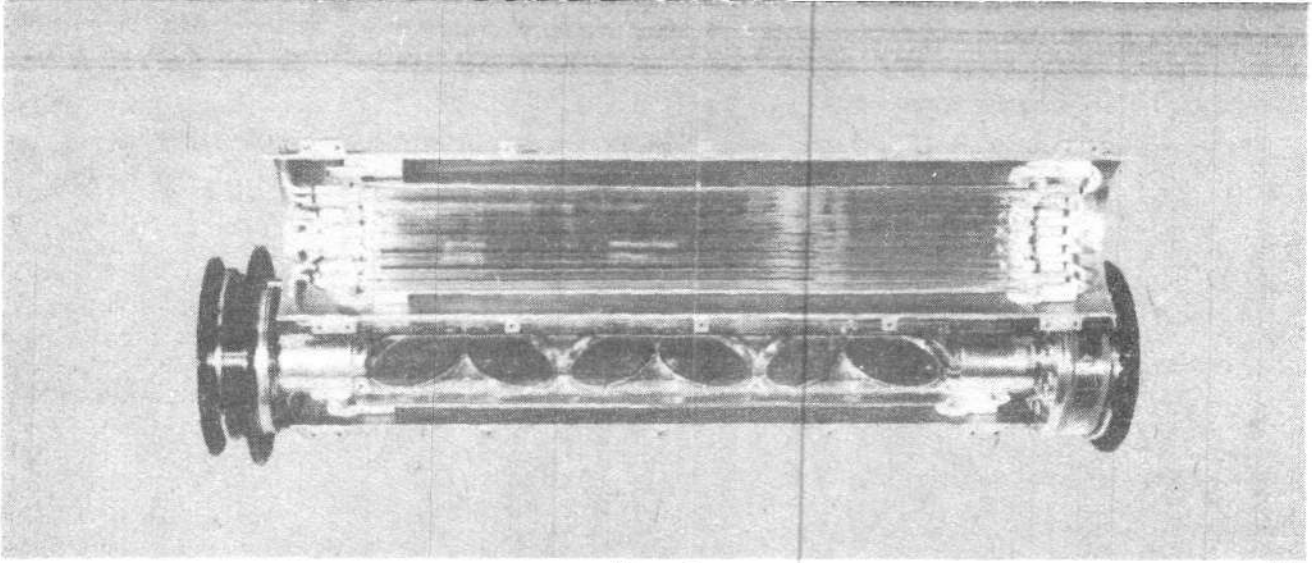


Figure 7 LLL

*A laser amplifier opened up to expose the neodymium glass disks (bottom) surrounded by flashlamps (above).*

sources of energy other than lasers can be used to drive an implosion. Each driving source will have its own characteristics and implosion efficiencies, of course, but scientists do not have to do a breakeven experiment for every possible driver to prove it can be done. This separability saves a great deal of time and expense.

Looking toward producing electric power, Livermore is beginning to develop the technology required beyond the physics experiments discussed here. To take some examples: we must have a driver that provides beam power not just in one pulse, but in pulses 1 to 10 times per second for years. This driver should have an electrical efficiency greater than 1 percent, in order to minimize the cost of electrical power supplies, and so forth. In addition, we must have an energy conversion chamber able to handle the fusion energy output without damage; cumulative neutron damage causes steel to get more brittle and lose strength. We also must have focusing mirrors to direct the light to the fusion pellet without being damaged by the output radiation. Finally, we must have the technology to produce the fusion pellets cheaply at the rate of 1 to 10 per second. All these factors must be orchestrated to come together in time for a demonstration power plant in the first few years of the 2000s.

## The Fusion Reactor

Researchers at Lawrence Livermore Laboratory favor a fusion reactor concept called the lithium waterfall reactor (Figure 8). Lithium is a metal that becomes liquid at 950 degrees Fahrenheit reactor temperature; and a similar metal, sodium, is commonly used in nuclear reactor heat transfer systems today.

The lithium would be used to establish a 50 to 100 centimeter thick wall of liquid metal surrounding the center of the reactor; no solid walls are exposed to the neutron or X-ray flux, just liquid metal. Thus, lithium gives us a reactor that can have its inner wall destroyed on every shot. (The pellet is injected into the chamber with a pneumatic gun similar to an air rifle.)

The cascade of lithium in the reactor is reestablished between shots using a flow velocity of 5 to 10 meters per

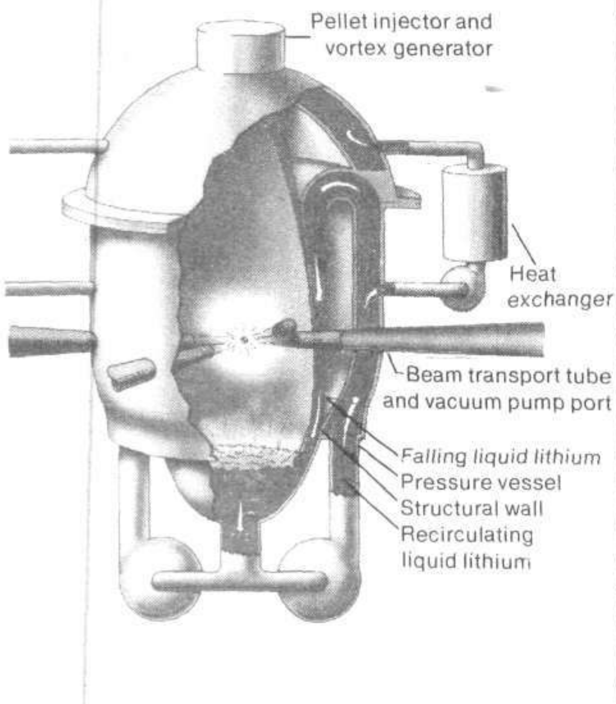



Figure 8
LASER FUSION REACTOR.
LITHIUM WATERFALL CONCEPT

*Cutaway drawing of a laser fusion reactor based on the lithium waterfall concept. In this closed-cycle system, the neutron and X-ray energy from the implosion of the pellet is absorbed in the liquid metal lithium that forms a thick wall around the center of the reactor. The lithium, circulated through a series of heat exchangers, is also the heat-transfer fluid. Electricity is produced with conventional turbine generators.*

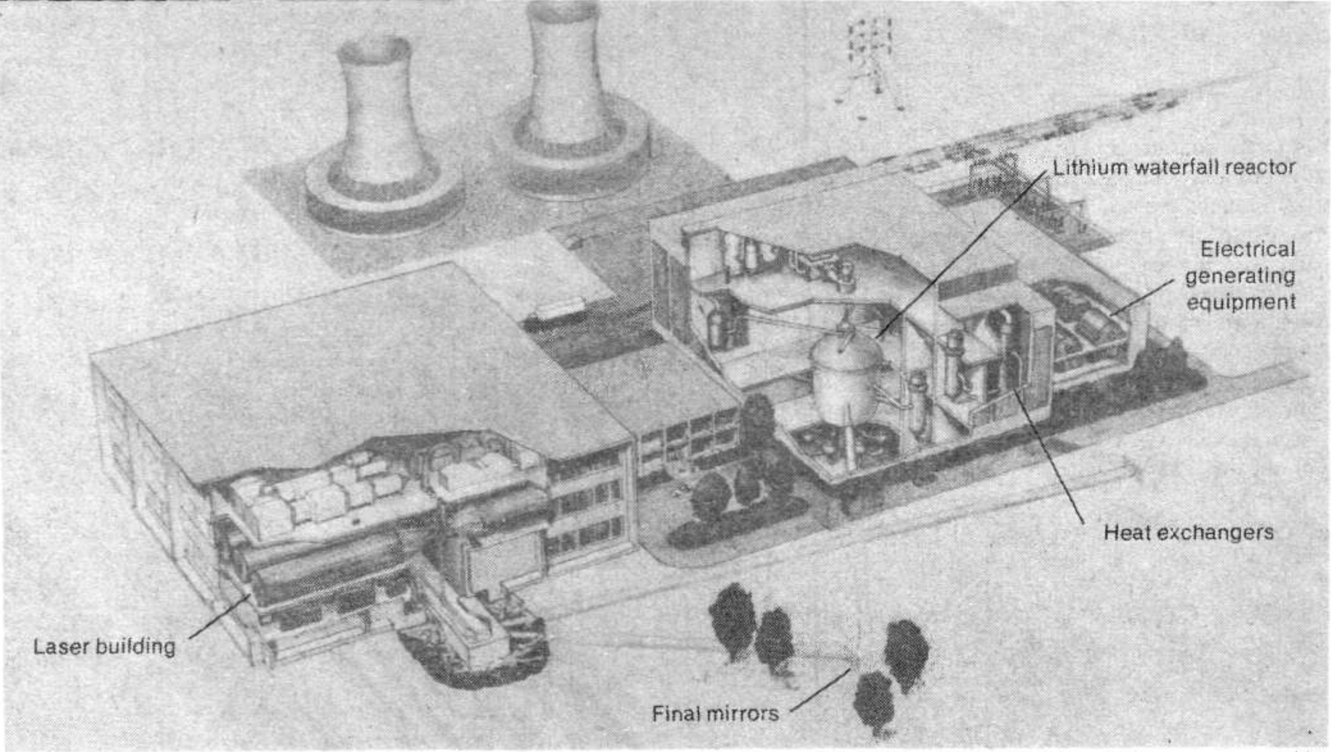



**Figure 9**
**REACTOR BUILDING FOR LITHIUM WATERFALL PLANT**

*Reactor building with a lithium waterfall reactor. The separation of the laser system and the lithium waterfall reactor lowers the cost of building and maintaining the system. The laser beams are conducted through underground tubes to the final focusing mirrors that look into the reactor chamber.*

second. This concept allows the containment of the microexplosions without sustaining permanent structural damage. The neutron and X-ray energy is absorbed in the liquid metal, which is also used as the heat transfer fluid. The lithium is circulated through a series of heat exchangers, steam is generated, and electricity is produced with turbine generators in the standard way. The pumping power required to circulate this lithium can be kept to less than 2 percent of the gross electrical power.

Livermore has done extensive modeling of this reactor concept, including many variations of the configuration of the waterfall as well as different approaches for bringing in the beams. All of the reactor designs of interest share two important common characteristics. First, the structures are designed to be constructed of common steel and to last the 30-year life of the power plant. Second, the designs emphasize techniques to minimize the effects of shock and fatigue that one would expect with a pulsed energy source.

As a result, the lithium flow is a very attractive concept compared to some fusion reactor designs that must change their first walls yearly because of radiation damage. There is a further benefit: In the lithium flow concept, all the neutrons must go through 1 meter of lithium before encountering steel. In doing so, the energy distribution of the neutrons becomes similar to that in a fast fission breeder reactor, and thus we can obtain pertinent data for the lithium flow without waiting for operating fusion reactors.

These factors give confidence that the majority of the materials and techniques required for inertial fusion reactor design are within the current state of the art, and, therefore, will not present extraordinary problems. An exception to this, which may be important, is that all the neutrons arrive in short pulses, instead of in the steady manner common in fission reactors. The effect of the pulsed nature of the neutrons is the major uncertainty in the materials science area.

Since we do not expect a first-wall replacement problem and do not have the fission product wastes of today's nuclear reactors, we expect very minimal radioactive waste. Of course, at the decommissioning of the power plant after 30 years there will be a waiting period for the steel structure to lose most of its induced activity. Although that steel probably won't be used to make cars, neither will it pose a hazard or environmental problem.

In the past, critics of laser fusion have been concerned with the survivability of the final optics that face the pellet fusion. We now have target designs that allow us to place the mirrors 50 to 100 meters away. The X-rays and debris are prevented from reaching the mirror by an absorbing region of low-pressure xenon gas placed ahead of the mirror, allowing only the neutrons to hit the mirror. Furthermore, our analysis shows that at 50 to 100 meters distance the flux of neutrons on the final mirrors is down to such a low level that the mirrors should last at least one year before their optical quality is degraded. This replacement rate will not compromise the availability of a power plant.

The placement of the optics can be better visualized in the power plant pictured in Figure 9. The lithium waterfall reactor is shown in the center of the building on the right, in conjunction with the liquid metal pumps, heat exchangers, and electrical generation equipment. The laser system is in a separate building on the left, which will lead to lower capital costs and greater ease of maintenance. The laser beams are conducted through underground concrete tubes to the final focusing mirrors that look into the reactor chamber.

Pellet fabrication and injection are also important elements in the power plant. Reactor-grade targets are more sophisticated than simple glass spheres containing D-T gas. In fact, some of the designs are classified because the ideas and techniques used might reveal similar aspects of nuclear weapons design. There is nothing classified about the laser or reactors, however; and I personally believe that there is a good chance classification will cease to be an issue by the time actual electrical power plants are built.

Livermore has thought about automated pellet production in some detail. Imagine suspending the small pellets in an electrostatic field, filling them with D-T gas under high pressure, coating them with different materials, rotating them, hopping each one over to the next coating station, coating it with ablative material, and so forth. Much of the technology involved is very similar to that required for mass producing calculator chips.

Another required task is to recover the tritium and target materials and recycle them, and although we have conceptual designs for accomplishing these steps, a tremendous amount of engineering will have to be done.

The pellets will be injected with a repeating gas gun and tracked with a viewing system. At the last moment, a very small correction will be applied to the beam-pointing direction in order to hit the pellet. This type of tracking and pointing system is within the current state of the art and could be constructed by the optical industry today.

To summarize: We have achieved record-breaking thermonuclear conditions in terms of neutron output and amount of burn. The predictive capability of our theoretical physics and computer modeling is being confirmed and refined by careful diagnostic experiments of laser-induced implosions. We have designed reactor-type pellets with energy gains substantially above 100, which relax both driver-efficiency and pellet-cost considerations. Techniques have been conceived for low-cost, high-volume reactor pellet fabrication, and concepts for long lifetime reactors look attractive. Both advanced lasers and heavy ion beams appear feasible, and many options are being evaluated for development. Experimental facilities are planned that in the early to mid-1980s are capable of igniting high-gain fusion pellets to demonstrate the scientific feasibility of inertial confinement fusion.

In short, the laser program is in the running as a feasible means of producing working fusion power reactors.

*Michael Monsler is in charge of Systems and Applications Studies in the Laser Fusion Program at the Lawrence Livermore Laboratory, University of California. His fields of expertise are high energy lasers and fusion reactors. This article is adapted from Monsler's presentation at the Fusion Energy Foundation conference on energy and jobs in an expanding economy, held in Detroit May 9.*

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# Inside Shiva, The World's Largest Laser

*Fusion Energy Foundation staff member Charles B. Stevens interviewed Dr. Hal Ahlstrom, associate program leader for fusion experiments in the laser department at Lawrence Livermore Laboratory in Berkeley, California last month. His aim was to give readers a sense of what it's like working on the frontiers of fusion technology and what we can expect from the Shiva laser.*

**Question: What is Shiva and what are the goals Shiva plans to achieve?**

Shiva is a 20-beam, neodymium glass, short-pulse (meaning on the order of 1 nanosecond), high-power (meaning it can deliver 15 kilojoules in that nanosecond pulse) laser. The wavelength of the laser is 1.06 microns. And the purpose of the facility is to make progress in the development of inertial confinement fusion for power production and for military purposes.

The initial experiments with Shiva are directed toward achieving the program milestone, significant thermonuclear burn. By that we mean that we expect to produce on the order of several joules of 14 MeV neutrons. The next program milestone...is to implode targets to high fuel densities, typically up to a thousand times the normal liquid density of the hydrogen isotope fuel. That would correspond to 200 grams per cubic centimeter.

**Question: Isn't that something on the order of densities found in the center of stars? Man has never looked at matter under those conditions.**

That's correct.

**Question: So this will be like a space exploration in a certain sense. We are expanding our horizons in terms of the extent of the physical universe we are able to see.**

That's right, and one of the spinoffs of laser fusion research is that you're looking at physics in a different parameter space than has been obtainable in the past.

**Question: You have a fairly large parameter space to examine in laser fusion experiments. Everything from the plasma corona and the ablation layer that is driving the implosion of the fusion pellet—which range over temperatures of millions of degrees—to the very high densities in the core of the pellet. Would you describe**

**what is involved in carrying out one of these experiments?**

The basic targets used today are glass microshells on the order of 100 microns in diameter. These targets are filled with gaseous deuterium-tritium (D-T), the two heavy isotopes of hydrogen. The pellet is placed in the experimental chamber and then laser beams are used to very accurately locate the pellet. Typical accuracies with these locating beams are on the order of several to 10 microns, depending on the size of the pellet. The high-power laser is fired, and the pulses arrive at the pellet simultaneously.

The way to imagine the pulses is as cylinders of light 8 inches in diameter, about 1 foot long, and propagating at the speed of light. They come from opposite directions with the fuel pellet in the center and they are focused by high-quality lenses so that the cylinder of light is turned into a cone of light. When the cone first touches the pellet, on either side, the cone has a diameter about equal to the diameter of the target. But then it extends backward in this conical shape about a foot. Then one can imagine the two cones of light acting like shaped charges. As they collapse onto the pellet, they deliver the energy to the pellet causing the outer portions of the pellet to turn into a low-density plasma.

The laser energy is absorbed and then carried into the fuel pellet by conduction, causing the outer portion of the pellet to expand away from the inner portion like a rocket. Only it's a spherical rocket. You can imagine a whole bunch of rockets lined up in a circle, aimed at one another. You light them off, they go flying at one another, and you have one big collision in the center.

That's what's happening in the implosion. The outer surface is ablated as the fuel drives the inward compression. Then when the material reaches the center, the material stagnates and achieves high densities and high temperatures, generating the fusion reaction.

**Question: What sort of phenomena do you have to measure in the ablating layer and what is the range of measurement?**

There are basically three different layers. The ablation regions, corona where the energy is absorbed, and the compressed fuel.

The only way of probing the ablation region is by looking at the self-emission of the X-rays or using an auxiliary X-ray source to probe that region, because the ablation region is well above the density at which we can use optical probing. One can imagine looking at this complex structure as it is going on with different wavelengths of light. As we go deeper, into the pellet, into the ablation region, and into the compressed core, the only things that we will propagate through there are very short wavelength light or X-rays.

The range over which we observe these light and X-rays is from 1 eV to 50 keV, with special resolutions of 1 micron and timespans of 1 picosecond.

The time scale of the implosion is on the order of 1 nanosecond, but once the core has gotten hot and compressed, its lifetime may be as short as 10 picoseconds. If you want to resolve something about the final phase of compression and the disassembly of the core of the fuel, you would like at least 10 resolution elements. The compressed core of targets that we are presently working with is of the order of 10 microns and again, you would like 10 resolution elements so you need a micron spatial resolution. As you go to a reactor pellet, a reactor pellet compressed core typically will be the order of a couple of hundred microns and its lifetime will be up to several hundred picoseconds. Therefore, the resolution problem gets easier as you go to larger systems.

### Measuring the Density

**Question: The key thing for demonstrating the feasibility of laser fusion is the achievement of isotropic compression, since this is the only way high densities can be reached efficiently. How do you plan to go about measuring these processes, especially in the compressed core?**

There are a number of ways. One that I've already mentioned is using either the self-emission of X-rays from the core or using an auxiliary X-ray source to do flash radiography of the compressed core. Another way of measuring what goes on in the compressed core is to take a spatial picture of the thermonuclear burn.

We do that right now on low-density targets using the alpha particles that are produced in the D-T reaction. The other particle emitted in the reaction is a 14 MeV neutron. And as we go to high-density, high-yield targets, we will be able to photographically detect the neutrons and actually see the structural shape of the burning region of fuel.

Another way of measuring the density of the burning fuel is to use a technique called radio chemistry. If we were to add, for example, a small percentage of argon to the fuel mass, then when the neutrons are born they would activate the argon to a radioactive chlorine state. We could collect the debris and count the number of activated chlorine atoms, and that, along with total yield of the pellet, gives us the density.

**Question: Livermore Laboratory has been in the lead in developing the type of diagnostics used in laser fusion experiments. Everything from streak X-ray cameras to X-ray microscopes. Do these types of diagnostics have applications in other areas?**

An example of the use of one of our developments is the optical streak camera, the basic, standard instrument—the only instrument really—that's capable of measuring the duration of short laser pulses used in other scientific fields. The model-locked dye lasers are used in various scientific measurements and many other kinds of fields. . . .Because of our developments in measuring short-pulse phenomena, we are involving American industry in producing fast recording devices that can be used in any process requiring fast recordings.

**Question: I understand that there have been a number of recent developments in the construction of target pellets, in terms of how cheaply they can be made and the accuracy**

**with which they can be constructed. Could you describe these developments?**

The early target experiments dating from 1974 up to this last year have almost all utilized a simple glass microshell. This was produced in a bulk process and used primarily in industry for wood fillers, reflectors, paints for highway signs, and many other processes. The original method we used was to buy this stuff in bulk lots of gallon cans. Then we would sort them optically and individually to find the particular diameter, wall thickness, and uniformity that would be useful for the target. Then these targets were placed in a tank of compressed D-T gas and the gas was diffused into them.

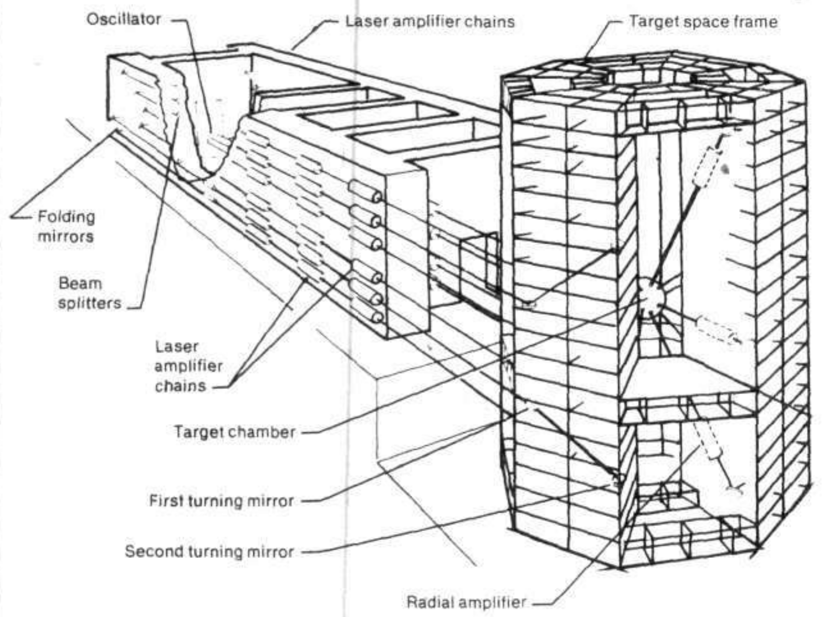
The way we get targets now is to actually make the microshells individually. This is done by our target fabrication group under the direction of Chuck Hendricks. They produce a stream of little spheres of a particular size of the solution to make the glass microsphere. This passes through a furnace where the glass microshell is blown under very careful conditions. These microshells are then coated. We have developed the capability of putting various coatings on them because the requirements for high-density implosion generally require a different material from glass to be used as the ablator and even as the pusher in some cases. . . . The techniques we are now using can definitely be scaled up to production-line techniques to make targets for a reactor, so that we could make them at a sensible cost factor.

**Question: What sort of tolerances are involved in these targets?**

The smoothness of the surface has to be around 3,000 angstroms.

**Question: In relative terms isn't that approximately the height of Mount Everest on the earth?**

That's a good way of comparing it. If you were looking at the earth from a long distance it would be difficult for you to see Mount Everest because you're standing there and you are one ten-thousandth the size of Mount Everest.




*Schematic of the Shiva laser amplifier and target chamber support structure. The laser beams enter from the left and are focused on the target pellet in the chamber at the right.*

**Question: Shiva has already begun to operate with 26 trillion watts on target, hasn't it?**

Yes, we have done three full system shots, one at nearly full power and two others at reduced power. And these were actual target shots where we put one of these glass microshell targets in and irradiated it, producing X-rays and neutrons. The purpose of these early shots is to understand the system performance. That's why after doing one full power shot we backed off to lower powers, because we are just learning how to operate this very large, complex system.

### On Target, On Schedule

**Question: Is Shiva the most powerful system laser in the world?**

The power of the system is actually about 50 times the electrical output of the United States during the billionth of a second it operates.

**Question: Is Shiva working right on schedule?**

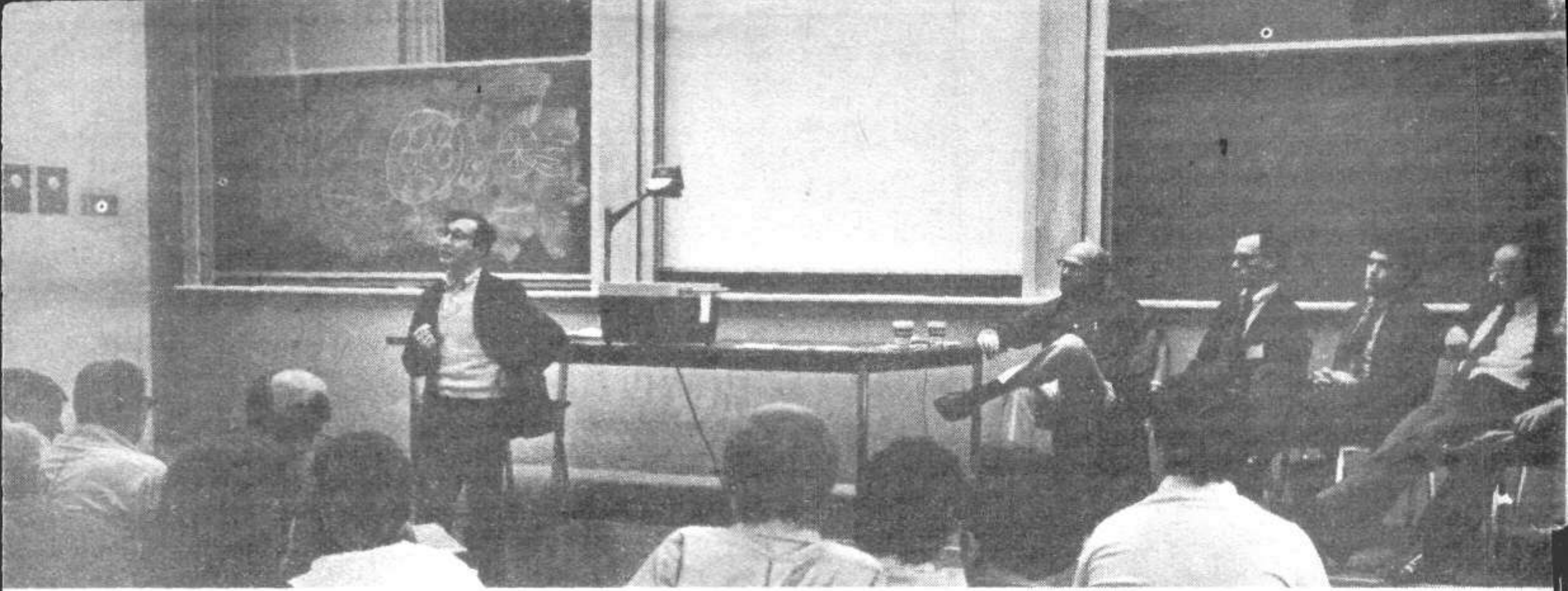
Within a factor of a couple of months, yes. It has been an extremely successful program to date, and we have met or exceeded all of the design goals of the system. We had promised that in one nanosecond pulse that we would be able to produce 10 kilojoules, and our present capability is more like 15 kilojoules; we promised 10 trillion watts in a 100 picosecond pulse, and we have already delivered 26 trillion watts.

**Question: Would you say that you are fairly confident of being able to go to the next step of scientific breakeven if you get the funds for upgrading Shiva into the proposed Nova system?**

We feel very confident that Shiva-Nova will certainly demonstrate scientific breakeven, and our present projections show that we should be able to get gains as high as 20 from the Nova system.

**Question: That would be a long way toward making laser fusion a practical reality.**

Well, the way we view a gain of 20 is that it is scientific feasibility. . . . However, we are quite confident when we have demonstrated a gain of 20 that with more energetic drivers than the Nova, we should be able to produce gains as high as 1,000.



# "The one organization that is really influencing the public is the Fusion Energy Foundation."

William Cornelius Hall
Nuclear News, March 1978

The Fusion Energy Foundation put the Princeton Large Torus results onto the front pages of the world press.

Your Membership in the Fusion Energy Foundation now can ensure that the news of progress in fusion research continues to reach the front pages of the international press. And that there will be commercial fusion power plants within this century.

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# The Princeton Breakthrough Is Only the Beginning

In results hailed around the world, scientists at the Princeton University Plasma Physics Laboratory have broken through the scientific barriers to achieving the temperatures required for continuous thermonuclear fusion reactions. The tokamak pictured on the front cover, the Princeton Large Torus, reached record temperatures of 60 million degrees in July, well beyond the 44 million degrees needed to ignite fusion reactions. Even more important, there were no plasma instabilities or leakages in evidence. The high temperature was made possible by a newly installed neutral beam heating apparatus (below) whose 2 megawatt deuterium beam shot the tokamak's temperature well past the previous record of 26 million degrees.

What does this mean in terms of realizing commercial fusion power? We quote Dr. Stephen Dean, director of the U.S. Department of Energy's division of magnetic confinement; "The question of whether fusion is feasible from a scientific point of view has now been answered. It's the first time we've produced the actual conditions of a fusion reactor in a scale-model device."

The details of the science and the politics of the Princeton story are the main feature in this issue. And as Charles B. Stevens and Dr. Steven Bardwell report inside, the best is yet to come. There is an exciting lineup of fusion breakthroughs expected in the next few months from a variety of tokamak machines. Furthermore, as a feature article on the Lawrence Livermore Laboratory's Shiva laser makes clear, the tokamaks have some good competition: laser fusion research is now on the verge of demonstrating the conditions necessary for economical energy production by the year 2000.

*Cover design by Christopher Sloan. Illustration courtesy of Princeton Plasma Physics Laboratory.*