FUSION

MAGAZINE OF THE FUSION ENERGY FOUNDATION

November 1978

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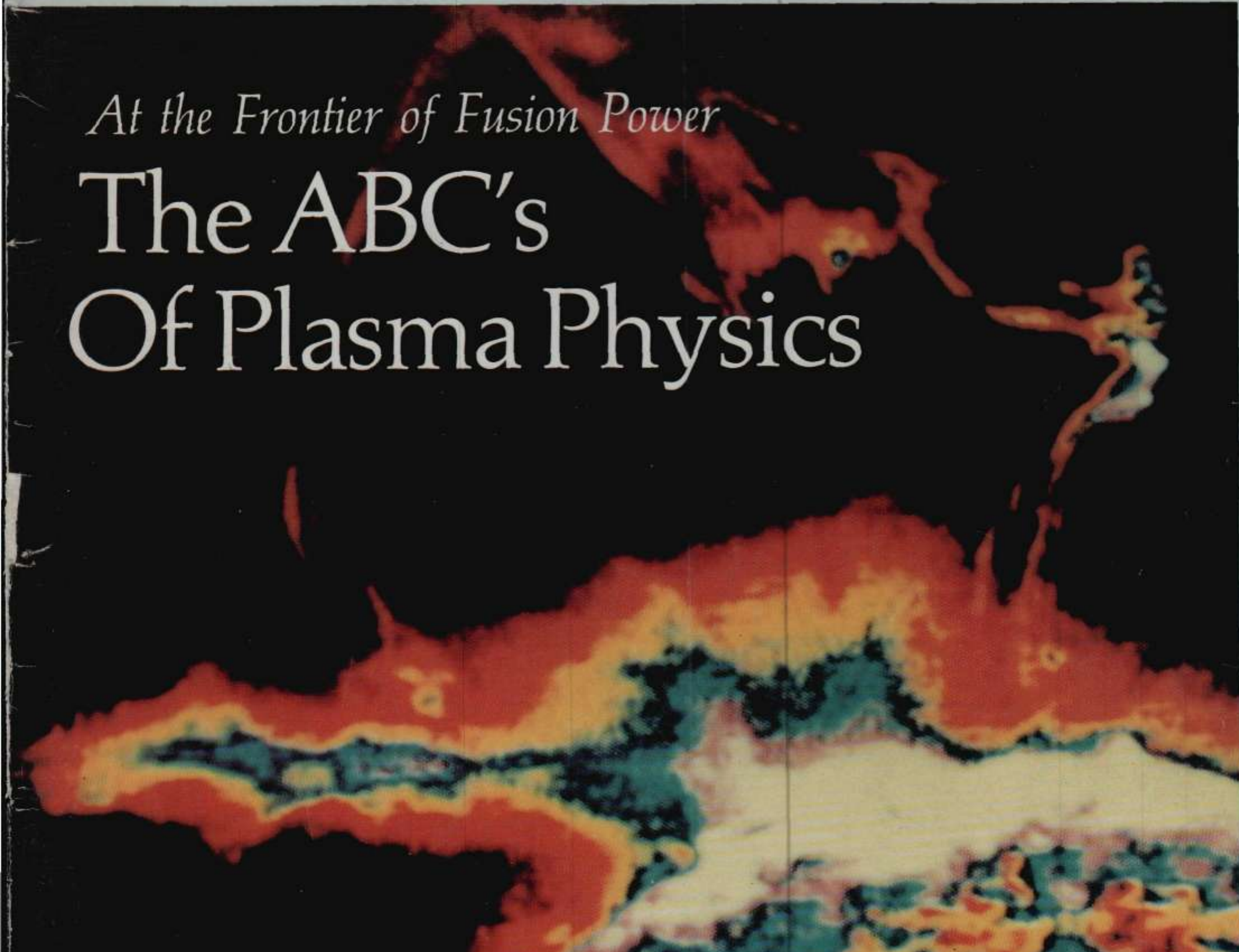
At the Frontier of Fusion Power

The ABC's Of Plasma Physics



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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.

Special Report

Features

News

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Editorials

The Energy Bill passes Congress

The Historic Role Of the FEF

The Sept. 23 meeting of the Fusion Energy Foundation's board of directors marks a major branching point in the life of the foundation. We will not review here the FEF's remarkable history and record of achievement. That is documented amply enough in a recently published 35-page report, "FEF Review and Prospectus 1977-1979," which is available to members and other interested persons.

The main question to address is the future. By this we do not mean the 10 to 20-year horizon, over which we can begin to see the shape of a world being transformed by the onset of fusion power and plasma technology. We mean the next few months to a year. First, our nation and the world must survive—and survive in the proper shape to usher in the fusion era.

This is where the role of the FEF is indispensable. In order to get the federal government and the nation as a whole aligned behind the necessary high-technology export and energy policies and advanced research and development (as opposed to the twin lunatic poles of "appropriate technology" and "fiscal conservatism"), the United States needs an institutional focal point for that policy now. The FEF is uniquely suited to provide a locus that will coordinate efforts by leading individuals in corporations, laboratories, universities, and civic groups to fight for a policy of economic growth.

First, the FEF is tax exempt. Therefore, it can accept large-scale contributions at little or no real cost to the donor. Second, it combines the best all-around scientific and technological competence in the nation with an international perspective on research, development, and investment.

Taken together, this means that "investment" in the FEF by individuals and corporations in the private sector on the order of $10 million to $100 million, combined with parallel policy initiatives in the larger political and economic arenas, would set in motion an irreversible tendency to restore U.S. global economic and scientific leadership.

The FEF Program

What would the FEF do with this level of funding? Working with top caliber collaborators, we would accomplish at least the following tasks:

(1) Provide crucial studies on the economics, technology, and detailed construction techniques for nuplex-based cities of various sizes as the main export item of the advanced sector. These studies would include full integration of capital goods and frontier technology capabilities for the advanced sector

and infrastructure and educational development programs for the developing sector. This not only would open the door to immediate large-scale technology transfer projects in the range of $10 billion to $100 billion, but also would pave the way for trillion-dollar markets in the medium term.

(2) Develop pilot projects for qualitative improvement in training the most qualified scientists and technologists. This would set the stage for breaking the scientific manpower bottleneck, and for launching the waves of scientific breakthroughs required for full global development. The key conception here is to provide an internship during which promising corporate and academic scientists and technologists approach science training and upgrading from the standpoint of breaking through the present theoretical obstacles to necessary technological advances. As we have described elsewhere, the internship would use the most advanced viewpoints developed in science—the actual humanist basis for science—instead of the standard textbook axiomatics.

(3) Launch a "grand hydrodynamics" project integrating FEF, corporate, and academic experts for fundamental investigations in the crucial research areas of ultraefficient fusion processes, desalination hydrodynamics, hydroponics, and climatology. This research is a necessity for providing the required resources in raw materials and water as well as the knowledge adequate for control of the global biosphere. It will prepare us to develop a world economy and nuplexes with energy throughput and productivity greater by orders of magnitude than those we now plan.

(4) Fund and bring to the crucial testing stage numerous new and existing fundamental research projects in the physical and biological sciences that crack the paradoxes posed in comprehension and control of nonlinear plasma processes, particle physics, low-temperature physics, and genetic and cellular biology (especially with respect to embryology and aging and their connections to evolution).

The United States can integrate itself into the massive trade, development, and high-technology deals now being launched in every major world sector in order to avoid war and end economic depression—if the FEF gets the necessary financial support and if the various progrowth forces begin to move along the lines indicated here. Only with a full commitment to the FEF and its research and education program can humanist forces in the United States regain their rightful control of the nation's destiny and the American republic's rightful place of world leadership.

Some Plain Facts About Energy

While most of Congress was mentally "out to lunch" at the end of the congressional session, the nation was saddled with a no-energy energy bill so pathetic that it has the rest of the industrialized nations wondering when the United States will return from Disneyland. In fact, it is probably the first time in U.S. history that Congress has so stupidly legislated against the concepts of progress and high technology upon which the nation is based—and for which most of the world is still fighting.

According to their own words, many usually responsible congressmen voted up the administration's energy bill with the rationalization that once the Schlesinger albatross was out of the way, Congress could move on to a serious discussion of a policy for energy production. It was necessary to help the Carter image internationally, they said.

This was a grave miscalculation. Because of it, Americans will now have to suffer through new waves of the kind of conservation propaganda that Schlesinger and the zero-growth faction have tried so long to promote—the glorification of windmills, wood burning, and the hardships that were everyday life 200 years ago.

Furthermore, the no-energy bill spells out clearly to the nation's allies around

Continued on page 4

Calendar

November

1-3
4th DOE Statistical Symposium
DOE
Albuquerque, New Mexico

6-9
6th Water Reactor Safety Research
Information Meeting
Nuclear Regulatory Commission
Gaithersburg, Maryland

6-9
Energy Technical Conference
ASME
Houston, Texas

6-10
International Symposium
On Water Reactor Fuel Element
Fabrication with Special Emphasis
On Its Effects on Fuel Performance
IAEA
Prague

9
A High-Technology Energy Policy
For the U.S.
Fusion Energy Foundation
Pittsburgh

12-17
American Nuclear Society
Winter Meeting
Washington, D.C.

13-17
IAEA/NEA International Symposium
On the Decommissioning
Of Nuclear Facilities
Vienna

13-15
1st AEE Annual Energy Conference
Association of Energy Engineers, Inc.
Atlanta, Georgia

14-17
Magnetism and Magnetic
Materials Conference
IEEE
Cleveland, Ohio

28-29
3rd International Conference
On Welding in Nuclear Engineering
Deutscher Verband fuer Schweisstecnik
Hamburg

Continued from page 3
the world that the U.S. Congress does not understand why the export of nuclear technology is the only economic development program that will get the dollar and the U.S. economy out of its depression.

The plain facts are that you can't meet energy needs without nuclear power. Without the breeder reactor to replenish nuclear fuel supplies, there is no sound basis for nuclear power. And without the infrastructure of the nuclear industry, there is no feasible basis for the transition to the fusion era.

Conversely, without a definite commitment to an aggressive, sound fusion development program, there is no adequate basis for the necessary use and depletion of existing forms of energy resources and technologies.

This means that the nation has a twofold problem to solve: First, to define a competent fusion research and development policy; second, to make operational a strategy for implementing this fusion R&D policy along with a rational energy policy.

The ABC's of fusion bear repeating. The fact that fusion is quantitatively an unlimited energy source is only secondary; the primary significance of fusion is qualitative. It represents an open-ended process for transforming energy generation and resource extraction. In other words, the forms of fusion energy can be continuously made more efficient and productive, at the same time that high-temperature, energy-dense plasma technologies—like the fusion torch—will open up the resource base without any forseeable limit. For this reason, fusion development is the indispensable strategic core of world development.

The crucial relationship of fusion to world development defines the appropriate political approach to a national energy policy. Americans who want a U.S. energy policy oriented to growth and production must align themselves through the relevant institutions with the international forces who back the Grand Design for global development. At this point the leading spokesmen for the Grand Design are Prime Minister Fukuda of Japan, Chancellor Schmidt of West Germany, and President Lopez Portillo of Mexico. For each of these world leaders, the dominant theme has been the linkage of oil to fission to fusion as the only road for human development. For the whole world, these leaders are saying, human progress is our most important product.

The Fusion Guarantee

The subject of human progress leads us back to the fusion program. The required policy is as follows: Shoot for the initial first-generation commercial fusion reactor in the 1990s. Begin the full engineering backup of a tokamak reactor now—a tokamak because of the advanced state of that device and because most of its engineering features have universal application to all fusion devices. Simultaneously, fully test all other magnetic and inertial confinement approaches through large scale-up experiments and smaller scale scientific backup research consisting of numerous "overlapping" investigations of details of macroscopic or microscopic device behavior. Finally, provide full support for basic plasma research in universities and elsewhere and begin to set up regional basic research centers for logistical support.

This kind of fusion program guarantees convergence on viable solutions to the first fusion reactor, opens up fruitful areas of investigation for more advanced and efficient reactors and spin-off plasma processing technology, and, most important, ensures the steadily expanding production of trained scientific manpower.

The cost of such an effort would be in the range of $1 billion a year, rising quickly to the $4 to $6 billion annual range, then leveling off in the reactor development phase at about $10 billion annually, later in the century. This could easily be paid for through international collaboration and with the expanded income base that will result from an increase of $100 billion in high-technology U.S. exports, centering initially on the nuclear and nuplex capital goods sectors.

The nation can afford nothing less.

Letters

SHIVA AND FISSILE PELLETS

To the Editor:

In the August 1978 *Fusion* the article on the status of fusion energy mentions the very interesting fact that Shiva laser fusion experiments [at Lawrence Livermore Laboratory] will test "the compression of fissile microspheres" (page 38).

You are right that there is little public information about that subject. However, there are publications on the subject matter, not from the U.S. but from us. For your information I enclose a copy of our first publication

The Lightning Rod

My dear friends,

What was in my youth a healthy disdain for the trappings of aristocratic polich seems nowadays to have sunken to a penchant for well-staged exhibitions of stupidity. Or so it seemed to me as I glanced back and forth from the *Washington Post* (the Other Newspaper still being unavailable) to the scenery shooting past the window of the railroad car, unable to bear but a few lines at a time covering the passage of the Energy Bill.

To my utter astonishment, who should appear striding down the aisle but my rustic farmer friend Richard, two years ago. . . and in the next issue of *Atomkernenergie* a review article will be published.

Do you have further information about these experiments on the Shiva-facility? As far as I know all pellet designs containing fissile materials are still classified. A few years ago we had a rebuttal in *Nuclear Science and Engineering* with the Livermore people about the energy release in microfission explosions, and the Livermore people were relatively pessimistic. Therefore, I am really astonished to see that such experiments are now planned. . . .

Dr. W. Seifritz
Head, Physics Department
Federal Institute of Reactor Research
Wuerenlingen, Switzerland

The Editor Replies

I am quite familiar with your most interesting research. I first came across your work at the June 1974 American Nuclear Society annual meeting in Philadelphia where Dr. F. Winterberg gave a presentation on your work. At this meeting I obtained a preprint of the article on "Laser-Induced Thermonuclear Micro-Explosions Using Fissionable Triggers" by you and Dr. J. Ligou, which you mention in your letter.

The section in my article to which you refer (page 38, Vol. 1, No. 10) contains an error of omission. The sentence should read as follows: "One of the more interesting experiments to be carried out on Shiva Nova, although one for which there is little public information, is the compression of fissile microspheres." The name Nova, which refers to the major upgrade of the present Livermore Shiva laser scheduled to be completed in the early 1980s, was inadvertently left out.

My sole source of information on these proposed fissile microsphere targets comes from the publicly available Lawrence Livermore Laboratory *Laser Program Annual Report—1976* (UCRL-50021-76), which is available from the National Technical Information Service in Springfield, Virginia. The particular passage in this report on which I based my observation on fissile fusion targets appears in section 7-6, "National Security Applications." The section reads as follows: "Either the high explosive or the fissionable material will be simulated to preclude nuclear yield. Because Shiva Nova II will accommodate target pellets that incorporate fissionable materials, remote-controlled radioactive disposal systems are already part of the design."

As for the classification issue you raise in your letter, I know that the majority of the scientists in the Livermore inertial fusion program sincerely desire to have the security classifications removed from most aspects of this most important research. Dr. Edward Teller has most emphatically spoken out on this issue on numerous occasions. And the fact that Dr. Vincent LoDato in the United States has been permitted to publish his work on fissile targets (see *Atomkernenergie* 1976, 1977) indicates that there is movement in this direction.

The "rebuttal" by Livermore scientists to which you refer in your letter is probably quite correct in terms of how much the Livermore scientists are permitted to state on this question in public. There are a number of areas along these lines, however, that point toward more fruitful designs; but these are currently classified and Livermore scientists are not allowed to speak publicly about them. For example, the report of the Electric Power Research Institute, "Proceedings of the Review Meeting on Advanced-Fuel Fusion" (ER-536-SR), states on page 153: "A paper by L. Wood [of Lawrence Livermore] was withdrawn due to classification difficulties." The paper was titled "Laser-Fusion Employing Direct Nuclear Pumped Lasers and Advanced Fuel (D-D-T) Pellets."

Charles B. Stevens
FEF Director of
Fusion Engineering Studies

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bearing a chicken beneath each arm. Barely had we greeted but he began an animated chatter.

"What do you think of my new energy bill?" he asked as he settled his hens upon my flattened newspaper. Diplomatically, I replied that I had not known it to be *his* bill, instead presuming we would all suffer equally under it.

"Oh no, it *is* my energy bill. . . . I've been in on all the consultations. . . I'm headed for the Department of Energy this morning. . ." he continued. Of a sudden, the scales fell from my eyes and I knew him to be speaking the truth.

"Of course you and not Sec. Schlesinger are the author of our new energy bill," I cried, "why, even in 1760 you argued for the marginal equivalence of saved pennies and earned pennies."

A smile of triumph broadened across his face. "Yes, but I have gone beyond that now. I have convinced the Congress that inflation must be fought by raising oil and natural gas prices. This is in line with the proposition I authored for Federal Reserve head Miller, to launch economic recovery by collapsing our American dollar. My reasoning was similar to the Kissinger doctrine that peace results from continuous war confrontations. It's all quite commonsensical."

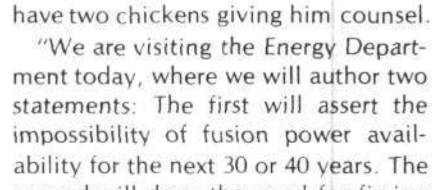
Poor Richard had grown quite agitated, so I attempted to shift the conservation by remarking upon the plumpness of his two fine hens.

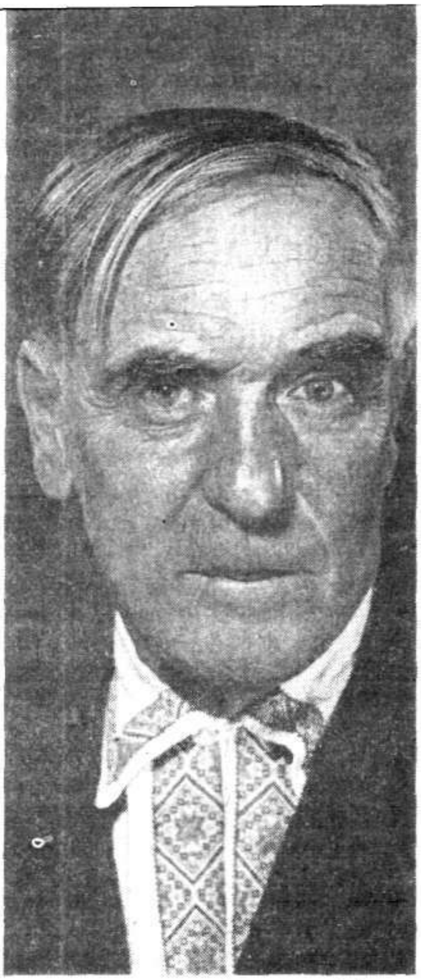
"Hens? Oh, you mean my advisers." I was momently taken aback, but reflected that, if two myna birds can run for mayor of Toronto—as they presently are—Richard could indeed have two chickens giving him counsel.

"We are visiting the Energy Department today, where we will author two statements: The first will assert the impossibility of fusion power availability for the next 30 or 40 years. The second will deny the need for fission development, citing the imminent availability of fusion energy."

I deemed his the better use of my *Washington Post*, and left for the adjoining car.

Yr. Obt. Svt.,





Nobel Prize laureate Peter L. Kapitza

News Briefs

ENERGY BILL SQUEAKS THROUGH CONGRESS

President Carter's energy bill finally squeaked through Congress, just before the mid-October adjournment. Within 48 hours, the U.S. stock market dropped 30 points and the dollar plunged to all-time lows against the German mark, Swiss franc, and Japanese yen—destroying Carter's claim that passage of the bill was vital to the U.S. economy.

The centerpiece of the bill, the so-called phased deregulation of natural gas worked out by Energy Secretary Schlesinger and Senator Henry Jackson (D-Wash.), will raise gas prices continuously until 1985, thus contributing to inflation at the same time that it creates a regulatory labyrinth of 17 categories of natural gas.

Although the final bill does not include the crude oil equalization tax, an antiindustry utilities pricing policy, mandatory conversion of plants from oil to coal use, an additional tax on gasoline consumption, or other features of Schlesinger's original program, the bill's grab bag of tax credits for home insulation, coal conversion, solar energy, and other wasteful gimmicks add up to a package perfectly coherent with Schlesinger's strategy of enforcing zero growth in U.S. energy production and consumption. As the *Washington Post* put it, the bill represents "a national commitment to conserve."

P. L. KAPITZA RECEIVES NOBEL PRIZE

Peter L. Kapitza, the nuclear physicist known as the grandfather of the Soviet fusion program, was awarded the Nobel Prize this month for his work in low-temperature physics. Kapitza, 84, works at the Institute for Physics Problems in Moscow.

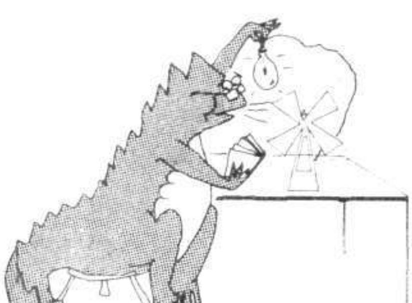
Among Kapitza's many important contributions are his discovery of superfluidity, his development of the concept of energy density, and his invention of liquid helium and the liquid air generating turbine, now used throughout the world. [For a discussion of Kapitza's work in superfluidity, see *Fusion*, March 1978.]

JAPANESE FUSION SCIENTISTS DEVELOP NEW HEATING TECHNIQUE

Scientists at Japan's Institute of Plasma Physics at Nagoya University have drastically raised the temperature of hydrogen plasma in a torus fusion device, using a new technique called "simultaneous heating." The Nagoya team achieved a temperature of 5.68 million degrees in the JIPP-T2 torus device by bombarding the plasma simultaneously with hydrogen particles and a radio frequency.

The latest results of the team show that the particle beam and the radio waves act synergistically, raising the plasma temperature to a higher level than either method achieves alone. Each method had been used alone successfully, but there was uncertainty whether the two methods together would reinforce each other or cancel each other out.

The *Mainichi Daily* Sept. 26 reported the success with simultaneous heating in an article titled "Advent of Nuclear Fusion Draws Near." It is "a step toward achieving . . . 'solar furnace' temperature and raises hopes for the success of the JT-60, a mammoth critical-plasma experimental assembly now under construction," the paper said.



LOUSEWORT LAURELS TO BRITAIN'S JUDITH HART

This month's lousewort laurels go to Judith Hart, Minister of British Overseas Development, who recently commissioned a special study on windmills as part of a government project to develop small-scale alternative sources of energy for Third World villages. "They need low-cost renewable sources of energy appropriate to village economies," said Hart.

Hart claims that the British have a prototype windmill that produces 30 kilowatts—when the wind blows. At this rate, it would take 33,333.3 windmills to generate the same amount of power as one nuclear or coal reactor.

Washington

Congressmen Criticize Go-Slow Fusion Budget

Just three days after the U.S. Department of Energy submitted its 1980 fiscal year budget recommendations to the Office of Management and Budget, the DOE's go-slow fusion budget came under attack in Congress. In Sept. 18 hearings before the energy subcommittee of the House Science and Technology Committee, congressmen grilled DOE representative John Deutch, assistant secretary for energy research, and called for an Apollo-style fusion program.

"If we were able to reach the moon within 10 years and harness atomic energy in World War II, why can't we develop fusion in the next five to seven years?" Congressman Robert Roe, a New Jersey Democrat, asked Deutch.

The DOE budget request for fusion, which Deutch defended, barely keeps up with inflation. A $35 million increase is proposed for the magnetic fusion budget, bringing it up to $365 million. (Inertial fusion is now part of the Defense Department budget.) In contrast, the proposed solar budget is nearly doubled, to a total of more than $700 million.

According to Deutch, who called fusion a "long shot," the United States will not make a decision on design for a fusion engineering test facility until 1984. Once a magnetic confinement system is selected, a test facility might come on line by 1992, Deutch said.

Congressman Roe told Deutch: "It's logical that we have a crash program. I look at Dr. Deutch's chart for $18 billion by 1997, and that's not enough money—we'll be 50 to 100 years behind."

Tennessee Democrat Albert Gore, Jr. who seconded Roe's call for a crash fusion program, stated: "The Princeton breakthrough demonstrates certainty that this can be developed. From the testimony today [referring to Dr. Melvin Gottlieb, head of the Princeton Plasma Physics Laboratory, and Dr. Edwin Kintner, head of the DOE Fusion Office, who had both emphasized the feasibility of fusion] it is clear that we can allocate the resources now."

An International Push

The U.S. go-slow fusion schedule may be jolted into a faster timetable by the speed of the international fusion effort.

The leaders of the world fusion energy programs who decided in a June meeting to move forward on the Soviet proposal for a joint experimental fusion tokamak are meeting again in mid-November in Vienna. According to *Nucleonics Week* Sept. 21, the group intends to put an international test facility, named Unitor, on line in 1988, and the meeting will discuss the best reactor design.

The international project was proposed early in 1978 by Soviet fusion scientist E.P. Velikhov, who suggested that the European nations, Japan, the United States, and the Soviets work together to construct a reactor under the aegis of the United Nations International Atomic Energy Agency.

When asked if this international push for a demonstration fusion reactor will have any effect on the U.S. fusion timetable, one DOE official replied: "We're banking on it. The view of the fusion office is that the results expected from the current experiments, plus the progress made in the international area, will cause a

Senators Call for UN Energy Conf.

Senators Charles Percy and George McGovern, with backing from the U.S. State Department, have convinced the United Nations Economic and Social Council, UNESCO, to hold a "Conference on Alternative Energy Sources" by 1981.

The senators define alternative energy sources as "sun, wind, and natural processes of photosynthesis and the tides and temperatures of the oceans and the seas."

According to Senator Percy, the developed and developing nations need to sit down together and discuss the ability of alternative energy sources to solve the world energy problem. The goal of the conference would be to establish an international alternate energy commission, under UN auspices, to encourage the worldwide use of alternative energy sources by providing information and other assistance. The proposal will be introduced at the 1979 UN Science and Development Conference in Vienna.

reevaluation of the DOE's timetable for fusion, within the next year."

The budget cuts and budget stagnation translate directly into program delays. Fusion scientists in the DOE and in the fusion program have noted that if design work is not begun soon on a demonstration reactor, the United States will not be able to catch up to the international fusion effort.

Scientists in the DOE had hoped to begin design studies and consideration of the next stage in the tokamak program in the fiscal year 1980, but the DOE has not allocated any money to begin these studies. Deutch and the DOE leadership have insisted that nothing can be done on the next generation of fusion experiments until the TFTR, the tokamak fusion test reactor now under construction at Princeton, is completed and has produced some results. Scientists in the fusion program, however, have said that they are confident enough in their ability to solve any remaining problems to warrant going ahead with a post-TFTR machine.

Postponing Difficulties

The test facility is just one of the projects that DOE budget cuts have relegated to the distant future. At the annual meeting of the Fusion Energy Foundation board of directors in New York City Sept. 23, Dr. John Clarke, deputy director of the DOE Fusion Office, commented: "If you take inflation into account...the total amount of funding is decreasing.... I think in our 1979 budget there are, at last count, $50 million worth of items that we would love to do that we're going to put off for the future years because we don't have enough money....The difficulty comes...in 1981, after the TFTR. What is happening here is that we're postponing the difficulities...."

In the DOE's proposed 1980 budget, the funding levels for all advanced technology are cut, or at best stagnant. The proposed funding level for fission development is exactly the same as the previous year, which amounts to an absolute cut, when inflation is taken into account; and the budget for magnetohydrodynamics in coal research is slated for an actual cut of over $10 million.

Giscard (left) and Schmidt: Leading the fight for high technology.

International

France, West Germany Push Nuclear Technology

In a four-day visit to Brazil in early October, French President Valery Giscard d'Estaing reaffirmed the role of France and West Germany in the transfer of nuclear technology to the Third World. Giscard, who signed a broad scientific cooperation treaty with Brazil, commented that although France lacked the immense natural resources of Brazil, "...fortunately, the progress of science and technology offers the men of our times other, nongeographical frontiers.... France is among the three countries of the world that guarantee developing countries all the technologies of the nuclear cycle, from fuel to reprocessing."

Giscard and West German Chancellor Helmut Schmidt are leading the political fight to implement the European Monetary Fund, a $50 billion gold-backed development bank that would center on high-technology transfers. The fund includes cooperative development deals with Japan, the Soviet bloc nations, and the Arab nations, and these countries are now working out details of specific joint projects. Although the fund backers have made their support for the dollar explicit, the United States has been conspicuously absent from the ongoing discussions.

At a summit meeting Sept. 15 in the Franco-German city of Aachen, Schmidt and Giscard reached agreement on the fund and set up a three-part joint program for border cities that includes a nuclear fission plant, a scientific-economic university, and an aerospace program. The fission plant, to be built on the Moselle River, will symbolize both nations' commitment to nuclear energy, the two leaders said.

Fukuda Renews Call for Joint Fusion Development

Japanese Prime Minister Takeo Fukuda opened a special session of the Japanese parliament Sept. 23 with a call for a "new era of technological innovation," in particular the development of fusion energy.

Praising the "comprehensive strategy" for trade and development discussed at the July meeting of major industrial countries in Bonn, West Germany, Fukuda said that for these international efforts to be successful, "it is essential that the dollar be stable as the key currency."

"In order to ensure a bright outlook for the 21st century," Fukuda said, "we must bring together the wisdom of all nations and realize a new era of technological innovation.

"We cannot afford to sit idly resigned to the limitations on mankind from the finiteness of our resources. In order to respond positively to this task, we must promote science and technology, seek the rational utilization of resources, and advance the development of new energy forms. . . ."

"I think we should set ourselves the target of commercializing nuclear fusion by at least the early years of the 21st century. I intend to institute comprehensive policies including the expansion of our research investment and to seek dramatic advances in research and development.

"International cooperation is essential in this task. Especially with regard to Japan-U.S. cooperation, it is our policy, as was agreed upon at the recent Japan-U.S. summit meeting, to vigorously promote Japan-U.S. joint research in nuclear fusion and other new energy fields.

"I believe the creation of new fields of development through the promotion of science and technology will be a fresh goal for the people as we approach the 21st century and at the same time is one of the areas in which Japan can best contribute to the progress and development of mankind...."

Top Priority

In May Fukuda proposed to President Carter a joint fund of up to $1 billion for the development of advanced energy resources, with fusion as the top priority. The United States has now agreed to the fusion priority, and the details of the joint research project are under discussion.

Japan recently announced that its 10-year energy plan allocates $4.7 billion to fusion and the development of high-temperature fission reactors, a sum that brings the Japanese fusion budget close to U.S. levels. In the past month, Japanese fusion scientists also announced new records in plasma confinement time and temperature.

UN Forum Says Technology Is Hazardous

The main speakers at the Sept. 25-29 forum on Science and Technology for Development at the United Nations headquarters in New York concluded that technology, science, and industrial development were bad for the environment.

Sponsored by the UN nongovernmental organizations, the conference was scheduled to discuss how to apply technology and science to the Third World, yet this crucial issue never was addressed. Instead, the main themes were "small is beautiful," decentralization, and horizontal income redistribution (share the poverty)—in short, the zero-growth programs of the World Bank and the International Monetary Fund. Speakers emphasized the need for greater population control, the preservation of the environment, and so-called basic needs.

In the opening conference presentation, Dr. Russell Peterson, director of the U.S. Congressional Office of Technology Assessment, claimed that there were only two choices for energy systems—solar or nuclear. Since the sun is nuclear, he said, why bother to bring it to earth.

As an alternative to high technology, conference panelists promoted what they called appropriate forms of technologies that would not damage the environment of the underdeveloped nations. The country often given as an example for appropriate technology was India, ironically, the leading Third World nuclear power. The director of the Bombay Urban Development Institute told the UN audience that 15 percent of India's energy could come from biomass (dung), and the rest from solar sources.

Conference participants included various environmental groups, the Population Council, the World Bank, the International Institute for Environment and Development, the World Society for Ekistics, the Council of International and Public Affairs, and the Bahai religious group.

This picture, whose caption asserts that "indigenous people" like these "are being thrown to the winds," illustrates an article titled "Development Against People" in the July 1978 issue of the UN Development Forum *newsletter.*

Despite the fact that the audience was receptive to the zero-growth rhetoric, conference organizers said they were skeptical that any of their proposals would be accepted by the UN General Assembly. Most of the Third World delegates at the UN who are the intended victims of the appropriate technology schemes are aware that per capita energy use is directly related to standards of living and have pinned their nations future on high energy use and high technology.

The forum is one of several events planned before the major UN Conference on technology transfer in August 1979 to give prominence to the zero-growth idea that the developing sector must fight the industrialized sector for a larger share of an increasingly smaller pie.

Brazil's Nuclear Plan Assailed

The head of Brazil's nuclear program and a number of Brazilian cabinet members joined West German nuclear industrialists to refute charges leveled against the Brazilian nuclear program by the Sept. 16 issue of *Der Spiegel* magazine, a West German weekly.

Der Spiegel's allegations against the nearly complete Westinghouse-built power station and other West German-built projects in Brazil included charges that the nuclear plants will cause ecological damage, claims that Brazil does not need nuclear energy, and allegations that several Brazilian government officials had been bought off by nuclear contractors.

The Brazil-West German Nuclear Agreement is one of the best examples of an advanced industrial country providing full transfer of the most modern technology to a developing country. For this reason it has come under continuous attack from the zero-growth faction.

Paulo Nogueria, president of the Brazilian state nuclear agency, answered the specific charges and told a Sept. 19 press conference that the *Der Spiegel* piece "demonstrates that there is a campaign designed to harm the Brazil-German Nuclear Agreement and the Brazilian nuclear program itself." *Der Spiegel* "always has held a position against the peaceful use of nuclear energy, and thus is also against the present West German government," Nogueria said. He also noted that the attack on the nuclear program was geared to provide ammunition for the antinuclear candidates in the coming national elections.

Happy 20th Birthday NASA!

The National Aeronautics and Space Administration (NASA) is celebrating its 20th anniversary in October. Although budget-slashing and cost-cutting have reduced NASA to a shell of the agency that achieved the 1960s pioneering breakthroughs in space technology, NASA at its height was a model for the kind of organization that must be created to realize a national commitment to a technological goal.

When mandated to put a man on the moon in ten years, NASA did it in nine. In the process, it trained 5,000 scientists, created 32 laboratories and research institutes, and coordinated the activities of more than 20,000 high-technology companies. Substantial side benefits of the program included the proliferation of solid-state and miniaturization technologies in electronics, which have had an immense effect on global communications, making possible satellite systems for weather monitoring and resource assessment.

"The obvious lesson to be learned from NASA is that once the national commitment to a technological achievement has been made, the United States has the know-how to carry it through," Fusion Energy Foundation executive director Dr. Morris Levitt remarked in honoring NASA's birthday. "At this time the need is for a commitment to the development of controlled thermonuclear fusion power to provide virtually unlimited energy in the near future. FEF university affiliate organizations will be organizing public meetings to commemorate NASA's anniversary and publicize the need for an Apollo-style program for fusion."

In its Oct. 2 attempt to ridicule the FEF and the Labor Party, Business Week *advertised the fact that the organizations were growing and that they were firmly committed to the American Way of growth, high technology, and progress.*

Business Week Warns Against FEF, Progress...

The Fusion Energy Foundation and the U.S. Labor Party came under the hatchet of *Business Week* magazine Oct. 2 in a three-page lead feature in the economics section that derides all the ideas both groups stand for—from the grand design for world development to nuclear power.

The unsigned *Business Week* article is a lesson in bad black propaganda. Ostensibly it was written to warn readers away from organizations that advocate progress and "big is beautiful." Yet the article's appearance has sparked new interest in the FEF and the Labor Party among industrialists and other *Business Week* readers who were excited to learn that at least a few people are organizing around specific programs to advance humanity.

As for some specifics, we quote *Business Week*: "The rapid development of nuclear power is the primary means to achieve rapid economic growth, says the USLP. To promote this view, the NCLC [National Caucus of Labor Committees, the parent political organization of the USLP] was instrumental in establishing the Fusion Energy Foundation. While the FEF was granted preliminary tax-exempt status, there are questions about its independence from the NCLC. . . . Harvey Kahn, editor of *The Public Eye* and a long-time NCLC watcher, argues that there is 'complete overlap' between the FEF's board and the NCLC's executive committee."

[A quick look at the list of FEF board members shows this to be a lie.]

The key to understanding the libelous article is understanding who Harvey Kahn is.

Kahn, who admitted that the *Business Week* piece was prepared largely with his collaboration, is a long-time environmentalist and terrorist supporter. The same week that the slander appeared, Kahn was the featured speaker at a Michigan conference of the Committee to Stop Government Spying, which included a Black Liberation Army proterrorist and Attorney William Kunstler, defender of Baader Meinhof terrorist Kristina Berster.

The explanation for a supposedly staid weekly suddenly embracing the likes of Kahn? Labor Party chairman LaRouche noted that once William Wollman, *Business Week* editor lined up with the British monetary faction against the European Monetary Fund, he "jumped into bed with the economic policies of the British-Canadian gang that control terrorism." "In this kind of a fight," LaRouche noted, "if you crawl into bed with . . . that crowd, you buy that crowd's whole package. . . . You tolerate their scummy environmentalist and terrorist operations."

FEF Board Member Replies

In an Oct. 2 letter to the editor of *Business Week*, William Cornelius Hall of the FEF board of trustees challenged the weekly to publish a factual story on the FEF: "FEF is exactly what its name implies," Hall said. "All board members are highly qualified professional people. What you have written is so far from the fact relative to FEF that it is only fair that you objectively investigate FEF and report your findings to your readers."

Hall, who has published widely on nuclear power and the structural design of reactors, is the president and chief scientist of the Chemtree Corporation.

Just to make sure readers understand that *Business Week* has planted itself firmly in the antiprogress camp, the magazine featured on its cover the following week a lead article on the solar power boom.

Maryland Energy Conf.

U.S. Must Join European Fund

The only way to cure the economic ills of the U. S. coal region is for the United States to link up with the European Monetary Fund, Maryland State Delegate Casper R. Taylor, Jr. told the Mid-Atlantic Energy and Economic Development Conference Sept. 26 in Cumberland, Maryland.

The conference, which attracted 100 regional businessmen and industrialists, was sponsored by the Allegheny County Economic Development Company with the participation of the Fusion Energy Foundation and the Office of Fusion Energy of the U.S. Department of Energy.

In his keynote address, Taylor stated: "As part of the recent Bonn agreements, our European allies are presently consolidating a new monetary fund, the European Monetary Fund, whose stated purpose is to support the dollar through channeling the billions of dollars involved in the Eurodollar market and in OPEC oil dollars back into the United States through the purchase of American technology."

Taylor is the first elected official to call for U.S. support of the European Monetary Fund.

Specifically, said Taylor, what western Maryland and the Appalachian region need is a national commitment to develop advanced magnetohydrodynamics coal technology (which would maximize energy output from coal) in the short term and thermonuclear fusion energy for the future.

Stressing the history of the "idea of progress" throughout his speech, Taylor continued: "Our country's existence today as the most technologically advanced industrial power in the world is a great tribute to the extraordinary efforts of our Founding Fathers to establish precisely this type of republic . . . positing America's future economic and moral vitality in increasing the productive power of useful labor through education and the utilization of the most advanced technologies in our manufacturing and agricultural production."

Malthusian Sabotage

Dr. Morris Levitt, executive director of the FEF, made it clear in the following speech that the British Malthusians ensconsed throughout the U.S. government are undermining this commitment.

"Why don't we have a national energy policy?" asked Levitt. Citing Energy Secretary James Schlesinger's 1960 book *The Political Economy of National Strategy*, Levitt explained that Schlesinger believes that "the age of progress is over, that Malthus was right."

Levitt was seconded by Dr. T. V. George of the Department of Energy. A strong national economic policy is needed fast, George said, since "energy has been, is, and will be the backbone of our society." George then described the progress of the Department and the fusion scientific community toward commercial fusion.

Real Coal Development

In the afternoon panel on coal for development, FEF representatives Marsha Freeman and Jon Gilbertson focused on future technologies as the answer to Maryland's coal-utilization problems—coal MHD and advanced steelmaking technologies.

Although the panelists from the coal industry and the Maryland utilities tended to blame each other for the problems in burning high-sulfur Maryland coal, all the participants at the conference were particularly struck by the fact that MHD makes it possible to burn coal at twice the efficiency of conventional systems and eliminate all sulfur pollution problems.

Governor Ray: 'We Don't Have to Take The Soft Path'

Washington Governor Dixy Lee Ray told the 85th annual convention of the Pacific Coast Gas Association in Seattle Sept. 13 that environmentalism was not the "American Way" and that commercial thermonuclear fusion should be developed now. Ray, who formerly headed the U.S. Atomic Energy Commission, has long been an outspoken advocate of nuclear fission and advanced industrial development. The speech, excerpted below, is the first time Ray has emphasized fusion energy.

. . . I want to focus this morning on the recognition that through intelligence, through knowledge, through the use of our minds and through learning, we can do things better. . . we don't have to give up and say 'we'll take the soft path.' The fact is that the modern world for all its ills is the best world that human beings have yet devised.

For all the trouble that plenty of people are willing to tell us about, for all of the problems and troubles that the modern industrialized society has to deal with, it is still the most humane, the most comfortable, the most uniquely desirable type of society that human beings ever evolved. We no longer use other human beings or beasts of burden for our source of energy.

If, in fact, we are going to continue in the path that industrialized society has set—that is, of making a life on this earth that is more comfortable, free from want and the necessities of life, and with a greater supply of the world's goods, services, and comforts for a larger number of people than any kind of organized society has ever known before—we must continue to use energy that we know how to use, that we have.

We must continue to study other possible ways of making energy faster. We must understand the basic principles and be able to engineer development that will bring the process of fusion to where we can begin thinking about commercializing it. We do know that it is possible to mimic the processes going on in the sun itself and to produce very large amounts of energy from a raw material (namely, water). The hydrogen molecules of water come about as close to an inexhaustible supply of an energy source as anything that we can dream of.

But we can never reach that age, where we can produce hydrogen as a starting point for all kinds of synthetic fuels and other materials, when we can produce electricity from a fusion process, unless we use the things we have now. . . .

The opposition is led by those of the environmentalist movement who truly believe that capitalism and industrial society are wrong, that America's society should be turned back to an easier, safer, more pleasant era where there is no central generation of electricity, where there is no central distribution of energy, where there are no large industries, where there is no institution of capitalism; where everyone lives peacefully and by themselves in some kind of semiagrarian society. They want us to return to an Edwardian sort of era in which there are a very large number of serfs with little choice. This is not the American way. . . .

MHD Generator Sets Record

The Avco Everett Research Laboratory in Massachusetts last month announced successful completion of a 250-hour endurance test on its Mark VI generator, which is used in the magnetohydrodynamics coal process. Previously, the generator's electrodes were not able to function to produce electricity from the coal plasma for longer than the 100 consecutive hours achieved in 1976.

MHD offers twice the efficiency of conventional coal processes.

The tests, conducted under power plant conditions, show that MHD generator channels with a 1,000-hour lifetime are now in reach, according to George Fumich, Jr., director of the U.S. Department of Energy's fossil energy division. As a result of recent rapid progress in MHD, the goal of commercialization may now be reached in the 1980s.

FEF Meeting Reviews Fusion Progress

How fast, how big, and how in-depth the U.S. fusion development program should be were the central questions addressed at the Fusion Energy Foundation's annual public meeting of the board of directors and board of trustees Sept. 22 and 23 in New York City. As participants from industry, government, fusion laboratories, and the international community stressed, the chief remaining problems in fusion are political and economic. The scientific and engineering problems have now been solved or are near solution.

The two-day meeting at the Hotel Biltmore, which included several dozen representatives from the business, scientific, and diplomatic communities as well as several foundation members, reviewed the scientific and technological requirements for fusion power and the activities and goals of the foundation, including a $1 million fundraising drive.

Policy Questions

The major policy discussion took place at the Saturday morning session, which featured Dr. John Clarke, deputy director of the Office of Fusion Energy in the U.S. Department of Energy, and Uwe Parpart, FEF director of research.

Clarke began his presentation by thanking the FEF for its educational work (see box). He then reviewed the magnetic confinement and inertial fusion programs and described in detail the projections and rationale for the present U.S. fusion policy, which foresees commercial fusion use sometime well into the 21st century.

Clarke said that this timetable, which he referred to as a "balancing act," was premised on the concept of not moving too fast too soon with any one fusion device, like the tokamak, because this might injure the chances for other promising research lines to develop.

Continued on page 16

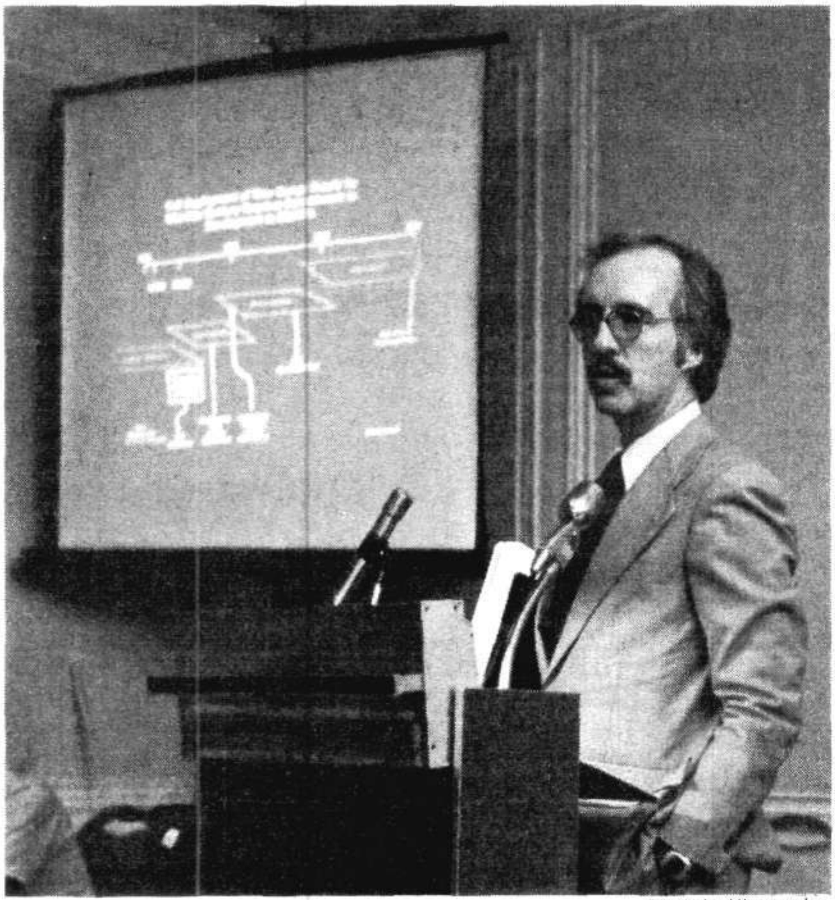


Photo by Ulanowsky

On the Role of the FEF

I want to express my appreciation of the work of the Fusion Energy Foundation. . . . You are one of the few organized groups I know of that has the courage to stand up and advocate high technology as a solution to some of the problems of the world, and for that I think that we owe you a debt of gratitude. Your ability to translate the mysteries of this horrendous fusion program into terms that the public can understand also deserves some applause. Fusion is very important for the future not only of this country, but of the world. But that has to be appreciated and understood by the people of the country and the people of the world before we're going to be able to mobilize the resources necessary to carry this program through to its conclusion. I think the Fusion Energy Foundation with its widespread public education activities really is making a great contribution to that end.

—Dr. John Clarke, deputy director, Office of Fusion

Continued from page 15

By the late 1980s, Clarke said, we should have enough concrete information to make some decisions. He noted that present funding levels were adequate to get us through the present phase of the department schedule.

In answer to a question, Clarke estimated that the date for commercialization could be moved forward 50 or so years to 1995 or 1998, if the money and political priority were provided. It would take us 20 years to develop a commercial fusion prototype, with a maximum effort, Clarke said.

In addressing the timetable question to Clarke, FEF staff member Charles B. Stevens noted that Clarke was particularly well suited to answer, since he had been director of the fusion program at Oak Ridge National Laboratories when the neutral beam heating system was developed.

Taking on the budget and timetable Clarke had presented, Uwe Parpart commented that people like Clarke in the Department of Energy should not really be put into the position of having to make program decisions based on a limited budget pie. "Congress, the administration, and the department have to reconceptualize the fusion budget completely," he said. "It's absurd to put fusion—which will determine whether or not we're going to have a future—on the same level as some trivial energy source like coal liquefaction."

The In-Depth Approach

"This is an issue on which the department is going to have to slug it out with the Office of Management and Budget," Parpart said.

Parpart then discussed the in-depth approach to fusion, on which he had commented earlier and which the FEF is now developing in more detail as a policy guide. This involves a pyramid concept, where many promising avenues of research are fully funded at the same time that there is a strong commitment to the basic task of solving the engineering problems of commercial fusion reactors. In the pyramid approach, each major fusion alternative is backed up by a series of small-scale projects designed to solve particular science and engineering problems.

In the discussions that followed, several fusion scientists brought up the problem of the finite budget pie, where alternative fusion research programs get a slender slice of budget money—if any. Many of the scientists

Recent Tokamak Advances

Dr. Frieman, deputy director of the Princeton Plasma Physics Laboratory, was the keynote speaker at the FEF dinner meeting Sept. 22.

The Ad-Hoc Experts Group on Fusion [the Foster Committee which recently laid out a blueprint for the DOE on fusion research] raised major questions concerning tokamaks.... The report said, and here I paraphrase their specific remarks, that we don't know the scaling laws; that is, we do not know how tokamaks will behave as you go to higher densities and higher temperatures, and we don't know how the time of confinement will behave as a function of these and other variables. It also said that we don't know the critical pressure involved.... This quantity is called beta, the ratio of plasma pressure to magnetic pressure.... If I raise the beta by a factor of 2, then I get a factor of 4 increase in the energy output from fusion. So the question of beta eventually involves the economics of these devices.

[The report] said also that we don't know how to run tokamaks with very long pulses or steady state.... It raised the question of impurity control, the fact that in our present devices we find all sorts of junk in our discharges—titanium, molybdenum, iron and so forth coming off the wall of the reactor. There is also the question of how well the reactor wall will stand up to the constant bombardment of neutrons.... Lastly, there is the question of reactor practicality....

Information not only from the PLT but from a number of other devices has given us some hope in the last short period that we have made improvements in a number of these areas....

The Improvements

First of all, the PLT actually achieved temperatures higher than 60 million degrees; it achieved 80 million degrees [minimum ignition temperature is 44 million degrees].... Now, if that was all we had achieved, most of us would have said: "Ho hum. This isn't very interesting." Far more important in terms of the advance in this whole program is ... that the ion losses are significantly better than the pessimistic theoretical predictions. In addition, the electron confinement has been improved at the center of the discharge, and we were able to control the impurities in the PLT by a process called gettering. In this, you coat the walls of the device with titanium, which absorbs the impurities and prevents them from getting into the discharge....

To make you understand the enormity of these results for us who have been working in this program, let me put it this way: We found that as we push toward higher temperatures, things get better, in fact, rather than worse.... It contradicts Murphy's law....

I'll try to indicate also what has happened around the world.... The ISX tokamak at Oak Ridge achieved a beta of 2 percent at the center. This is an enormous increase in terms of anything we've been used to in this field. The Soviets have achieved a beta of 4 percent at the center in a smaller tokamak called the T-11. The Culham Laboratory in England ... and the Kurchatov Institute in Moscow have used divertors in their tokamaks to achieve impurity control.

So if you go back to some of the points raised by the Foster Committee, you can say that the scaling laws we have seen quite recently are working in our favor.... Major advances have been made in the past few months with the basic physics problems. Wall lifetime, long pulse, reactor practicality are things that will come in future devices....

in these smaller programs are bitter against the larger national laboratories whose scientists, they feel, are an in-group that controls the scientific journals as well as the purse strings for research funding.

Answering a variety of such remarks, FEF executive director Dr. Morris Levitt noted that we "have to remember that the real enemies are the people who want to stop the fusion program altogether, not the scientists in the mainline programs who may occasionally pursue narrow goals."

The real problem has to be attacked on a much broader epistemological basis, he said. "We have to challenge the fundamental assumptions of most physicists. We have to recreate and advance the type of thinking that produced science in the first place, thinking that is represented by the work of Riemann and Cantor."

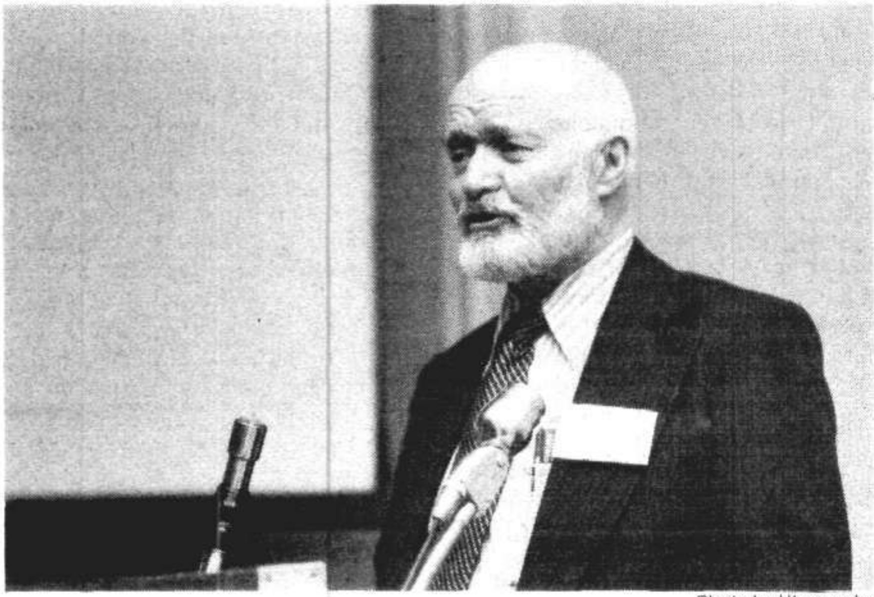


Photo by Ulanowsky

FEF board member William Cornelius Hall.

The Manpower Question

Much of the discussion concerned the critical question of fusion manpower. In his earlier presentation Parpart reviewed the decline of scientific higher education in this country and the severe manpower problem this presents for fusion development. Using the National Science Foundation's 1977 book, *The State of Academic Science,* Parpart showed that the full-time graduate enrollment in physics PhD programs had been cut in half between 1968 and 1975, and he noted that the downward trend has continued.

As a model for what a good science research and development program should look like, Parpart discussed the late 19th century education efforts of Felix Klein, the theoretical mathematician, and Friedrich Altoff, the German minister of culture and education. Klein, then at the University of Goettingen, worked closely with Altoff, industrialists, and other scientists to develop an experimental program that would give graduate students the capability to test crucial theoretical ideas.

Similarly, Parpart said, the fusion program today has to tackle theoretical problems—such as the behavior of the electron—and at the same time put a much greater emphasis on basic research. It is this close interplay between small-scale experiments and the basic theoretical work that will clarify the actual dynamics of critical phenomena.

"The crash program for fusion must be tailored to the unique promise and character of fusion," Parpart said. "Because it is the frontier of science—which neither the Manhattan nor Apollo projects were—it is not sufficient to propose a purely engineering brute force approach. We must train the tens of thousands of scientists in plasma physics, and new kinds of engineers who can work with a fusion torch, with high-intensity electromagnetic energy, and the like."

The manpower question was also a main topic of discussion at the Friday night session. The featured speakers—Dr. Edward Frieman, deputy director of the Princeton Plasma Physics Laboratory, and Dr. William Grossman, assistant director of the magnetofluid dynamics division of the Courant Institute of Mathematics—concurred that any Apollo-type program in fusion would face a tremendous shortage of skilled engineers and plasma physicists.

While both speakers expressed pessimism about the U.S. capability, given adequate funds, to train the required cadre in less than 10 years, a nuclear engineer who had worked on a number of crash programs in weapons development commented: "That's not true. When you've got good administrators and people who are motivated to work 18 hours a day, I've seen us train these people in two or three years."

The FEF Challenge

The final session of the meeting addressed the progress of the FEF over the past period and the challenge that lies ahead. The session opened with remarks by William Cornelius Hall, acting chairman of the FEF board of trustees. Hall, who is the president and chief scientist of the Chemtree Corporation, emphasized the positive situation of fusion today. "When I was 12 years old, I looked around and saw that fossil fuels were finite energy sources, and I wondered how we would provide energy for the future. Today we don't have that problem; we know that fusion can provide energy for many generations to come.

"We know more now about fusion than scientists knew about nuclear energy at the start of the Manhattan project. They developed the atom bomb, and we can develop fusion in just as short a time," Hall said.

Hall then introduced the FEF executive director, Dr. Morris levitt, who reported on the organization's activities and plans.

The FEF annual meeting marked a

Continued on page 56

Elementary Plasma Physics From an Advanced Standpoint

by Dr. Steven Bardwell

The hot, ionized plasma state of the fuel in a fusion reactor is the most complex, intriguing state of nonliving matter known today. Two crucial plasma experiments in the past 10 years have fundamentally challenged the currently accepted ideas of physics. The experiments show that a plasma has an unmistakable tendency to progress from initially disordered states to highly ordered, globally coherent final states; and these final states have such spontaneously high energy density that a fusion reaction occurs. The implications of this highly nonlinear plasma behavior are that the evolution of all systems is governed by a self-changing set of laws, a kind of nondeterminist causality that provides a striking parallel to social and biological evolution.

IN THE NEXT SEVERAL YEARS, the development of nuclear fusion energy will create an astounding conjuncture. Within inches of each other will be states of matter that have never existed in the universe before. On the inside of a fusion reactor, the heavy hydrogen fuel will be maintained at temperatures hotter than any star known; several inches from this hydrogen fuel, a magnetic coil cooled to a few degrees above absolute zero (about −260 degrees Celsius) will be conducting electricity without measurable resistance; and at a temperature almost exactly in between those of the superconducting magnet and the fusion fuel, man will be watching the whole process of his creation.

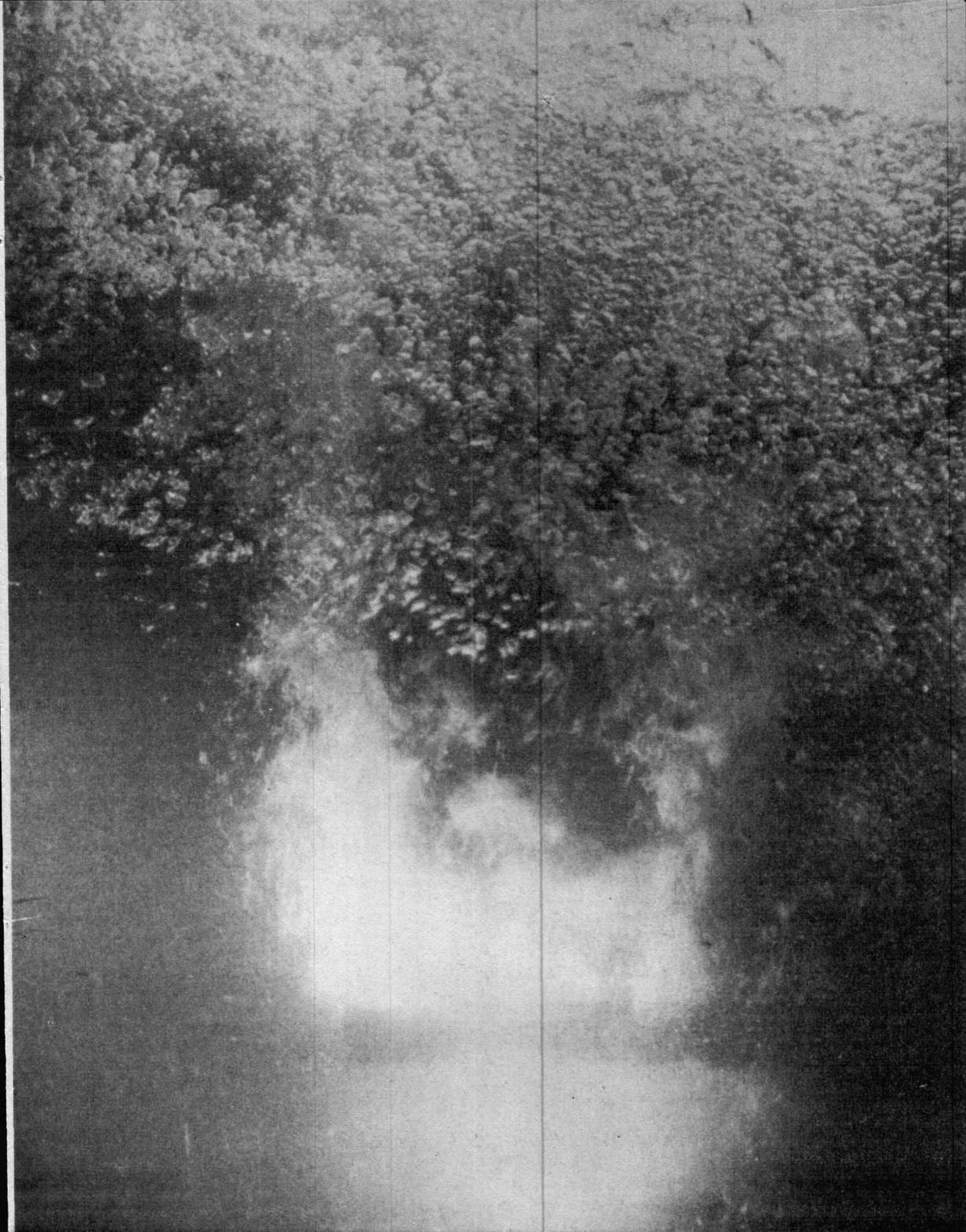
None of these three extraordinary states of matter has existed in the known universe before man; yet, the same fundamental scientific approach is required to understand each of the three. Fusion plasma, superconducting metal, and, most of all, man evolve in a self-organizing way, proceeding naturally from states of chaos to states of higher and higher order and structure.

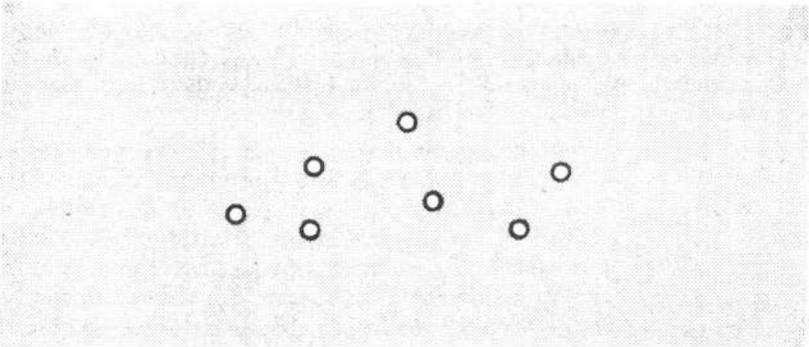
It seems uncanny that a practical understanding of superconductivity and plasma physics is demanded of man at just the point that his own self-ordering progress, the continued development of humanity, would be aborted without the mastery of fusion energy. For the same reason, plasma physics opens the door not only to a revolution in the technological foundation of human society, but also to the most experimentally accessible realm for the mastery of the new scientific frontier without which that technological leap is impossible.

Editor's Note

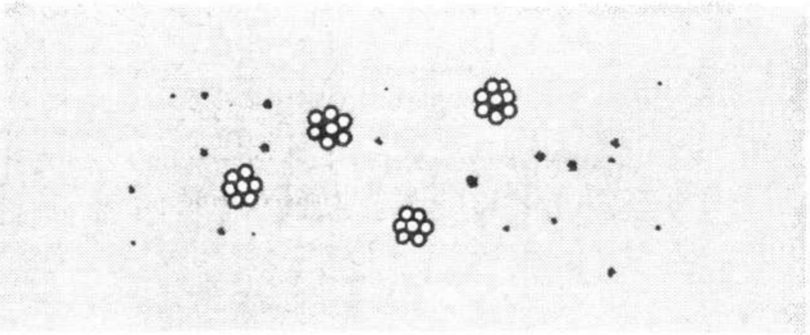
This article was written to provide the layperson with a nontrivial, yet accessible, answer to the frequently posed query "What is plasma physics?" Although the material is elementary from a physics standpoint, it is advanced from a scientific-conceptual standpoint.

A plasma torch, under water, cutting a piece of 1-inch-thick stainless steel.
Oak Ridge National Laboratory

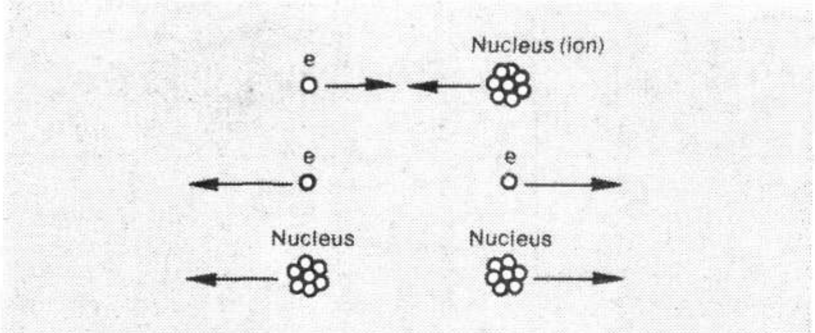




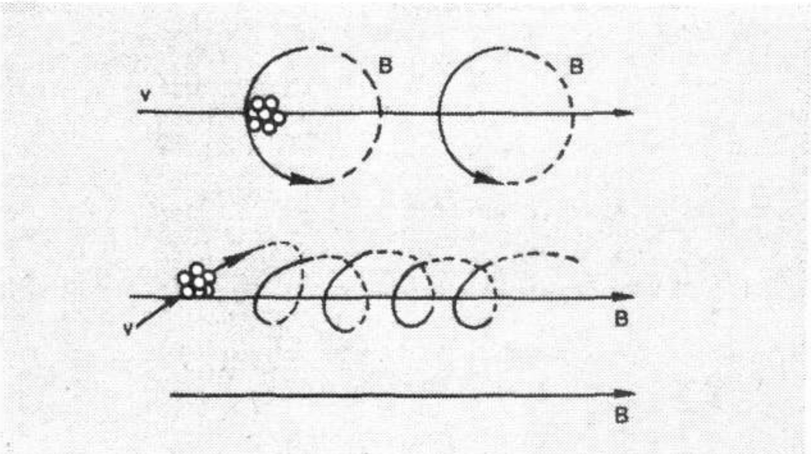
(a) A neutral gas



(b) Usual view of a plasma



(c) Electrostatic forces



(d) Magnetic forces

Figure 1
OVERSIMPLIFIED VIEW OF A PLASMA

A plasma state, according to the prevailing picture, is a collection of charged particles in a gaseous state.

Most of the gases familiar in daily life are made up of neutral atoms or molecules that interact with each other at usual temperatures and densities only through very weak and short-range forces. To a good approximation, they "know" that there are other gas particles only when a collision occurs.

As a neutral gas is heated, the increasingly forceful collisions knock electrons off the atoms or molecules and, at sufficiently high temperatures, the collisions prevent the maintenance of any stable neutral association of electrons and nuclei. The gas is then a collection of electrically charged particles, electrons, and nuclei.

The plasma particles, however, interact very strongly through electrostatic and magnetic forces, which are both long range and strong. The electrostatic force is attractive between electrons and nuclei and repulsive between like-charged particles. Thus, the particles in the plasma all strongly affect each other's motion by virtue of the fields each produces.

The magnetic force between charged particles is more complicated. The force occurs only when the particle is moving. A moving charged particle creates a magnetic force perpendicular to its direction of motion, as shown in **d.** *A charged particle moving in an external magnetic field is pushed in a direction perpendicular to its direction of motion. In the simplest case, this results in a spiral motion of a particle moving in a straight magnetic field, where the particle spirals about the direction of the magnetic field (labeled* **B** *in the diagram).*

A plasma is the most puzzling of all the states of matter, because it seems so simple. Scientists in the 20th century have been able to rationalize their inability to describe the self-developing characteristics of superconducting metals because superconduction is a quantum effect. In a similar fashion, living systems carefully have been put outside the realm of physics. A plasma, however, should be totally describable by classical physics.

WHAT IS A PLASMA?

In the conventional description, a plasma is the state of matter that results from the deposition of tremendous amounts of energy into any matter. First the matter becomes an ordinary gas, made up of chaotically moving atoms or molecules. As the energy input increases, these molecules break up into atoms. The increasingly violent collisions of these atoms then strip the electrons away from all the nuclei, leaving a very energetic mixture of electrons and nuclei moving independently of each other. A flame, a neon light, and a spark are examples of such low-energy plasmas.

If the mixture described here were really a plasma, then its behavior should be comprehensible within the scope of classical physics, since the particles influence each other by electromagnetic interactions according to Newtonian mechanics. It should be even more straightforward to explain because the high energy of the particles (according to classical statistical mechanics) assures that the plasma should quickly achieve a random final state at equilibrium. The electric and magnetic fields produced by the plasma and the motions of the plasma induced by these self-produced fields should easily account for everything that a plasma does macroscopically.

This simple explanation, however, doesn't work. Plasma physics is the most challenging field in physics today precisely because the plasma always behaves anomalously; that is, contrary to these classical reductionist expectations. Yet, most physicists have avoided this fundamental challenge to physics. Although no scientist with eyes can deny the unusual behavior of plasmas, physicists usually explain away such behavior with several otherwise-important observations about the uniqueness of a plasma, as follows:

The first rationalization holds that the forces that connect the particles in the plasma are very long range. In the usual neutral gas, the particles interact with each other only when they are very close—when they collide. This means that most of the time the particles act as if they were independent of the other particles, and their mutual interaction can be regarded as a minor perturbation of their independent movement. In a plasma, however, the particles interact by means of electric and magnetic forces that remain strong even at great distances from the particles that cause them.

In a gas, doubling the distance between particles reduces the effective interaction by a factor of 100 while in a plasma the interaction is decreased only by a factor of 4! By conventional reasoning, this means that the particles are strongly coupled to each other and that the difficulty classical physics has in describing a plasma is due only to the complicated equations involved. In a normal gas, the particles can be treated one by one, but in a plasma, this argument goes, the equations for all the particles must be solved at once—a job that is just too hard for present-day computers or mathematics.

The second rationalization for the discrepancies between contemporary physics and plasma experiments is closely connected to the first. In the usual situations encountered in physics, the forces that determine the motion of a particle are external to the particle. The motion of a satellite and the path of an electron in a magnetic field are both standard situations in which the force moving the particle is due to another body that is not affected by the motion of the satellite or the electron. For example, the sun is not moved any appreciable extent by an earth satellite, nor is the magnet in a particle accelerator changed by the motion it induces in the electron. In a plasma, however, the source of the forces and the things moved is the same. Because the particles are electrically charged, they act as sources for electric and magnetic fields that influence the charged particles near them. In turn, these particles change the motion of the first particles, and so on. From the standpoint of contemporary physical theory, the result is a complex set of mathematically nonlinear equations in which the motion of the sources of the fields is due to the fields the sources themselves create. Again, the conventional reasoning goes that plasma physics has a hard time describing what a plasma does because these equations are so complicated. The laws are known, the argument goes, it is just that at present we cannot deduce the consequences of these laws.

The third rationalization is that this same situation has arisen in physics before, but physicists usually achieved some approximate understanding of the problem because the so-called nonlinear effects were small enough to be only small perturbations of the overall linear properties of the system. As this argument goes, both of the above properties of a system (long-range forces and self-created fields) give rise to so-called collective behavior, and as long as this collective behavior is not too strong, it can be described by looking at it as a sort of complicated coincidence of individual particle motion.

In a plasma, however, even this ploy is unsuccessful. The plasma is too nonlinear; it is dominated by collective behavior. There are only a few (uninteresting) plasmas, usually cool and sparse, that behave as if they were collections of independent particles. All interesting plasmas, especially those encountered in fusion studies, have incredibly complex properties, most of which have not yet been discovered, let alone explained.

Long-range forces, self-created fields, and collective effects are all exceedingly important features of a plasma, but there is a deeper lesson here: *Present physics is fundamentally inadequate to describe a plasma, and in fact, is fundamentally inadequate to describe the universe as a whole.*

Any single fixed set of laws is in principle insufficient to describe a universe that is evolving. The astounding self-organizing behavior of a plasma cannot be explained away by the ideas of collective and coherent effects. These striking characteristics are important because they are *inanimate indications that the universe as a whole shares the creative qualities of human evolution.* Contemporary physics obviously cannot explain a lifelike phenomenon because it has explicitly excluded life from its purview. The rub is that everything is lifelike.

WHAT DOES A PLASMA DO?

A survey of plasma phenomena must start with a healthy skepticism about present-day physics and with a firm commitment to master the implications of a changing universal lawfulness. Once we know where the investigation must proceed, however, classical physics can provide indications of the processes involved, and we have no choice but to use the tools of the best physicists and mathematicians, like Bernhard Riemann, who themselves understood this paradox.

It must be absolutely clear, however, what these physical and mathematical investigations are all about. The science of the investigation comes in formulating a hypothesis about the overall process of development a system is undergoing. Then mathematics and physics can be used to unravel each stage of this evolution, sharpening and testing the hypothesis. In a fundamental sense, mathematics and physics as we presently know them are incapable of touching the evolutionary process itself. They point to the footprints of the beast, but the prey will always elude them. A scientist, as opposed to physicist, however, cannot be content with only the scent.

The science of plasma physics, *from an advanced standpoint*, is to use the tools of physics and mathematics on the behavior of a plasma to get at the real process of self-developing evolution of which a plasma is one experimentally accessible expression.

There are two archetypical experiments in plasma physics that are crucial experiments in the history of the science. These two experiments—the propagation of an electron beam through a plasma and the propagation of a plasma through a weak magnetic field—make the fundamental implication of a universe governed by an evolutionary lawfulness inescapable, for anyone not otherwise convinced. More important, the experiments provide critical empirical data about how this evolution really works.

CASE HISTORY 1: e-BEAM MEETS PLASMA

In 1974, A. Wong and B. Quon at the University of California performed one of the simplest and most astounding experiments in plasma physics. Although their results had been theoretically anticipated by a number of physicists, their experiment started a profound process of reevaluation of the adequacy of plasma physics.

The experimental apparatus is very simple. Wong and Quon directed a high-intensity beam of electrons, which were traveling at about 0.002 the speed of light, into a uniform unmagnetized plasma. The equivalent experiment with matter that is not electrically charged is to shoot a stream of water into a large container of water. As the photograph in Figure 2 illustrates, the obvious result of the experiment with a water beam is that the beam disappears in a mess of turbulence after penetrating a short ways into the water. This result seems so clear that it hardly seems worth an experiment.

However, a careful examination of the water beam experiment provides some further results that must be looked at before going on to the plasma case. The first effect of putting ordered energy into the water bath is the formation of a large, almost perfectly formed vortex ring whose cross-section is shown in the photograph. As the beam goes farther into the water, this single structure breaks up into many smaller and smaller swirls, until eventually any visible motion ceases.

In fact, careful measurements show that the energy of the water beam is transformed into heat (microscopic, disordered motion of the water) and that the initial motion pattern gets both smaller and more disordered. These two observations have been quantified in other experiments and have demonstrated first, that the viscosity (the resistance of the water to differences in flow rate, or the friction of the water) makes the turbulence decrease in characteristic size according to a specific law that is repeatable for many fluids in similar beam experiments. Second, these observations have demonstrated that the smaller and smaller swirls never pile up to make one strong (but small) vortex; they always are distributed randomly.*

These results are certainly what we intuitively would expect. We all know that when we stir our coffee in the morning, the sugar and milk will be evenly distributed by the randomization of the turbulence. The first process going on here is called *energy cascade*, because the energy in the fluid motion cascades from large-scale motion down a series of steps to smaller and smaller scales. The second process, the disordered arrangement of these motions (which increases as the scale gets smaller) is called the *randomization of phase*. This randomization is in analogy with the property of the phase of a wave that is responsible for the wave's ability to combine with other waves to form a single large wave (coherent phase) or to cancel out all the waves (random phase).

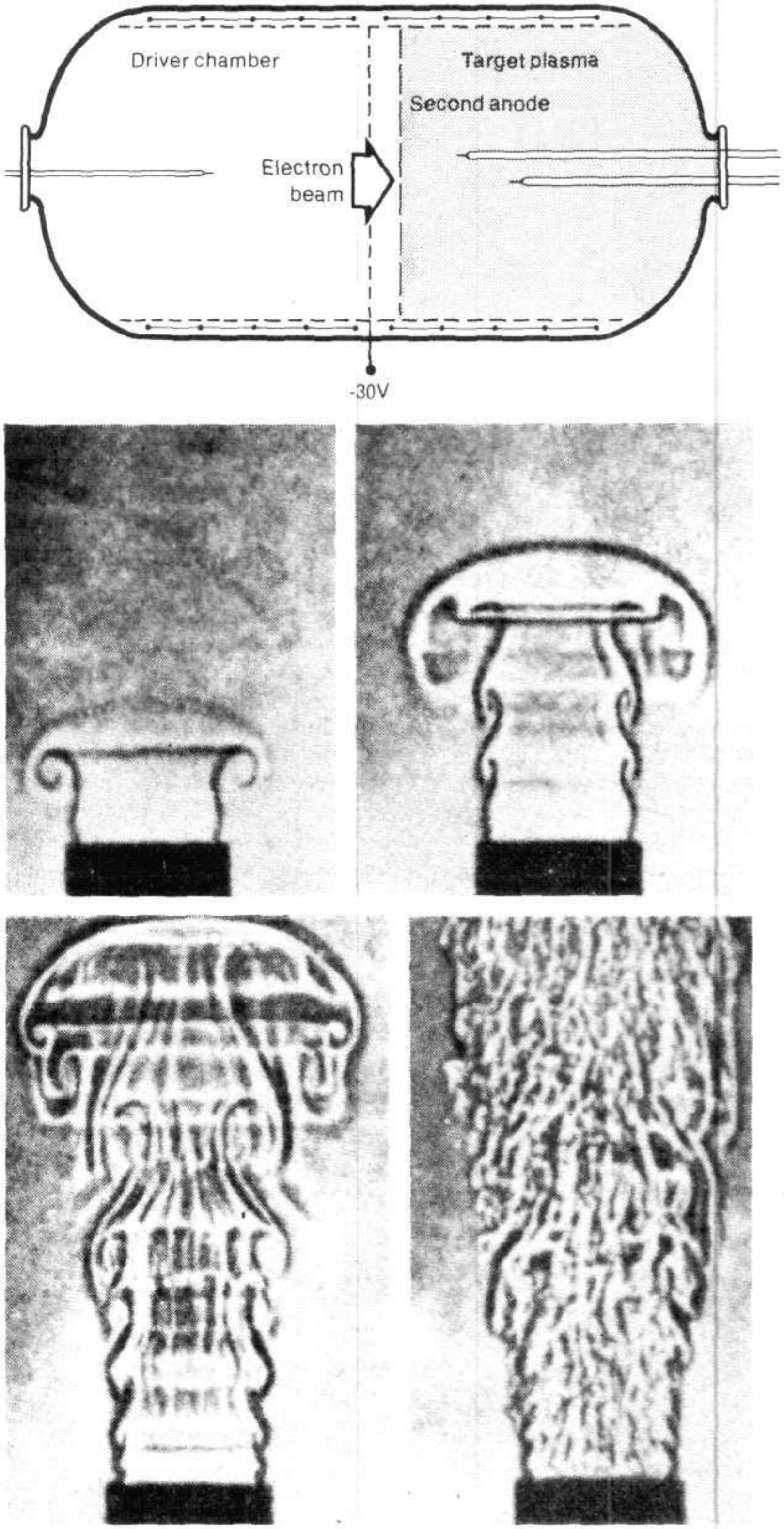
In other terms, these two concepts are more rigorous versions of our common sense ideas about the evolution of almost all matter; namely, that left to itself matter becomes more disordered, and any large-scale motion breaks down as time goes on (Figure 3).

Imagine a situation where this did not happen. As you carry your coffee to the kitchen table in the morning, you jiggle the cup and the initially disordered ripples lose their random phases; a stronger and stronger vortex twists up out of the coffee until a tornado of hot coffee jumps out of the cup. Unbelievable? This is exactly what happened in the plasma experiments of Wong and Quon.

The plasma reacts differently to this experimental situation because of the physical properties described above: its long-range interactions, the mutual deter-

* Randomness occurs only in the simplest fluid configurations. In most others, even a fluid exhibits self-ordering phenomena.

Figure 2
COMPARISON OF BEAM EXPERIMENTS IN A PLASMA AND WATER



(a) Wong and Quon's electron beam-plasma experiment

Some of the most striking and unequivocal evidence about a plasma and its evolutionary properaties comes from a conceptually simple set of experiments done by Wong and Quon at the University of California in 1973 and 1974. Their experimental apparatus shown here diagramatically. It consisted of an electron beam, traveling at about 0.002 the speed of light, hitting a plasma. The total plasma size was about 5 feet.

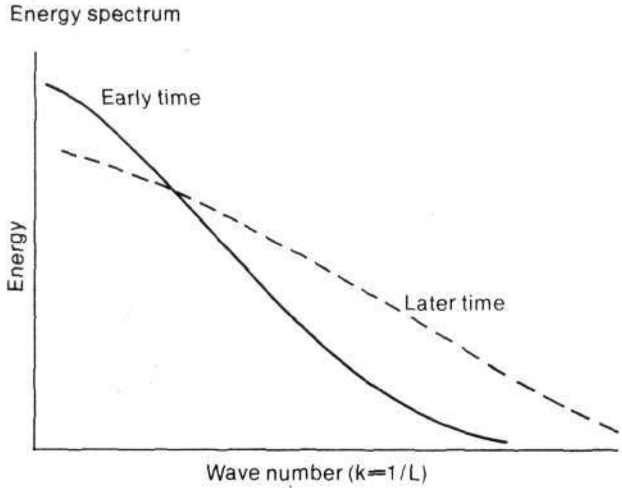
(b) Results from the same experiment in a neutral medium (water)

The same experiment for an uncharged fluid medium like water is shown here in a time series of photographs. A beam of water, traveling upwards in the photographs, goes into a bath of water. Time increases from left to right, and the initially large swirls created by the water jet quickly decay into smaller and smaller turbulence.

*In the commonsense theory of thermodynamics (embodied in the Second Law of Thermodynamics of increasing entropy), the injection of ordered energy into a system will result in the eventual heating of the system by the progressive disordering and dissipation of the energy into the systetmaeexperiments shown here—the injection of an electron beam into a plasma (**a**) and a jet of water into a water bath (**b**)—test this idea. In a fluid like water, the simplicity of the medium results in the seemingly entropic evolution of the beam-water system. In a plasma, something quite different happens, as discussed in detail in the text.*

Figure 3
TWO ESSENTIAL CONCEPTS IN PHYSICAL EVOLUTION

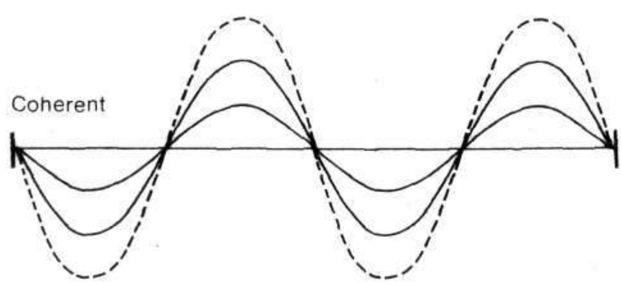
The two concepts described here, energy cascade and random phase, are important indications of the quality of evolution going on in a physical system. Both cmcepts can be analyzed in terms of continuum mechanics, since fluids and plasmas each have a large number of properties attributable to a continuous medium. The ideas of an energy cascade and random phase are important chiefly because they indicate the limit points of the continuity or smoothness of the system.



(a) Energy cascade

The spectrum of a system is its energy plotted against the characteristic scale length of that energy. In the graph here, the energy is plotted against the inverse of this scale length, called the wave number, k. The scale length corresponds to the wavelength of any energy-containing mode, like the fundamental or its overtones on a piano string. The spectrum of a piano string would consist of a series of spikes at the fundamental (the largest spike) and at each harmonic. The characteristic scale length (whose inverse in the characteristic wave number) for the first frame of the fluid motion shown in Figure 2 is simply the diameter of the large vortex ring. As the motion becomes more chaotic, the characteristic length becomes some suitable average over the various, smaller and smaller, diameters of the little swirls that compose the overall turbulent motion.

The concept of energy cascade describes the usual behavior of a system in which the energy begins in large-scale motion (large swirls, and so forth), with a spectrum peaked at small wave numbers, and goes to smaller and smaller scale lengths, "cascading" down the spectrum as the system evolves.



(b) Random phase

The usual entropic system also becomes disordered; both the cascade and disorder are essential to the commonsense idea of a progression from order to disorder (and to the formal expression of this idea in the Second Law of Thermodynamics). In usual situations, the smaller and smaller scale-length motions occur with a random orientation with respect to each other and, on the average, their motions cancel out. This is expressed mathematically by noting that the phases of the modes are randomly distributed and so the crests of one wave tend to cancel out with the myriad troughs of all the other waves. To take the analogy with the piano string again: As the wave dies out on the string, the multitude of harmonics that the string supports becomes more and more chaotic, eventually turning into the heat energy of the string.

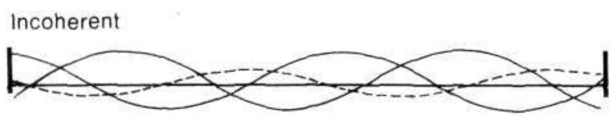


Figure 4
THREE CENTRAL PLASMA QUANTITIES

The electron plasma frequency, the characteristic high-frequency mode in an unmagnetized plasma, is caused by the oscillation of the electrons in the electrostatic field that their own motion sets up with the ions. The ions are essentially stationary on this time scale. This quantity and the actual motions exist only in the limit of small electron motion.

The coherent energy density is the ratio of the energy in any coherent electric field to the random energy in the temperature of the plasma. When this ratio is small, the plasma is said to be weakly turbulent. When it is large, the concepts of both parts of the ratio break down.

Alfven velocity is the characteristic velocity with which coherent energy is transported in a plasma with a magnetic field. The magnetic field supports Alfven waves that travel at this velocity. When the energy in these waves becomes more than infinitesimal, the wave motion organizes new magnetic field configurations.

$$\sqrt{4\pi n e^2/m}$$

(a) Electron plasma frequency

$$E^2/8\pi n T$$

(b) Coherent energy density

$$B/\sqrt{4\pi n m_i}$$

(c) Alfven velocity

These three numbers offer insight into the fundamental plasma processes. They are derived from strictly linear considerations and do not describe the experimental behavior of a plasma with any rigor. However, they are valuable guides to the general classes of phenomena that characterize specific stages of the plasma's more complicated evolution.

mination of sources and fields, and the essential nonlinearity of the interactions. There are several key quantities that help measure the importance and effect of these considerations (summarized in Figure 4). The one that enters most immediately in the case of the electron beam-plasma interaction is the *electron plasma frequency*. This frequency is the characteristic high-frequency response of a plasma.

A similar quantity can be defined for almost all physical systems. Consider a piano string for instance. In the case of a single string, there is a characteristic sound called the fundamental that the string makes no matter where it is hit. The mixture of overtones to the fundamental may differ, and the hammer is designed to produce as pleasing a combination as possible; but the string's response is dominated by this tone. As we shall see, a plasma has a myriad such so-called normal modes, and the highest of these is the electron plasma frequency.

The physical mechanism that produces this oscillation is the simplest electromagnetic interaction possible between the particles, a purely electrostatic attraction. If the electrons are perturbed slightly away from the ions in the plasma, an electrostatic attraction will pull them back to their equilibrium positions. If this perturbation is vanishingly small, then classical calculations (which are accurate in this limit) show that the electrons will overshoot their original position and oscillate at a characteristic frequency.

The analogy can be made to a collection of balls on springs, all of which are interconnected. If the balls are displaced by hitting the whole apparatus, they will continue to oscillate about their original positions. The value of the electron plasma frequency is $\sqrt{(4\pi n e^2/m)}$, where m is the mass of the electron (the frequency decreases with increasing mass), *n* the density of the electrons (the frequency increases with increasing density since the restoring force is stronger), and e is the charge of the electron.

When the electron beam first enters the plasma, it "plucks" the electrons very strongly, and the first reaction of the system is the deposition of a large amount of energy in the electron plasma oscillation. Figure 5 shows a time history of the plasma-beam system, and the first set of pictures in the figure shows the time evolution of the electron beam and the plasma. However, there is an immediate problem with the idea of a plasma oscillation. The electron plasma mode exists only when there is a definable equilibrium position and only when the electrons are slightly removed from this equilibrium position. This equilibrium position ceases to exist almost immediately in the experiment that Wong and Quon performed.

The breakdown of this assumption of mathematical linearity can be measured by the coherent energy density of the plasma, the second quantity noted in Figure 4. (This assumption holds that the perturbation of the electron position is small enough that only the first power—the linear power—of the perturbation need be considered; the higher, nonlinear terms are so small under these conditions that they can be ignored.) This quantity is the *ratio* of the energy contained in the electron plasma waves

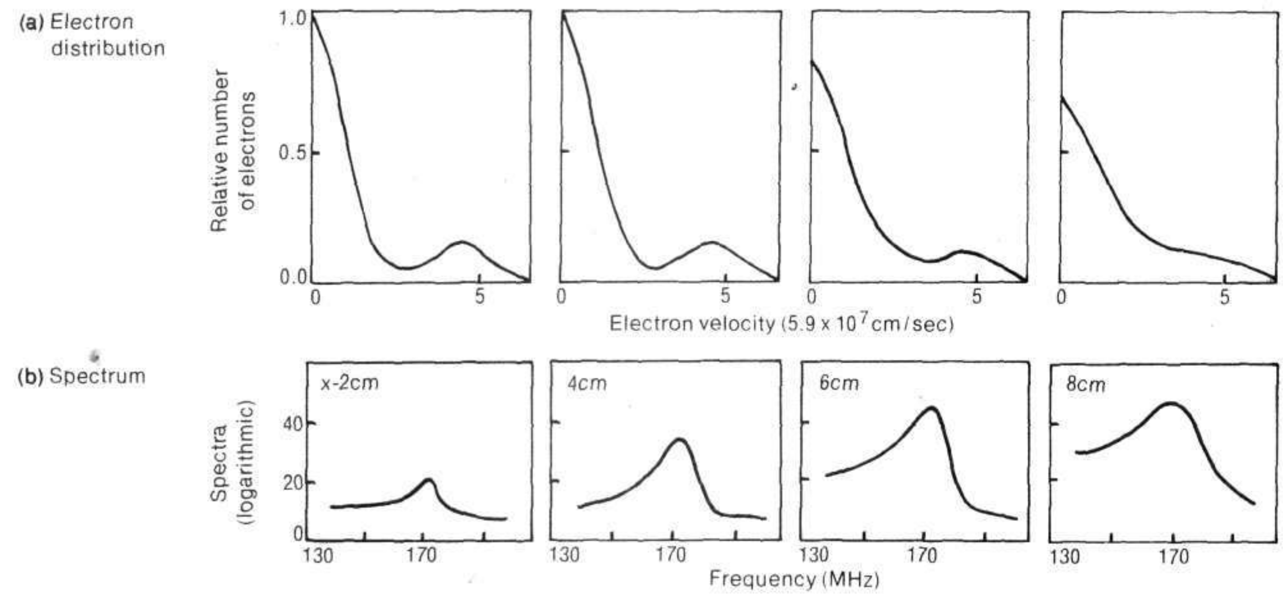


Figure 5
ELECTRON AND PLASMA WAVE EVOLUTION IN WONG AND QUON'S EXPERIMENT

The graphs in **a** *show the distribution of electrons as a function of velocity as the beam propagates farther and farther into the plasma. In the first frame, the large central peak represents the thermal equilibrium background of the plasma before the beam has entered it. This is the classical Maxwellian distribution of electron velocities. The vertical axis represents the proportion of electrons with the velocity specified on the x axis. The smaller peak at about 5 represents the beam electron. Two things happen as the beam propagates farther into the plasma: The beam energy gets decreased, and the central hump changes shape. The beam energy goes partly into heating the central bulk of the electron distribution and spreading it out, and partly into the energy of the high-frequency Langmuir waves.*

The graphs in **b** *show the corresponding energy in the high-frequency range of the electrostatic field. The four positions in the plasma are at roughly the same positions as the above electron distributions. As the electron beam loses energy, the high-frequency waves, known as Langmuir waves, gain it. The plasma frequency is at about 170 MHz (million cycles per second). This peak grows rapidly in magnitude as the beam propagates into the plasma. Not evident on these graphs is the other process of the decrease of wavelength of this energy and of the coherence of the phase of these waves.*

to the energy in the random (thermal) motion of the plasma. Since the energy in the electron plasma waves can be measured by the electric field they create (the same field that pulls them back), it has an energy density given by $E^2/8\pi$, where E is the field strength, and the energy density of the thermal motion of the plasma is just its density times its temperature. The ratio of these two quantities is a measure of the orderedness of the motion in the plasma. The linear regime (called weak turbulence) has a value of $E^2/8\pi nT$ much less than 1; that is, the disordered energy is much greater than the energy in the electron plasma oscillation.

The graphs of the spectrum of the time evolution of the energy in the plasma (Figure 5) show that very soon after the beam enters the plasma, the beam energy drives up a large amplitude electron plasma oscillation. The evolution of this energy is extraordinary. It does not decay into random disordered plasma motion (heat); rather, it creates a highly ordered, localized structure in the plasma, a particlelike concentration of energy called a *soliton*.

The process of the evolution of the beam-plasma system at the new energy level due to the beam excitation is shown in the first set of graphs in Figure 6. These graphs show the energy as a function of its *physical position* in the plasma. (These graphs are not spectra showing the energy as a function of the characteristic length or inverse length of the motion carrying the energy.) Instead of dispersing into the plasma as a whole, the energy has concentrated itself into a set of very sharp spikes whose energy density, in the final state of the spikes, is equal to the random energy density in the "background." This is amazing behavior.

In the case of the evolution of the water jet, its random final state was describable in terms of the cascade of energy to small lengths (large values of k, the inverse of the wavelength) and randomization of the phases of the motions containing this energy. Both processes were critical. In the case of the strikingly different beam-plasma evolution, these two concepts shed some light on why the

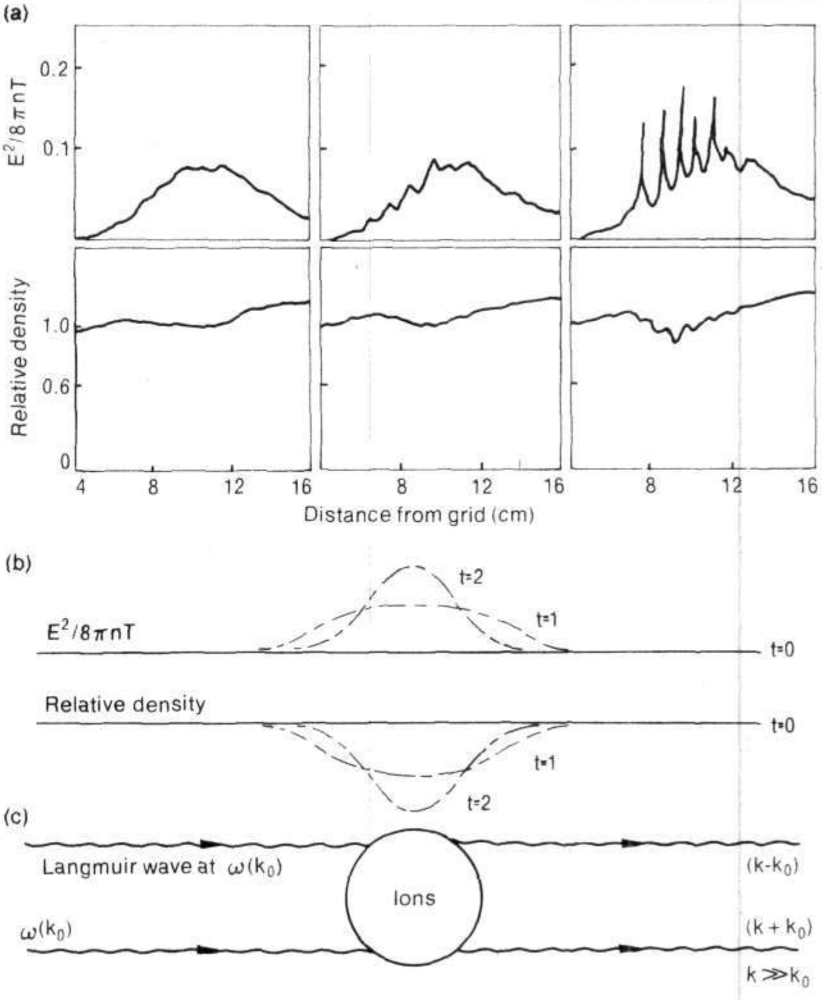


Figure 6
MODULATIONAL INSTABILITY

The graphs in **a** *show the time evolution of the energy-density ratio in the plasma (top row) and the ion density (bottom row). Most striking is the coincidence of the soliton in the energy ratio with the hollowing out of the ion density. The final state in Wong and Quon's experiment was of five solitons, separated by about a half-inch. This state is shown in the final frames.*

In **b**, *Tsytovich schematically shows the first stages of soliton evolution as predicted by standard model equations. The process is what he calls the modulational instability, in which the increasing energy density in the high-frequency field pushes out plasma, which in turn intensifies the short wavelength (high k) components of the field.*

The nonlinear wave-wave interaction responsible for shifting wave (field) energy to smaller wavelengths (higher k) is shown schematically in **c**. *Two plasma (Langmuir) waves interact through an ion density perturbation (labeled ions), transferring momentum in this "collision"; two plasma waves with smaller wavelengths leave the collision.*

plasma acts so differently. The energy in the plasma case does cascade to smaller wavelength (larger k), as is clear from examining Figure 6. The spectrum corresponding to the earliest time would be peaked at large scale lengths because the energy is smoothly spread out through the system, and as the time increases, the sharp spikes indicate that the spectrum is shifting toward large k (small scale lengths). This is the usual energy cascade, which in the case of the fluid is accompanied by the macroscopic phenomenon of energy dissipation.

In the plasma, however, these now-small energy concentrations occur with a very precisely determined phase. The lack of random phase means that the many small energy bunches add up constructively, so that in the physical space of the plasma (shown in the graphs), there are *very intense, localized, and highly structured energy concentrations.* In some situations, these structures can result in a 100,000-fold increase in the energy density of the plasma. In the experiment of Wong and Quon, the electron beam created five of these solitons, spaced about a half-inch apart, which are visible in the last panel in Figure 6.

Attempts to understand the origin of the striking soliton phenomenon have confronted plasma physicists with serious questions that are identical to the paradoxical situation in most of modern physics. Available concepts and mathematical tools can provide valuable insights into the general process; and, if one is willing to jump over one or two key problems, like the existence of the solitons, then their behavior and interactions can be understood. However, attempts to deal with the phenomena rigorously have encountered an internal contradiction in the mathematical formalism or the obvious necessity for new conceptual tools.

Plasma physics based on Maxwell's electromagnetism and Newton's mechanics does give some insights into the formation and dynamics of solitons, but proves inadequate to account for the very existence of solitons or the stability of the resulting plasma made up of a collection of these solitons.

The currently accepted view on how solitons form is described in Figure 6. The first stage in the process is the existence of a heightened level of plasma wave turbulence. In the simple type of plasma in Wong and Quon's experiment, these waves are the electron plasma or Langmuir waves. The enhanced Langmuir spectrum can be the result of an electron beam as in the case noted here, a laser beam, or some other mechanism. In the usual linear approximation, these waves do not interact with each other; like the piano string, the different wavelengths of the Langmuir waves are independent and do not exchange energy with each other.

However, as soon as the energy density of the plasma's Langmuir waves reaches a well-defined threshold, these waves begin to exchange energy among each other in a well-defined way. The dominant mode of such interaction in the formation of solitons is thought to be the so-called *modulational instability*. This instability is responsible for the transfer of energy from Langmuir waves with long wavelengths (small k) to those with short wavelengths (large k), producing the usual kind of energy cascade in the Langmuir spectrum.

Picture the modulational instability as the result of a simple feedback loop within the plasma dynamics. When the electric field of the plasma reaches the threshold for this process, the pressure of the field pushes ions in the plasma out of the way, creating a small depression in the density of the plasma. Inside this depression, the ratio of coherent field energy to the background energy (the parameter $E^2/8\pi nT$) is larger since there is less plasma, the modulational instability is driven harder, and more energy is shifted to small wavelengths.

In turn, this pushes out more plasma from the depression, which starts the process over again. This self-feeding process is shown in Figure 6b, and can also be seen in Figure 6a where the close correspondence is clear between the solitons in the field energy with density depressions in the background ion plasma.

The third part, Figure 6c, shows the hypothesized mechanism for the critical link in the development of the modulational instability. The linearly independent plasma waves are shown diagramatically on the left; when the intensity of these two waves (part of the same plasma wave spectrum) is great enough, they cease to be independent and can interact with each other by their effect on the ion density (shown in the center of the figure). The net result is the formation of two new plasma waves that turn out to have smaller wavelengths (larger values of k). It is as if the two plasma waves collide with the ion density fluctuation, taking momentum from the plasma ions and moving them farther out of the density depression. Then the waves themselves leave the collision with greater overall momentum (smaller wavelength and greater k).

This picture is valid, however, only in the limit of very small plasma wave intensity; that is, small values of the parameter $E^2/8\pi nT$. It is not hard to see that if there are nonlinear wave-wave interactions like those in Figure 6 involving two plasma waves, similar interactions must occur with three, four, and even more waves. These interactions depend on increasing powers of the parameter $E^2/8\pi nT$. As this ratio gets larger, there is no hope that *powers* of it will be much less than 1.

Even on its own terms, the physical picture described graphically in Figure 6 is inadequate to describe the development of solitons in a plasma. There is no question that it continues to supply valuable insights, but it does not provide a scientific explanation of the phenomena.

Plasma physicists have had two responses to this situation. Some have recognized that there is a fundamental difficulty but they have gone ahead to develop a physics that could describe the interaction and mutual influence of the solitons while ignoring how they come into existence; others have attempted to describe *rigorously* the existence of the soliton on the basis of already understood mathematics and physics.

The choice here is similar to that in electromagnetic theory: physics today cannot account for the existence of the electron, and either one can assume the existence of this particle and go on to do physics without inquiring about the reasons for the stability or existence of the electron itself; or, like modern quantum mechanics, one can try to account for it on as rigorous a basis as possible—and fail.

The Tsytovich School

A number of physicists have taken the first approach, most notably a Soviet school under the influence of V.N. Tsytovich, whose program is still in its infancy. Tsytovich has built a mathematical model of what he calls a new plasma state, that of strong turbulence (when $E^2/8\pi nT$ is approximately equal to 1), made up of a collection of solitons. These solitons and their relatives are the new elementary particle out of which the plasma is constructed. The method Tsytovich uses does not attempt to describe with any rigor the fact that the soliton is the new elementary particle of the plasma. Tsytovich presumes this and goes on to describe how a plasma made up out of particles with soliton properties would behave.

Tsytovich and his group have tried to build up a plasma out of the conglomeration of new modes that occur in a strongly turbulent plasma—solitons, cavitons (the name given to the density depressions accompanying the solitons), spikons (another form of the soliton), and the like. All these entities are then used to define a new statistical background state, with a characteristic temperature and a new equilibrium distribution of energy and velocity. The Tsytovich method then prescribes the deduction of a new hierarchy of linearity from the new background configuration of the soliton plasma. Tsytovich writes:

> A program for founding a theory of strong turbulence by investigating particular dynamic motions like solitons, cavitons, spikons, etc. [by themselves] apparently cannot be consistent, not only because it is practically impossible to take into account all the real variety of such phenomena, but also due to the fact (and this is more essential) that the interaction of these dynamic motions qualitatively changes their properties. Therefore, we think that the approach in which the three-dimensional statistical principles are used to describe the modulational disturbances can be regarded as a first step toward a theory which is required for an adequate description of this new plasma state.

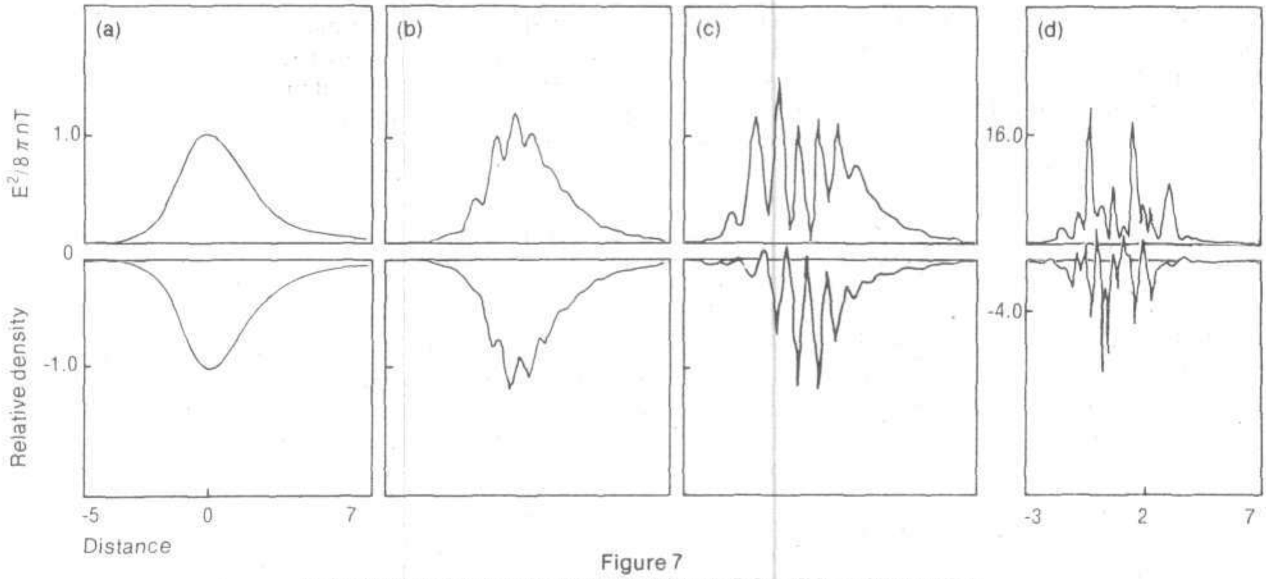


Figure 7
COMPUTER-GENERATED SOLUTIONS FOR SOLITON FORMATION

The first stages in the computer's numerical simulations (a and b) show the same type of behavior that is seen experimentally and that is to be expected from simple physical considerations. Note especially the confirmation of the modulational instability shown by the simultaneous hollowing out of ion cavities with the formation of solitons in the electrical field (high-frequency) energy.

*Later stages of this same numerical solution show a quite astounding divergence from the simple physical model of the modulational instability. In the advanced nonlinear stages of the evolution (**c** and **d**); the solitons and cavitons have independent existences and do not form or travel together. Morales and Lee stress that this still unexplained phenomenon occurs mathematically with development of phase coherence in the electrical field energy, and they speculate that this ill-behaved mathematical property causes the pathological behavior of their solution.*

In addition to the Tsytovich group, a handful of plasma physicists have pursued the question of the rigorous description of the existence and stability of the modulational instability and solitons. Figure 7 shows some very surprising results from a computer-derived solution for the equations thought to describe the generation and evolution of solitons. The graphs show the plasma at increasing times, like frames from a movie. For the first several frames, the computer-generated solution behaves very much like the plasma Wong and Quon experimented with. Most striking is the apparent verification of the basic physical process of the concentration of energy in the soliton (the formation of solitons) and the hollowing out of the ions wherever there is a soliton. This is the feedback mechanism, which is central to the idea of the modulational instability.

This process in the computer-generated solution breaks down after a short time, however, and the solitons continue to form in an apparently random way without regard to the presence of the ion cavities. The last frame shows a plasma in which a number of solitons are not correlated with the ion depressions. The authors of this work, B. Morales and Y. Lee, who studied this anomaly at some length, concluded that the mathematical description they were using began to break down at the point that the phase coherence became the dominant effect. The ordering of the phases of the solitons that were formed by the modulational process caused a qualitative change in the properties of the solitons that the equations generated. This created a plasma that was fundamentally different from its initial state and seemed to be characterized by different physical interactions. The point at which the breakdown occurs is exactly where the linear solitons noted above cease to describe the plasma adequately, and the new property of self-ordering of phase takes over.

These numerical solutions to the equations thought to describe solitons raised some serious questions about the adequacy of the description. The difficulty of studying the rigorous implications of the equations plasma physics uses to describe solitons (as well as most other nonlinear phenomena) derives from the properties that distinguish a plasma. Most important is the fact that the fields and forces in plasma must be self-consistently determined along with the motions of the sources of those fields and forces. That is, to know the forces on the electrons and ions, we must know where the ions and electrons are and how fast they are moving; but to know the positions and velocities of the particles, we must know the forces acting on them. In a linear approximation, it is usually possible to make an approximate set of calculations; for example, first take positions and velocities of the particles, then calculate the forces created by this arrangement of particles.

The effect of this set of forces can then be calculated. In the linear case, the effect is small enough that the new positions and velocities of the particles differ only slightly from the initial approximation; and after several rounds of this calculation, one can obtain a self-consistent solution for both the fields and particles. This procedure allows the linear solutions to be corrected so that they become rigorously correct solutions of the equations—provided the calculation process converges on one plasma state.

In an attempt to use this technique to describe the modulational instability and thereby derive a rigorous solution to the problem of the existence of the soliton, a group of scientists at Los Alamos Scientific Laboratory derived a calculational process like the one described above. The first stage gives the usual solutions of the soliton, based on the initial assumption of static ions. Just as in the physical situation where plasma (Langmuir) waves exist, the Los Alamos group started with ions moving so much more slowly than the electrons that their motion (on first approximation) could be ignored, and the same restoring electric field that causes the characteristic oscillations in a plasma wave could give rise to the soliton picture described above.

In a usual plasma problem, the new fields the electron motion creates will perturb the ions only slightly, and this effect can be introduced in the second part of the calculation with only a small change of the electron and ion motion. However, the Los Alamos group found an astounding result: this calculation does not converge for the modulational instability. As soon as they attempted to calculate the second order effect, taking into account the force of the electric field from the modulational process, the equations became infinite.

These infinite equations constitute a severe problem. The whole rationale for any linear treatment of a problem is the assumption that the terms being ignored are small and that the entire series of terms could be calculated, in principle, but the effect of each additional term would be only a small improvement in accuracy. The soliton presents a case where the first term in the series (the linear one) is well understood, but where attempts to calculate the second term show that it is infinite!

Mathematically, the problem occurs because of the phase coherence of the modulational instability. The phase coherence of the soliton energy creates a singularity in the equations making terms in the equations infinite. This phase coherence is responsible for the mathematical difficulties in the analytical treatment of the Los Alamos group as well as the computer-generated solutions by Morales and Lee.

Like all calculations of this sort in plasma physics, the convergence of the series of terms depends on the validity of an approximation called *random phase approximation*, which assures that the different modes in the plasma are not coherently affected by one another. In the case of the solitons, however, the physical dynamics of the plasma *create* a coherence where none existed (or alternatively, these dynamics amplify a small preexisting coherence) and so invalidate the basis of the theory. The immediate result is recurrent infinities; zero phase difference gives zero denominators.

Most amazingly, the singularity that phase coherence creates is essentially identical to the singularities that plague attempts to describe the electron in quantum electrodynamics. To describe the soliton phenomenon it is critical to account for the self-ordering of the phase. However, when one attempts this in a rigorous way, the equations blow up in the same way the equations blow up in trying to describe the singular source of a simpler electromagnetic field problem—the electron. Note that the phase coherence is responsible for the fact that the energy from all the various plasma waves piles up in the same place to give rise to the soliton in the first place. Without the coherence of the phase in this wave energy, the small wavelength energy would dissipate, as it usually does in a plasma or fluid, into random energy.

Physics versus Experimental Evidence

Physicists today generally accept that the inability to describe the existence of the electron and the numerous infinities that arise in trying to do so, portend a *fundamental* difficulty in physics. However, they usually think that this difficulty does not infect other areas in physics, which, since they are at different energy regimes, will not have to be revised when a new theory of the electron is devised. Most physicists imagine the situation to be much like that in astronomy before relativity: On the energy scales of the solar system, old celestial mechanics remains adequate to describe all but the smallest effects in the motions of the planets.

The problem is that evidence from plasma physics shows that this belief is wrong. On an energy scale (that is, energy density) universally assumed to be describable by physical laws that could safely ignore the questions of the stability and existence of the electron, the same problem of coexistence of a field and its source has come back to plague attempts to theoretically describe the plasma. This is a problem that cannot be swept under the rug.

The fortunate thing about the appearance of this difficulty in plasma physics is that this field-particle phenomenon can now be attacked experimentally. A number of important aspects of the problem not only are more clearly delineated here than in the field of quantum electrodynamics, but also are accessible to empirical investigations.

Perhaps the most obvious feature the soliton data of Wong and Quon exhibit is the central role of energy density in characterizing the process of soliton development. The situation is paradoxical. On the one hand the conventional concept of energy is certainly correlated with essential features of the plasma problem. The central role of the ratio of coherent energy to random energy, for example, is essential to understanding even the phenomenology of the soliton.

Yet, the concept of energy as a simple scalar quantity is insufficient. First of all in the case of a plasma, the energy is a *modal* quantity. The usual idea of energy is a *scalar*

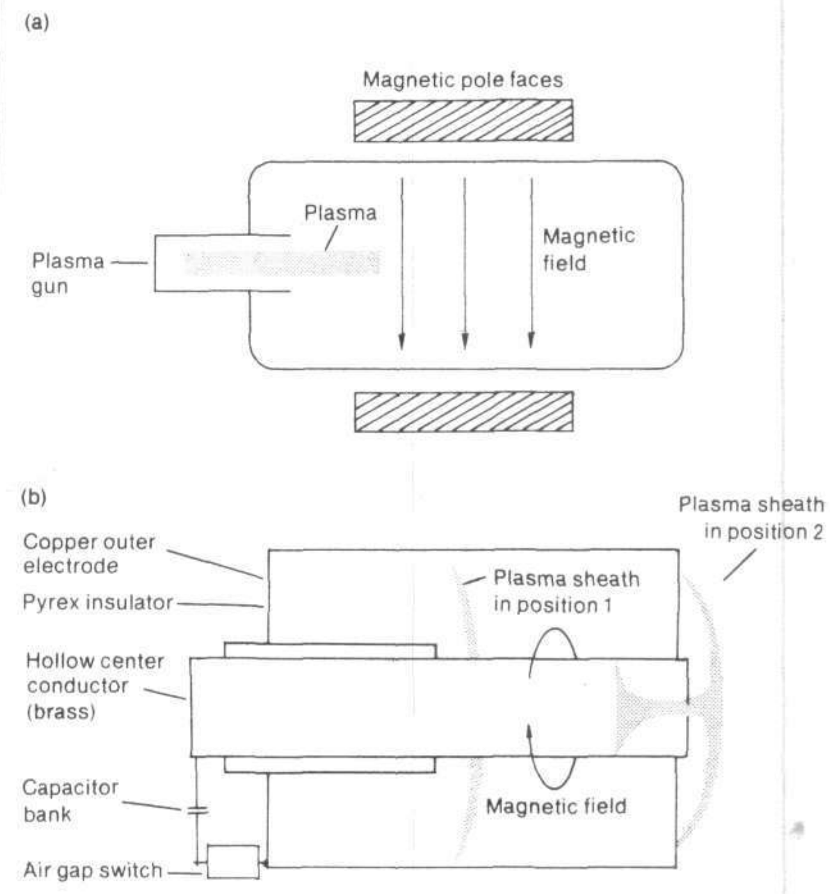


Figure 8
PROPAGATION OF A PLASMA ACROSS A MAGNETIC FIELD

The simplest variation of critical experiment number 2 is shown in **a**, *where a plasma very similar to Wong and Quon's is subjected to a uniform magnetic field perpendicular to its axis and a blob of plasma is shot into a cylinder lightly filled with plasma.*

A cross section of a plasma focus machine is shown in **b**. *It has the same geometry as* **a** *with the exception that the magnetic field is wrapped around an inner cylinder. As in* **a**, *the plasma is shot down the cylinder, perpendicular to the magnetic field. In this cross section of the two concentric cylinders, (1) and (2) are the positions of the plasma as it travels from left to right in the space between the cylinders.*

projection of some property of the system that prescribes its evolution. A correct concept of energy, however, is not just a question of "how much" but also of "in which direction" or "wherefore."

This is very clear in the case of the evolution of the soliton: The energy of the plasma was measured in at least three different ways in describing the solitons, each of which presumed an evolution of the plasma. First is the random background thermal energy of the plasma, which corresponds to our usual idea of temperature. This concept is coherent only when there is a definable, accessible equilibrium state that the plasma (at that energy density) can attain. If that reference state does not exist physically, then there is no temperature for the system.

Second is the use of the idea of energy to describe the energy in the coherent linear motion of the plasma, specifically the energy density of the high-frequency plasma waves, $E^2/8\pi$. Again, this application of the energy concept presumes a specific kind of time evolution, based on the existence and dynamics of the (linear) plasma waves. If such a plasma frequency or Langmuir wave cannot actually be defined for the plasma (for example, if there is no equilibrium for the ions about which the electrons can oscillate at the plasma frequency), then this ratio has no positive significance.

The concept of energy assumed a third qualitative aspect when the ratio $E^2/8\pi nT$ was on the order of 1 (*Tsytovich's strongly turbulent plasma*). The ratio itself has no quantitative significance in this regime, but it serves to indicate that a new quality of physical interaction is determining the evolution of the plasma--the phase coherence of the small-scale motions in the plasma that conspire to form solitons.

The essential point here is that the energy cannot be defined in some a priori way before a knowledge of the physics of the plasma. In each of these three phases, the energy is contained in different modes of the system—modes that, especially in the case of the solitons, take on a life of their own and fundamentally change what the plasma is.

In fact, the assumption that such a definition of energy is possible a priori, leads directly to the paradox of the soliton's existence. Once it is assumed that the electrons and ions are the building blocks of the plasma—building blocks that are unchangeable and interact according to unchangeable laws—then the equations that purport to govern these particles will "blow up" just at the point that the physics of the system changes. The currently accepted equations of plasma physics, based on Newton's laws and Maxwell's equations, cannot explain phenomena like the soliton precisely because they cannot reflect the qualitative changes that a plasma can undergo. At the point that the plasma in actuality experiences a phase change, the equations describing it become divergent. In this sense, the electron and the soliton are analogous entities: both are the singularities that induce a qualitative change in the evolution of the system that generates them by its own internal processes of energy concentration.

These changes in energy density are manifested in dramatic changes in the internal differentiation in the plasma. The property of self-ordering or self-organization, which is so striking in almost all nonlinear phenomena and especially in a plasma, is a qualitative indicator of the more basic feature of the evolution of the system, a feature that the usual idea of energy as a simple quantitative magnitude approximates only roughly. The significance of the spontaneous appearance of order out of disorder, which has struck many scientists, is not merely its nonentropic character. More important, its significance is the evidence it provides of the conjunction of new energy domains with increasing self-differentiation *and* the appearance of singularities at these junctures.

The power of plasma physics as a discipline at the present time is the experimental data it provides for unraveling the interconnection among the appearance of singularities, the qualitative change in the laws governing a given physical system, the increasing tendency for energy densification, and the onset of self-ordering evolution. These qualitative features dominate the character of the universe as a whole (and certaintly that of man and his science). Plasmas are a laboratory where such changes can be studied now, and, in fact, must be mastered now for our own survival. The evidence from the experiment by Wong and Quon shows quite dramatically that this mastery demands a fundamental change in our understanding of physical law. The simple fact is that current physical laws not only are insufficient to explain their results, but also are contradicted by the implications of these results.

The work of Wong and Quon raises a number of serious questions:

First, if increasing energy density is associated with different kinds of characteristic evolutions in a plasma, what happens to the measurement of the rate and quality of this evolution? Time seems to be relative to the interactions that go on in the plasma rather than functioning as some uniform, continuous background for the plasma dynamics. How is this possible?

Second, how does the plasma "know" to evolve to more and more complex states with higher and higher energies? What is driving this nonentropic evolution? Entropy, the usual concept of dissipative evolution, is a derived conception applicable only when a singularity does not exist that induces a change in the laws governing the system. But what is to rigorously correspond to such an invariant feature of negentropic (as opposed to nonentropic) evolution?

Third, what is the relation of the concepts of an energy cascade and phase coherence to the evolution in a plasma? These two concepts are litmus tests for the underlying phenomenology of Wong and Quon's experiment, but what systematic feature of plasma behavior do they reflect? Why does a singularity in the phase bunching of a soliton disrupt the otherwise continuous aspects of the fields in a plasma? What does this mathematical singularity indicate about the plasma itself?

CASE HISTORY 2: PLASMA MEETS MAGNETIC FIELD

Wong and Quon's experiment has received considerable scrutiny from the plasma physicists because it strikingly illustrates the deep-rooted nature of the nonlinearities in a plasma. In addition, there are a series of experiments conducted in a number of laboratories that shed even a clearer light on the nature of a plasma and the fundamental difficulties it presents for modern physics. These experiments also offer some absolutely critical empirical data for answering the questions that Wong and Quon's experiments sharply raised but could not answer.

These experiments are very simple in outline, and Figure 8 shows schematically their unifying feature—the propagation of a plasma across a magnetic field. The experimental setup is similar to that for the beam-plasma experiments, except that a uniform magnetic field is imposed here perpendicular to the direction of motion of the plasma. There is no useful analogy to other fluids of the propagation of the plasma through a magnetic field; the magnetic field and its energy relations are a new degree of freedom that differentiates a plasma in an essential way from a nonelectrical fluid.

First, let's look at the simplest, least adorned instance of this phenomenon, depicted in Figure 8a. These experiments, carried out at the Stevens Institute of Technology in the late 1960s, produced some surprising results. When a plasma is propelled across a magnetic field, large vortices form! Figure 9 presents several photographs taken with an extraordinarily high-resolution technique that show the basic fact. When a plasma traverses a magnetic field, even in the very low-energy cases shown here, the plasma gets twisted up into large vortices that are oriented perpendicular to the background magnetic field. These photographs are the clearest, most unequivocal demonstration of this behavior. The other situations we shall examine have pursued this phenomenon into higher energy regimes and with more complex experimental devices (like the plasma focus shown in Figure 8b), but the outstanding plasma behavior can be seen even in the simplest case.

As in the case of the soliton, and with the same proviso about classical plasma physics, some machinery from contemporary concepts about a magnetized plasma is essential to unravel these vortices. On the most reductionist level, the effect of a magnetic field like the one above is to distort the orbits of individual charged particles in the plasma. In Figure 1d, for example, the representation of this distortion shows that the charged particles tend to spiral around the direction of the magnetic field (around the lines of force).

At the level of this single particle-external field picture, in fact, the particle will experience a force that is always perpendicular to its direction of motion, and so it will execute circular motion about an axis defined by the magnetic field. (This is strictly true in the case of a uniform magnetic field; the case of a nonuniform field is more complicated but the same general phenomena obtain for our purposes.)

A plasma, however, is not a collection of single particles in an externally created field. The conventional next step in conceptualizing a plasma is to find the natural normal mode that characterizes the interaction of the plasma and the magnetic field—a mode corresponding to the electron plasma wave in the case of interactions between the electric field and the plasma. This mode is called the *Alfven wave*, and the characteristic velocity of the energy the wave carries is shown in Figure 4.

The Alfven wave is a collective interaction of the plasma and the magnetic field that is dominated by the ions; therefore, it is very slow compared to the plasma wave. The basic reasoning behind the Alfven wave follows from the fact noted above that an individual particle has an orbit that will rotate around the direction of the magnetic field. Provided that the motion the particle might otherwise have is small, a sufficiently strong magnetic field will tie that particle down near a magnetic field line, because of the tight spirals the particle executes about the line. The particle is not constrained in its motion *parallel* to the line, but it cannot move away from the magnetic field line. Therefore, the plasma has a tendency to stick to the magnetic field lines. In fact, under the simple conditions considered here, if the plasma has no electrical resistance, it must stay on the field line on which it begins. This assumption of no resistance amounts to assuming that the magnetic field is strong enough and the collisions of the plasma particles few enough that the particles cannot knock each other off the lines or that the ideal orbits about the magnetic field line dominate everything else.

Within this limit, the Alfven wave exists in a way analogous to the plasma wave. If the plasma is plucked, it will take the magnetic field lines with it, stretching them. However, in this approximation, the field lines resemble rubber bands; they are under tension so that they spring back, setting up an oscillation with a characteristic velocity of the Alfven velocity. The oscillation back and forth of the magnetic field line is entirely analogous to the waves on a piano string, where the field line supplies the tension, and the plasma the mass.

In the linear limit, where the displacement of the magnetic field line by the Alfven wave is vanishingly small, the Alfven wave is the natural energy-containing mode of a magnetized plasma. The situation is similar to an unmagnetized plasma with plasma waves. In the case of the Alfven wave the small, additional oscillating magnetic field (that is, a reflection of the movement of the background field line) must really be small. As in the case of the plasma wave, the ratio of this small perturbation magnetic field to the background field must be small enough that only the first power of the ratio is significant; hence, the term linear. If this limit existed, it would be subject to the same considerations relevant for the water jet; namely, that any dissipation or friction in the system would result in the simultaneous cascade of any ordered energy to

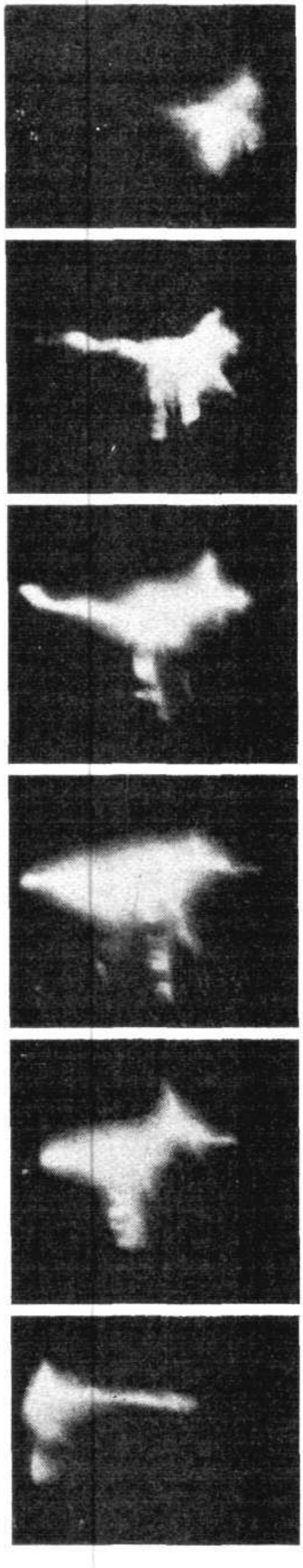
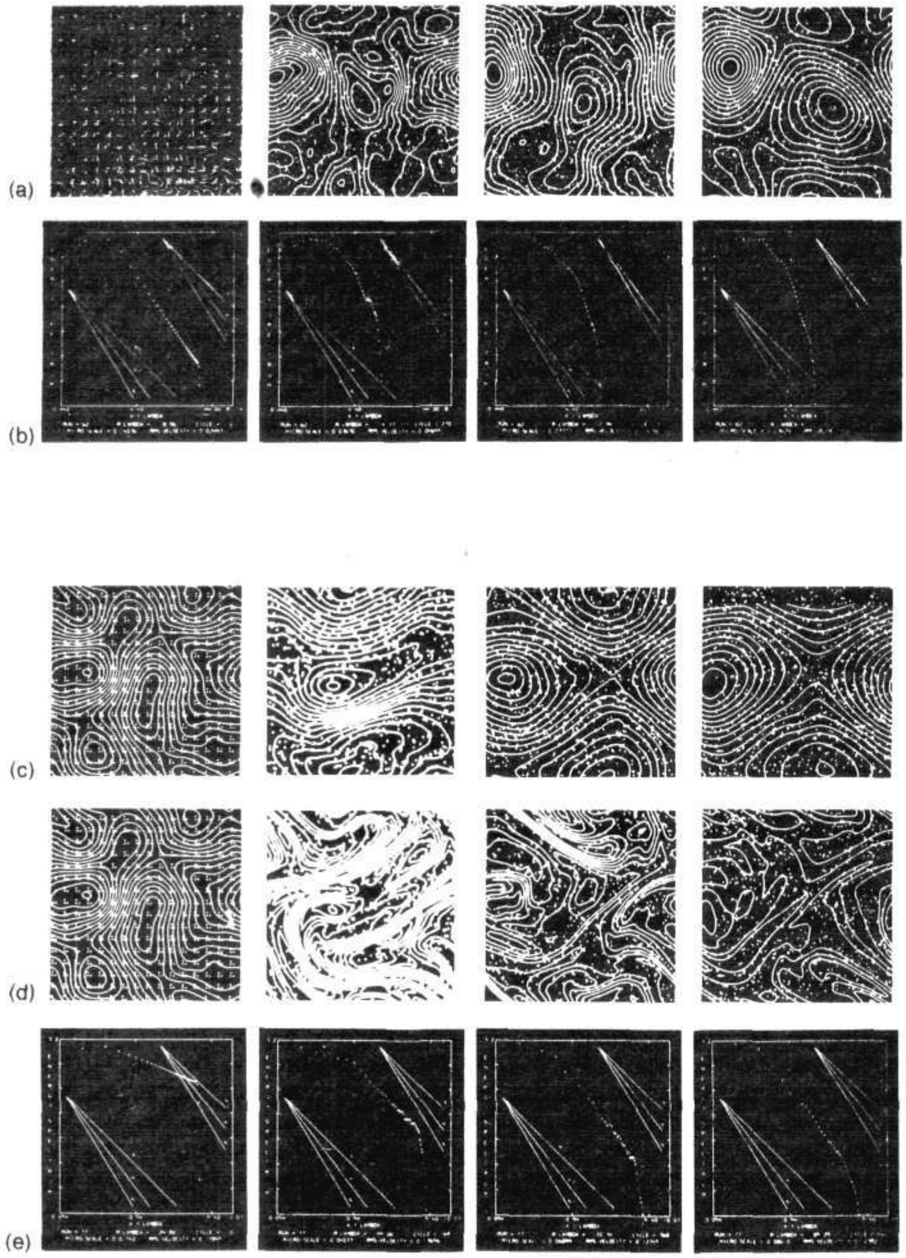


Figure 9
PLASMA TRAVERSING A MAGNETIC FIELD

This series of photographs shows a low-energy plasma propagating across a magnetic field of varying strength. The blob is a small piece of plasma from a "plasma gun" traveling (head-on out of the page) across a magnetic field against the background of a diffuse plasma. Even in the case of the very low-energy interactions here, the plasma is twisted up into easily recognizable filaments, which on closer study, are vortices of plasma. The magnetic field curls up the plasma into these characteristic shapes at almost every energy level.

Figure 10
COMPUTER SIMULATION OF TWO-DIMENSIONAL FLUID MOTION AND MAGNETIZED PLASMA MOTION



The first two sets of graphs show the fluid motion (**a**) *and spectrum* (**b**) *as simulated by a computer solving the classical equations governing a fluid. The frames in* **a** *are from a computer-generated movie of the fluid motion, with time increasing from left to right. This fluid is like a real (three-dimensional) fluid, except that its motion is mathematically restricted to a surface (like a soap film). This constraint introduces a very striking physical effect: The evolution of the fluid proceeds in exactly the opposite direction from that in a three-dimensional fluid—the fluid orders itself. The initial state of the fluid (far left column) shows a random collection of small-scale turbulence; as time goes on, these small-scale motions coalesce into larger and larger vortices, until, in the final frame, there are two, large counterrotating whirls.*

The spectrum (**b**) *shows the same effect of the transfer of energy from small scale lengths (large k) to large scale lengths. This is called an inverse cascade of energy.*

The last three sets of graphs are the analogue of **a** *and* **b** *for an ionized fluid. The graphs in* **c** *show the time evolution (from left to right) of the plasma flow;* **d** *shows the self-generated magnetic field at the same times; and* **e** *shows the spectrum for the total energy of the plasma (the plasma plus magnetic field).*

Although they are done in two dimensions, the graphs model very closely the three-dimensional behavior of a plasma; as the graphs show, the plasma orders itself, generating large vortices out of chaos. Since this correspondence between the (idealized) two-dimensional solution and the three-dimensional actuality does not hold for a fluid, the question is, what made the three-dimensional plasma behave like a two-dimensional fluid? Since these computer simulations were done, it has been shown that the magnetic field creates a new constraint on the plasma motion, called the magnetic helicity, that has the effect of reducing the actual dimensionality of the plasma dynamics. The result of the mathematical constraint of constancy of magnetic helicity is to "force" the self-ordering of the plasma and the formation of force-free structures like the vortices shown in **a** *(note the almost parallel field and flow in the last frame). However, this nonlinear treatment cannot answer the question of what happens when these energy-dense, self-created structures interact.*

smaller and smaller scale lengths and the randomization of the phase of this energy. The combination of these two processes then results in the smoothing out of the energy and an eventual heating of the new equilibrium.

The magnetized plasma violates all of these expectations. Dissipation produces ordering, energy has an inverse cascade, going to longer and longer scale lengths, and phase-coherent processes dominate the evolution!

The pictures of the plasma in Figure 9 show this extraordinary behavior clearly, at least on a phenomenological level. To analyze this experiment further, however, requires a twofold approach. On the one hand, we can apply present theoretical ideas to this nonlinear phenomenon, deriving some important insights. However, this kind of nonlinear analysis can take us only up to the point at which the plasma begins to change qualitatively. Within the relatively fixed geometry of a low-energy plasma traversing a magnetic field, many of the self-organizing effects, like vortex formation, can be illuminated. But the plasma is doing more than just ordering itself; it is participating in a larger evolutionary process that is inaccessible to present physics. These qualitatively new phenomena become dominant in higher-energy experiments, and these experiments must be examined and contrasted to the limited understanding possible within present physics.

What we have here are actually two kinds of nonlinearity. One is the simple nonlinearity of present physics, which, even though it is comparatively simple, has gone largely unrecognized in physics today and is sufficient to account phenomenologically for a large variety of self-ordering phenomena. These self-ordered structures, however, are not significant in and of themselves; rather, they point to the more fundamental characteristic of the universe and its negentropic evolution. The real nonlinearity is negentropic evolution on the global scale. The job of science is to use the first kind of nonlinearity to unravel the second.

A number of scientists in the last six years have attempted to isolate the source of the striking changes a magnetic field creates in a plasma. These studies have shown from a number of different points of view that the primary effect of a strong magnetic field in a plasma—including self-generated magnetic fields—is the introduction of a new global constraint on the plasma motion. On an overly simple level, this is obvious from the above discussion about the way a magnetic field can restrict particle motion to the direction along the field line. These studies showed something more basic, however: The magnetic field in a plasma introduces a constraint that has the effect of ordering the large-scale plasma motion.

The Two-Dimensional Fluid Example

To understand this effect, let us look at a situation where the constraint has been introduced artificially. Figure 10 shows graphs of the motion of a two-dimensional fluid, as generated by computer solutions to the equations describing the linear mechanics of a fluid. (Such computer solutions are necessary here since there are no truly two-dimensional continuum systems.) We saw before the characteristic evolution of a three-dimensional fluid (that is, a real fluid), and deduced from it the two dominant features of its evolution—an energy cascade and randomization of phase. A two-dimensional fluid differs only in that its motion is restricted to a plane surface (a soap film, for example). As Figure 10 shows, however, this constraint of a two-dimensional motion totally changes the behavior of the system. Instead of large vortex motion breaking up into small chaotic vortices, small-scale tur bulence *coalesces into large, ordered vortex motion!*

This effect is due purely to the change from three to two dimensions. The vortices are not attracted to each other nor to any other mechanical interaction that is different in the two cases. In the language of statistical mechanics, if the vortices are constrained to move in two dimensions, it is simply "more likely" for one to find the vortices bunched up in coherent structures than to find them randomly distributed at small wavelengths.

The second line of graphs shows clearly that there is a so-called inverse cascade of energy; the energy goes from the initial distribution with large energy at large k (small wavelength) to energy concentrated at small k (that is, large wavelength). From a look at the distribution of energy in physical space, it is obvious that this energy is highly phase coherent, with the final state in each case having two, large, counterrotating vortices.

Two-Dimensional Magnetized Plasma

Figure 10 (c) and (d) contrasts this fluid self-organization with a similar situation in a magnetized plasma. Here the magnetic field is shown in Figure 10(d) and the motion of the plasma in 10(c). Although again this is a two-dimensional situation, it models very neatly the three-dimensional plasma. The same self-ordering effects are obvious, with the tendency for small-scale motion to coalesce into large. Again, the final state is of two large, counterrotating vortices, obvious both in the plasma motion and in the magnetic field. Furthermore, the plasma-magnetic field configuration is force free, in that the plasma experiences no force from the self-generated magnetic field, since the flow is always parallel to the field.

These are not just characteristics of the computer solution; they occur in real, three-dimensional plasmas, much in the way shown in the pictures in Figure 9. A magnetized plasma is dominated by an evolution that is characterized by inverse cascades of energy, phase-coherent energy-containing modes, and force-free coherent structures. The theoretical studies of computer solutions like these have shown reasonably clearly what is responsible for the fact that a three-dimensional plasma shares these self-ordering characteristics with a two-dimensional fluid: The magnetic field creates a new constraint on the plasma evolution that acts mathematically like a reduction in the dimension of the system.

In the case of the fluid, restriction to two dimensions forces the conservation not only of energy and momentum (which are conserved in three dimensions as well), but also of *vorticity*, a global measure of the twistedness of the flow. Since the vorticity cannot change in two dimensions, the allowable motions of the fluid are restricted, resulting in a seemingly unnatural tendency toward order.

In the three-dimensional plasma, the magnetic field introduces a new conserved quantity called *magnetic helicity*, a measure of the twistedness of the field and flow together, which must be unchanged by any motion of the plasma. When this helicity is very large (that is, the plasma is prepared in a state where the helicity is large to begin with and so must stay large whatever the plasma does), the motion is constrained in a way almost identical to two-dimensional motion. The magnetic field introduces an effect qualitatively similar to two-dimensional fluid motion, and the plasma is forced to be self-ordered.

As we shall see, the evolution of the plasma does not stop with this vortex formation; energy concentration continues and more extraordinary things happen. But this is as far as conventional plasma physics, even in its more nonlinear forms, can take us. If these computer solutions are allowed to progress for an indefinite length of time, the plasma motion predicted by the computer slowly runs down, and the ordered motion becomes weaker and weaker. In a real plasma, this emphatically is not what happens; but this is as far as we can follow a theoretical description constrained within a mathematical physics that cannot predict from the outside a qualitative change in the system.

The formation of these force-free vortex structures is an important signpost, however, to the more fundamental processes underlying all of negentropic evolution, and for this reason bears closer study.

It might be suspected from analogy with the formation of a soliton out of the nonlinear states of a plasma wave that the nonlinear states of an Alfven wave are related to vortex formation, and this is the case. A careful look at the wave properties of these vortices shows that, in fact, they are the nonlinear stage of the linear Alfven wave.

The most important indication of this relation is the basic geometric feature of an Alfven wave. As noted above, the Alfven wave is a small periodic perturbation of a background magnetic field that results in an oscillation back and forth of the field line while the plasma is stuck to the field line. The wave supports part of its energy in the form of a small magnetic field that is perpendicular to the background field but parallel to the displacement of the field line. As long as the magnitude of this self-created field is small compared to the background field, the linear Alfven wave exists. The important common characteristic of the Alfven wave is that it is a force-free oscillation, in the sense that the magnetic field the wave creates (the small perturbation) is parallel to the motion of the plasma. Since the velocity and magnetic field are parallel, there is no Lorentz force (the magnetic force a charged particle feels when it travels perpendicular to a magnetic field).

This phenomenon is strictly a *collective* motion of the plasma. The motion of a single charge always creates a magnetic field perpendicular to its own motion; but when the plasma as a whole creates a magnetic field, it is parallel to that motion! This is also the case for the plasma vortices described above, and is the best indication that they are the nonlinear states of an Alfven wave. It is difficult now, however, to talk about an "Alfven wave" in the same sense, since the necessary assumptions underlying an Alfven wave no longer are satisfied. The perturbation of the magnetic field, that is, the self-created field, is as large as or larger than the background field, and the background field no longer dominates the orbits of either individual particles or the plasma as a whole. In fact, the formation of these vortices allows the plasma to "leak" across the magnetic field that was supposed to be so strong that it would confine their motion.

The rather disturbing conclusion of this observation is as follows: Although classical (linear) plasma physics predicts that a strong magnetic field will confine a plasma and prevent its moving in a direction perpendicular to that field, the plasma finds a way of creating its own magnetic field in vortex rings and filaments, and it then uses these to "diffuse" across a magnetic field at will. This is a well-known experimental phenomenon called *anomalous diffusion*, although few plasma physicists appreciate the role of vortex motion in its occurrence. Actually, it is neither anomalous nor diffusion, but the ordered, self-concentration of plasma and magnetic field in a force-free structure.

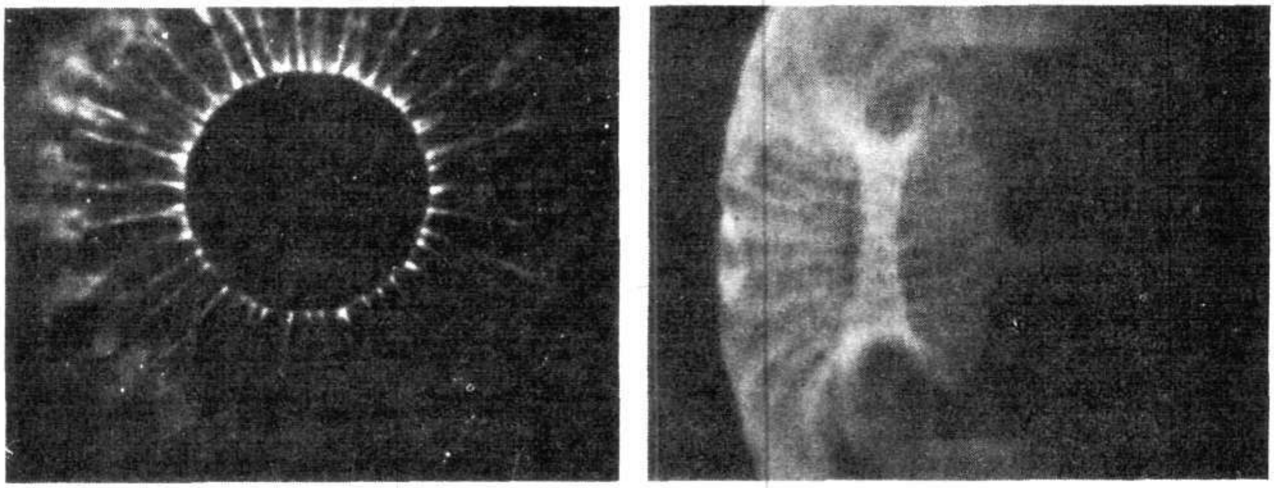
High-Energy Plasma

With these tools we can now look at the full evolution of a high-energy plasma traversing a magnetic field. Again, it is essential to stress that the concepts from currently understood physics are only guides to the actual behavior of the plasma, and they are most informative when they fail to explain phenomena, not when they succeed.

An actual plasma undergoes many energy regimes in the course of its natural evolution, each stage in the evolutionary series qualitatively distinguished from the previous ones. The concepts appropriate to any one of these stages, however, are not important in and of themselves, but only in so far as they provide insights into the transition from one stage to another. The most important task facing plasma physics is to use the concepts derived from observation of the self-ordering phenomena in any given regime to the understanding of the transition in the plasma to a new regime where those old concepts, by necessity, become inapplicable.

The most critical aspects of the behavior of a plasma as it travels across a magnetic field are evident only by implication in the low-energy experiments described above, since the computer solution shown in Figure 10 and the experimental results shown in Figure 9, as well as the conceptual tools of the nonlinear Alfven wave and the force-free vortex, all apply only within one plasma energy regime.

The experiment shown in Figure 8b makes these implications almost inescapable. The plasma focus in essence is the same experiment described in 8a, except that the plasma energies are now much larger. In the plasma focus, the magnetic field is wrapped around the center conductor and the plasma travels down the space between the two concentric conductors. In a cylindrical configuration this is the same experiment of a plasma with a velocity perpen-



(a)

(b)

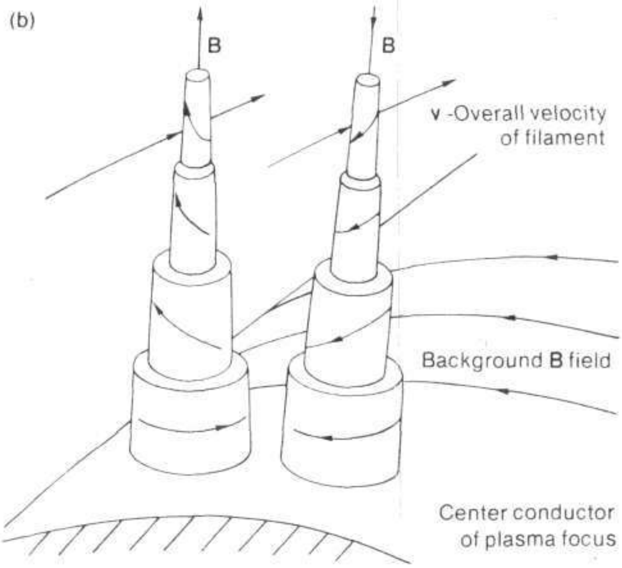


Figure 11
THE EVOLUTION OF THE PLASMA SHEATH IN A PLASMA FOCUS DEVICE

The photograph of the first stage of the evolution of a plasma sheath in a plasma focus device (left) shows the already formed plasma filaments. Note that the filaments occur in pairs and that some of them have begun to unravel at the outer ends. In the later photograph (right), the sheath has begun to fall off the end of the electrode and concentrate at the focus. The intricate structure of the sheath has been conjectured by a number of scientists, but its details remain a mystery.

*A pair of plasma vortex filaments, whose photographs appear above, is shown in the diagram (**b**). The magnetic field and local plasma velocity is always parallel, so that the filaments are force free. Note that the overall configuration is of a plasma moving transverse to a magnetic field since the external field is supplied by the inner electrode's magnetic field, which is wrapped around the electrode. The plasma in the filament twists around, like the **B** field.*

dicular to the magnetic field externally imposed on the moving plasma. In the first step of the experiment, a sudden burst of electrical energy is switched from the capacitor to the inner and outer electrodes of the plasma focus. When the voltage reaches a high enough value (depending on the type of gas that fills the space between the cylinders), the gas in the machine is ionized; that is, the electrons are stripped away from their nuclei and a plasma is formed. This initial plasma is an amorphous blob in the back end of the machine. The plasma interacts with the magnetic field that surrounds the central electrode and the plasma gets pushed down the machine toward the end of the electrodes.

Now interesting things begin to happen. The plasma does not travel as a uniform blob down the machine, but first forms a very thin sheet, like a curved surface of a bubble being blown down the annular space between the electrodes. This extremely thin, smooth *plasma sheath* is the first step in self-concentration of energy in the plasma. It is very short lived, since it is quickly perturbed and begins to ripple, and in the indentation of each ripple, the plasma rolls up into a filament!

In many ways, this stage of the evolution of the plasma is the most intriguing. The plasma has created tight, twisted filaments that have a detailed internal structure out of an initially totally disordered plasma.

Figure 11 shows photographs of the plasma filaments and a diagram of their hypothesized internal structure. Several things are very striking about these filaments. First, in simple quantitative terms, the energy density of the plasma in these filaments is thousands of times greater than the energy density of the initial background plasma. The spontaneous evolution of the plasma has generated on its own a tremendous "graininess" in the plasma (very reminiscent of the formation of solitons).

Second, the filaments are not just local, randomly formed phenomena. As the photograph shows clearly, the filaments form in pairs, and more detailed measurements show that these are pairs of counterrotating filaments, as depicted in 11b. Each filament is formed of tightly wound magnetic fields and plasma currents that get more and more vertically aligned toward the center of the filament.

Furthermore, the arrangement of these currents and fields is force free. Since the magnetic field in the filament, which is self-created, is everywhere parallel to the plasma velocity, the filament is a Lorentz force-free configuration. Its resemblance to the computer-generated vortices in Figure 10 is quite amazing. Both show a tendency for the formation of large-scale structure out of initial disorder (that is, an inverse cascade of energy and coherent phase processes); and both form a structure of force-free vortex motion with pairs of oppositely directed vortices.

Compare this behavior to what usually happens when energy is put into a system. To heat a cold room, we take advantage of the usual property of gases whereby the energy put into them is very quickly distributed evenly throughout the gas and the heat energy becomes randomly spread out. In the plasma focus, this would work very differently. It is as if after one turned on the radiator to warm up a room, the radiator would suddenly spew out not just very hot streams of air, but jets of molten iron made out of the melting radiator. And if the air in that cold room could spontaneously concentrate this energy by a factor of thousands, as the plasma focus does, we would be in trouble.

The filaments in the plasma focus continue to tighten and become more intense, hotter, and more concentrated as the plasma continues down the space between the electrodes. At certain points they unravel slightly (see the ends of some of the filaments in Figure 11, where the outside end of the filament looks like an old rope), and occasionally they cross and annihilate each other. In general, however, they move unimpeded down the machine. It's when they come to the end of the electrode that the fireworks begin.

The plasma focus was designed to take advantage of the self-forces in the plasma that tend to pull the plasma into a tight ball at the end of the inner electrode.

Figure 11 also shows photographs of the plasma focus in this stage. As the plasma filaments fall off the end of the inner electrode they begin a process of mutual annihilation and re-formation. The whole process goes on in less than a millionth of a second as the filaments form and re-form into a tight plasma nodule at the end of the machine. The exact structure of this nodule is a subject of current research, but seems to be a higher-order conglomeration of filaments, like a ball of rope made up of strands of rope.

Whatever the exact internal structure of the nodule, the macroscopic results of the destruction and re-formation of filaments is well known. The intense magnetic fields in the filaments create concentrated and highly energetic beams of ions in the plasma. These beams of deuterium ions (when deuterium gas is used to fill the plasma focus) are at a temperature of 350 million degrees! The beams of particles are highly localized and occur every time the plasma focus is discharged.

The effect of the beams on the plasma is amazing; fusion occurs. Deuterium ions in these beams collide with ions in the background deuterium plasma, fusing to form helium and tritium in a series of fusion reactions. In fact, the plasma focus remains the most prolific producer of fusion neutrons in the whole zoo of fusion plasma experiments.

The neutrons that are observed in the plasma focus come out of the following sequence of events: the self-concentration into a plasma sheath, the formation of filaments in that sheath, the collapse and mutual annihilation of the filaments, the acceleration of ion beams out of that annihilation process, and the fusing of beam particles as they collide with other deuterium ions. This is not at all an equilibrium thermal process; every step requires highly nonlinear, self-organized structure for the necessary energy storage and densification. In fact, in the minds of most of the plasma physics community, this nonthermal origin of the neutrons (which could be measured just from looking at the neutrons themselves and did not presume an understanding of their origin in the destruction of the filaments) doomed the plasma focus as a contender for the role of a technological fusion device. The reason? If the plasma focus neutron production was not from an equilibrium, thermal plasma, then it was not kosher because it was not *thermo*nuclear fusion. Besides, it was thoroughly suspect because of its nonlinear parentage.

Whatever one's opinion of it, however, the plasma seems to have a natural tendency toward energy concentration and the "natural" end result of that process is fusion; fusion is where the plasma seems to head on its own.

SOME CONCLUSIONS

To look at the evolution of the plasma in a plasma focus demands a more global view of the process of its development than the theoretical tools from plasma physics described above. It is not enough merely to describe the local forces operative at each point in the life-history of the plasma; there must be some thread connecting them together. In the case of the formation of solitons, this problem could not be answered, since there was only one "stage" whose real characteristics are experimentally available at this point. Nevertheless, the question about what is "driving" the evolution of the plasma has to be answered. For the plasma focus, much more can be said. A number of physicists have attacked this problem within the confines of the specific problem of accounting for the creation of the plasma filaments out of the plasma sheath. This process of the "winding up" of the plasma cannot be dismissed (as most physicists dismiss it) with the statement that an "instability"—variously called the *tearing instability* or *tearing mode*—accounts for the destruction of the smooth sheath. This is not sufficient either qualitatively or quantitatively.

A much more enlightening attempt at solution has been pursued by a group of physicists around Dr. Dan Wells at the University of Miami. The Wells group has used a purely fluid model of the plasma (that is, treating the particles as

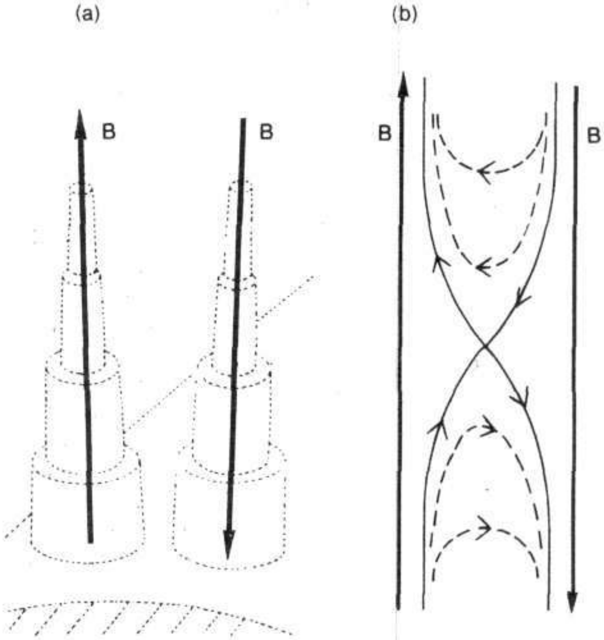


Figure 12
FORMATION OF A DOUBLE LAYER IN THE MUTUAL ANNIHILATION OF TWO PLASMA FILAMENTS

Two adjacent plasma filaments are shown in **a**, *with the dark lines representing the central and most intense magnetic field of the filaments. Since the filaments are counterrotating, the fields are aligned in oppoiste directions. In between the filaments, a so-called neutral layer is formed, containing no net magnetic field. The whole configuration is called a double layer.*

If there is any process in the plasma that allows the magnetic field lines to free themselves from the plasma, even locally, this double layer becomes unstable, and the field lines will reconnect (**b**). *The sudden release of tremendous amounts of magnetic energy as the stretched field lines now contract (dotted lines) appears as kinetic energy in the plasma particles in the form of intense particle beams. This diagram is grossly oversimplified; in reality, there are accompanying shock waves and the like. At this point of reconnection, intense electric fields are also formed, in association with the rapidly changing magnetic field.*

spread out and acted on only as a whole by fluidlike forces from the magnetic field) and has applied this model to the problem of a plasma moving across an external magnetic field.

This magnetohydrodynamic approach has generated a number of important insights. First and most striking is that the plasma changes its internal and external configuration so as to minimize its available or free energy; in other words, the global behavior of the plasma is such that it is as efficient as it can be with the energy available to it. Within the framework of magnetohydrodynamics, the possible motions of the plasma are restricted by the fact that several quantities *cannot* change their value as in the computer studies of the two-dimensional fluids and plasmas—energy, number of particles, and magnetic helicity, for example. In the case of plasma moving across a magnetic field, when these constraints are applied at the same time that the free energy is minimized the most efficient motion for the plasma is the formation of nonlinear Alfven waves in the form of vortex filaments! These filaments can take various shapes depending on the configuration of the plasma, but the overall "necessity" within this theory is the formation of the same sort of filaments observed in the plasma focus. Furthermore, the theory predicts that the filaments must be force free (that is, with their plasma motion parallel to the self-created magnetic field).

Notice carefully what Wells has shown. Magnetohydrodynamics starts from a global picture of the plasma; it is *not* viewed as a collection of charged particles. Furthermore, the dynamics take the plasma as a whole as its starting point; the motion of the plasma as a whole, not the individual particles, is the source for fields. Within this fixed physical geometry, the plasma acts to minimize a well-defined parameter related to its excess energy, and in conforming to this strict requirement, it forms a highly structured metastable equilibrium. This metaequilibrium, as we have seen, comes from an inverse cascade of energy and *non*random phases.

Wells's work was taken up by David Montgomery of the College of William and Mary and of the Los Alamos Scientific Laboratory who showed that the criteria Wells used to perform this extremal calculation had a deeper implication. Wells had specified that the energy had to be minimized subject to the constraints of the problem, but Montgomery noted that the energy and magnetic helicity, the two most important constraints in the problem, are not actually on an equivalent footing. He showed that the energy does in fact have a tendency to decrease (from various entropic effects), but that the magnetic helicity cannot.

Furthermore, in this situation the magnetic helicity measures precisely the degree to which the plasma forms a large-scale, force-free structure. In other words, Montgomery showed that the evolution of the plasma is governed by a principle that requires the maximization of the large-scale coherent structure in the plasma motion! The significance of the striking effects introduced by a magnetic field (noted above) can be reduced to this amazing qualitative implication of the magnetic helicity.

For all its sophistication in comparison with the usual particle pictures of plasma motion, however, this model is based on a fixed geometry of physical interaction; and whatever the plasma does, it must remain within that geometry. As long as the plasma does so in reality, we have a very powerful tool for predicting its motions and for understanding its behavior on a deep level. But, like any *fixed* geometry, this geometry is unstable; the plasma does things that force it out of that framework.

This is especially clear in the case of the plasma focus, much more so than in the formation of solitons. The obvious question that arises out of a comparison of the Wells theoretical work and the Bostick experiments is: Why do the filaments annihilate each other? Although the empirical details of this process are not clear, there are a few basic things that can be said to answer this question.

Consider the configuration formed by the adjacent pairs of counterrotating filaments, called a *double layer* (shown schematically in Figure 12). There are two regions of intense oppositely directed magnetic field right next to each other. The region of plasma between them is called a neutral layer. This double layer configuration occurs in many other plasmas, most spectacularly in the region where the magnetic field associated with the plasma that is continually emitted by the sun (the solar wind) hits the earth's magnetic field.

Magnetohydrodynamics can describe this double layer with the filaments around it in terms of the magnetic field configuration shown in the figure. The magnetic field is the only force needed to formulate the problem. In real life, however, the double layer is not so simple. Remember that the magnetic field lines can be imagined to be under tension; they are stretched all the time. If there is any process in the plasma that allows the field lines to move through the plasma (without taking the plasma that is stuck on the lines with the lines as they move), then the lines can break apart and reconnect.

In the double layer, as long as the plasma is perfectly conducting (or, equivalently, under most circumstances, as long as there are no collisions between the particles), the lines are stuck in the plasma and the double layer can exist indefinitely. Imagine what happens if two of the oppositely directed field lines on either side of the neutral layer touch each other and then reconnect. Since they are both being "stretched," they will immediately pull upwards and downwards, like a pair of rubber bands from a double-barreled slingshot. This hypothetical sequence is shown in the series of diagrams in Figure 12. In gross outline, this is what happens in double layers; they are unstable, and they discharge their stored magnetic energy by a very violent process of line reconnection.

When these lines reconnect, all hell breaks loose from the point of view of the particle in the plasma. First, even from simple magnetohydrodynamics, we would expect the particles in the region of the reconnection to be violently affected, since they would be flung out of the region along with the reconnecting field line. In fact, this does happen; but more important, the qualitative character of the system also changes. In magnetohydrodynamics, the only electromagnetic field needed is the purely magnetic one. However, it is clear from the same classical considerations that give rise to magnetohydrodynamics that when the magnetic field is changing this quickly, the electric field must be put in the equations. The rapid changes in the magnetic field caused by the violent reconnection of the field lines generates an intense electric field. This electric field then sends the particles flying. The electric field, which is highly localized at the site of the reconnection, accelerates intense beams of deuterium ions; and these, in turn, cause the fusion in the plasma focus.

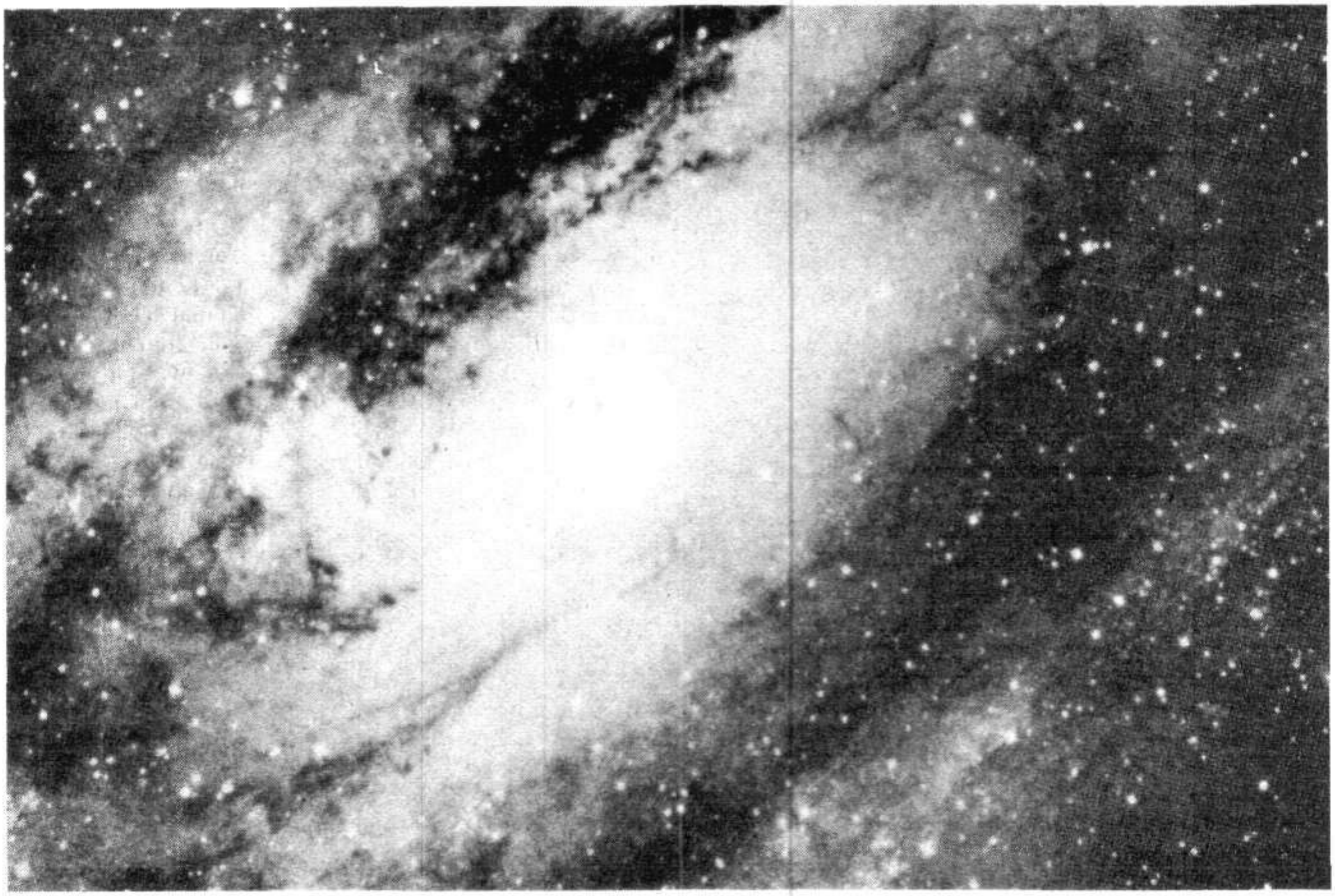
The Role of the Singularity

As soon as that magnetic field line reconnection begins, the whole quality of the dominant interactions in the plasma changes. The smooth, minimal geometry of magnetohydrodynamics is split, like a stretched rubber membrane that is pricked with a pin. As was clear in the case of the formation of solitons and the problem of electrons in classical electrodynamics, the introduction of singularities into a continuum like magnetohydrodynamics fundamentally changes the character of that continuum. In fact, the singularity precipitates a change to a new geometry; it is the seed for a qualitatively new stage of evolution of the system.

This much was clear from the simpler case of the soliton, but now much more is evident about the details of this transition. First, it is *not* the topological character of the line reconnection that makes this a singularity. Magnetohydrodynamics could (and does) support any number of reconnecting lines and changing topologies of its magnetic fields. The topology change, although the most evident feature of ths problem, is necessary but hardly sufficient to induce the sort of change in the whole plasma that actually occurs, a change that is violent to the point of changing the type of particles that make up the plasma! The singularityness of the line reconnection provides the introduction at that topological singularity of a qualitatively new interaction into the plasma—the electric field. In the middle of a self-consistent and self-contained geometry (the minimal surface of magnetohydrodynamics) suddenly the plasma has created an interaction that cannot even be placed in the geometry of minimal energy dynamics. In reality, that point of magnetic field line reconnection is *not* in the same universe as the rest of the plasma. It is already part of the *next* geometry that the rest of the plasma will soon enter, a new geometry characterized by high-energy electric fields, particle beams, and fusion.

The singularity is not an unadorned dot; it is qualitatively different from the rest of the manifold. Although it has been created out of the natural (and determinist) evolution of the system that gave rise to it, it introduces into that system a new, noncommensurable set of interactions. These qualitatively new interactions change the course of evolution of the system is a way that could *not* have been deterministically determined from the old system. This is empirical reality, not only of the plasma system described above, but of all the dominant processes in the universe; they are negentropic. Superfluids, plasmas, and man all show this quality of evolution.

Plasma physics makes this critical quality of the universe experimentally accessible in a way that no other discipline can. With the experimental evidence accumulated to date,



The understanding of self-organizing effects in plasmas as truly negentropic, as opposed to simply nonlinear, must await the story of the history of the universe as a process of plasma evolution. At this point in time, the kind of nonlinear effects researchers find in a plasma are no longer determining for the development of the universe; human evolution, for example, is occurring on a much more rapid scale. However, at some point in the past, the sort of nonlinear effects now observed in laboratory plasmas must have been responsible for the phenomena that ultimately led to the earth and its inhabitants. With this historical understanding of plasma physics—nonliving phenomena—we can approach the coherence of physical, biological, and human processes.

the plasma focus experiment makes it possible for researchers to unravel the mechanics of this negentropic evolution in several key ways, as follows:

(1) The basic fact that must be concluded is that a fixed set of laws is inadequate. A plasma evolves rapidly from one regime to another, each of which is different from the last. The two critical experiments examined here show this overall feature very clearly.

(2) This overall process of evolution occurs by and large in a discontinuous manner; in other words, the system jumps from one stage to the next in a series of violent transitions.

(3) Each of these stages can be relatively well modeled by a fixed set of determinist laws, but the whole process cannot be modeled in this way. The usual idea of determinist causality is sufficient to understand much of the physics within a geometry, but it breaks down totally when faced with the transition from one geometry to another.

(4) The immediately most troublesome questions for current plasma physics are posed by the singularities that are central to the whole process of negentropic evolution. Specifically, how do these singularities transcend the geometry that created them to induce a new one? And how can one geometry create a process that results in a succeeding geometry that is *qualitatively* different from itself?

Obviously, the singularity is the key to the problem. However, we cannot be content with the general fact that they exist; we must have a rigorous, particular description of how they induce transitions from one geometry to another. The most evident feature of the whole course of this plasma evolution (as well as of other manisfestations) is the tendency for concentration of energy. In fact, the singularity is most distinguished as the site of tremendous energy densities. Recall the plasma experiments where the soliton and the disintegrating filament were both immediately distinguishable by their self-created concentrations of energy. The "why" of this energy concentration must be closely tied up with their role as singularities.

As we have seen, the not-yet-understood part of this energy is its role in determining (or, even better, in creating) the evolutionary possibilities in a system. The means for this creation is the singularity, and the unique quality of the singularity is its energy density! In a crude way, the energy density reflects the rate of evolution that the system can endure. The singularity sparks a change in the evolution because it introduces a new rate, and thus a new quality of evolution. In the case of the soliton and the filament, for example, there was a local concentration of energy that, by virtue of that energy density, started a new set of plasma processes characterized by higher energy (namely, fusion). These new processes also are much more rapid than their predecessors.

(5) The close interrelation between quality of interaction and energy density shows its deeper significance in the case of a singularity. Because of its higher energy density, the singularity has the evolutionary properties (the time metric) of the succeeding manifold. It brings these to the manifold that created it, and in so doing induces that new time metric to the manifold as a whole, qualitatively changing the manifold in this specific way. This is why a singularity cannot be placed inside the manifold that it seems to belong to; it may have the spatial characteristics of that geometry, but it is part of a qualitatively different temporal world, because of its energy density.

The most significant achievement of 20th century physics was the translation of a Riemannian idea of relativity into physics with the understanding of a relativity of *space*; namely, that space is created and structured by the energy-mass it supports. Time also must be relative, relative to the processes that go on "in it." However, time and energy density are closely intertwined; the singularity is the knot that ties them together.

(6) These considerations also make clear in a more precise way the significance of self-ordering phenomena in general. The striking characteristic of almost all physical processes, which violates the initial common sense expectation of their spontaneous disordering in accordance with the Second Law of Thermodynamics, is not to be found by studying the remarkable structures themselves. Rather, as the formation of the vortex filament in the plasma focus demonstrates, these structures are the means by which a geometry outgrows itself.

These structures are significant because they can generate a singularity out of their own increasing energy density. Consider the chick embryo, certainly one of the most amazing "self-ordered phenomena." The embryo develops a small toothlike part of its beak, which lasts only a few days, and the chick uses this egg-tooth to cut its way out of the shell. Self-ordered structures in plasmas are egg-teeth that the plasma uses to cut its way out of a geometry it has outgrown.

(7) Finally, we must understand what guides the plasma from one geometry to another. How does the plasma "know" where to jump to (or how to land on its feet) when it makes a discontinuous leap from one manifold to another? What is the invariant that replaces a determinist causality, the lawful but nondeterminist connection between manifolds?

Laboratory plasma physics cannot answer the harder parts of this question, unless astrophysical plasma becomes the laboratory, because this is the place where plasma physics *in itself* played out its historical role as a stage in the evolution of the universe. At some point in the past, the universe must have been one big plasma. Ultimately, we owe our own existence to that plasma.

At this point we can at least describe the invariant feature of this negentropic evolution in two senses. First, even in the limited section of plasma evolution that laboratory experiments make clear, each stage of evolution is characterized by its giving rise to a more advanced stage, one with higher energy densities, more rapid rates of evolution, and, in turn, more rapid self-extinction in favor of its successor. Geometries do not merely succeed one another; they occur in a definite progression from simpler to more complex. And, at any point that evolution stops, the system rapidly collapses.

Second, the sense in which plasma physics really makes negentropic evolution clear is evident only now in 1978—10 billion years after the age of the plasma. The reason for this specific timing should be clear. Plasma physics, especially in the mastery of fusion energy, is the key to the next stage of mankind's evolution. Without a mastery of its secrets we will not survive. If we succeed in putting it to our own uses, unimaginable progress becomes uniquely possible.

Dr. Steven Bardwell is the FEF director of plasma physics.

References

Bardwell, S. 1976. "History of the Theory and Observation of Ordered Phenomena in Magnetized Plasmas." *FEF Newsletter* (Sept.). Further reading on the problems of magnetized plasma.

Bezzerides, B. and DuBois, D. 1976. *Phys. Rev. Lett.* 36: 729. Work on the foundations of the plasma problem.

Boley, F.I. 1966. *Plasmas—Laboratory and Cosmic.* (Princeton, N.J.: Van Nostrand). A good elementary discussion of plasma physics in textbook format.

Bostick, W. 1977. "The Pinch Effect Revisited." *International Journal of Fusion Energy*, Vol. 1 p.1. (March). A general review of the work at the Stevens Institute of Technology.

Grad, H. 1978. "Magnetic Confinement Fusion Energy Research." *International Journal of Fusion Energy*, Vol. 2 p.1. (Summer).

Montgomery, D. 1978. *Phys. Fluids* 21: 757.

Morales, B. and Lee, Y. 1976. *Phys. Fluids* 19: 690. Basic work on the foundations of the plasma problem.

Quon, B.H., Wong, A.Y., and Ripin, B.H. 1974. *Phys. Rev. Lett.* 32: 406. Original account of the electron-beam experiments.

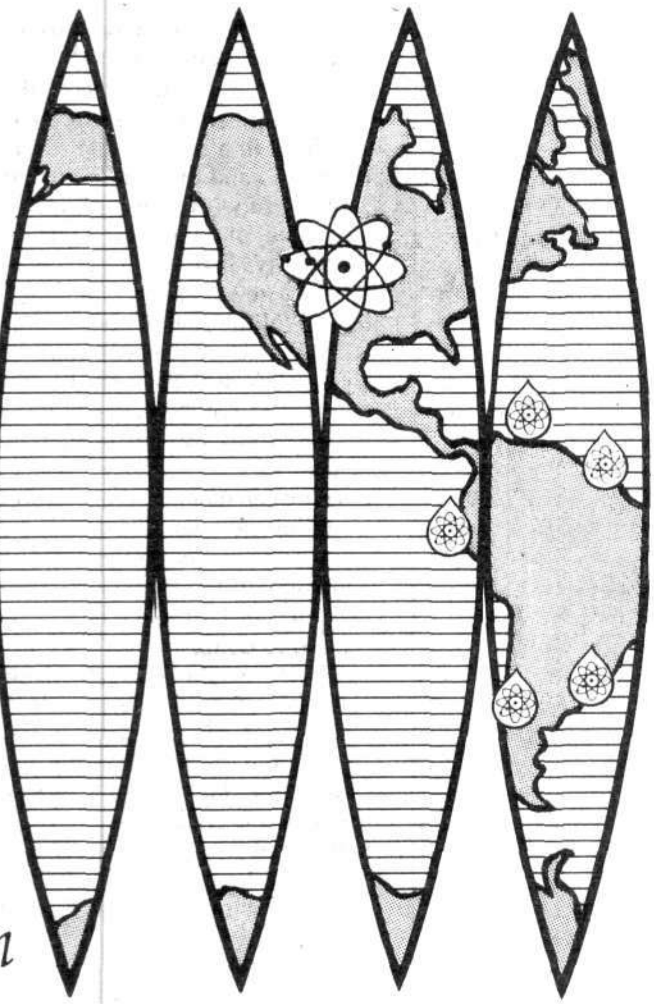
Tsytovich, V.M. 1976. *Physica C* 82: 141. A penetrating study of the conceptual problems posed by solitons and beam-plasma phenomena.

Wells, D. and Ziajka, P. 1978. "Production of Fusion Energy by Vortex Structure Compression." *International Journal of Fusion Energy*, Vol. 1, Nos. 3-4, p. 3 (Winter). A review of Wells's work.

Wong, A.Y. and Quon, B.H. 1974. *Phys. Rev. Lett.* 34: 1499.

Nuplex City Building

The Transition to Fusion



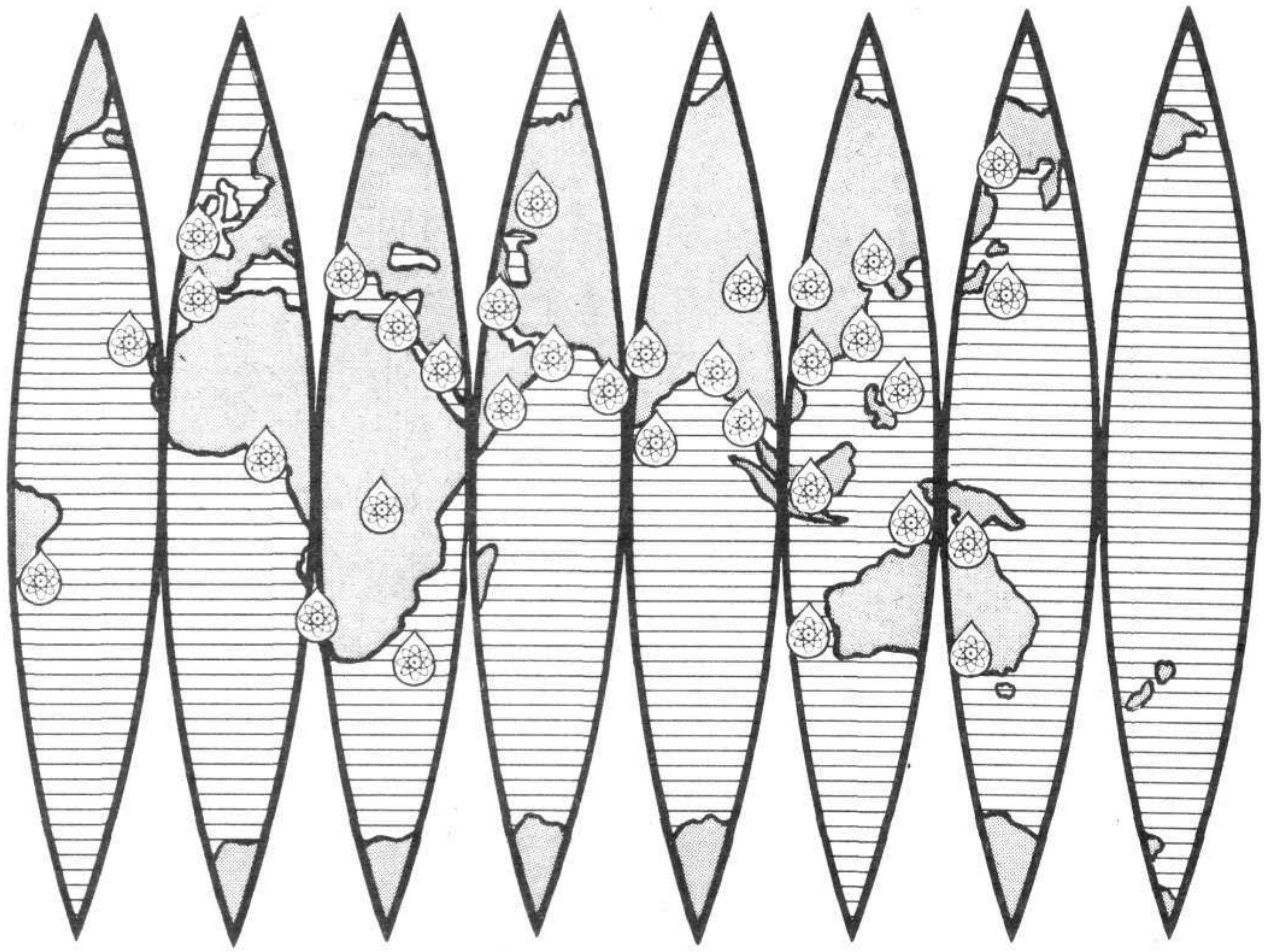
This first in a series of articles on nuplex building was prepared for the Fusion Energy Foundation by staff members Marsha Freeman and Dr. John Schoonover. Future articles on the nuplex will cover nuclear steelmaking, city building, and manpower training.

IF THE U.S. FORCES who want economic growth are to win out over the zero-growthers, they must fight to implement a policy that will permanently rescue the economy from its depression, putting U.S. production on a real growth level. Such a policy cannot merely divide up a slightly expanded industrial pie with a little more for everyone, or force through a nuclear plant here and there. A winning policy must use to advantage the unique capabilities of the United States—a broad-based industrial base, in-depth scientific capability, high technology, and the most educated workforce in the world—in order to put the United States back into a leadership role worldwide.

The key to such a policy is gearing up this combination of unique qualities to produce the capital goods necessary for the export of advanced nuclear technology. Recently this approach to a healthy economy has been put forward in policy statements by several heads of state. Mexican President Lopez Portillo, Japanese Prime Minister Fukuda, Soviet President Brezhnev, West German Chancellor Schmidt, to name a few. In this country, the idea of exporting high technology has been discussed in industrial and government circles, most notably in congressional committee hearings sponsored by Senator Adlai Stevenson.

Nuplexes, nuclear-centered agroindustrial complexes, provide the ideal answer for the United States and the rest of the world. The challenge of building hundreds of new cities in the developing sector over the next 20 years will require exactly what the United States has to offer in terms of scientific and industrial capability and at the same time will provide the United States with what it needs to put the domestic—and world— economy on solid ground.

As described here, nuplexes will be the core of Third World development and advanced sector industrial rebirth into the next century. Over the next 20 years, the industrialized nations, led by the United States, will build up to 1,000 new cities in the developing sector to urbanize the overwhelming majority of the world's population and thereby bring modern culture, education, technology, and the potential for realizing human creativity to every corner of the globe.



The nuplex-powered city will be the focal point for a series of technological revolutions. These revolutions not only will involve breakthroughs in the production and industrial utilization of energy, but will mean the full integration of the modes of energy generation and use. This will be achieved on the basis of the transition to a fusion and plasma-technology-based economy, as more efficient sources of nuclear power are continuously developed to power an ever broader spectrum of chemical and industrial processes.

The city itself will be built by modular construction techniques in such a way that technological transformations can occur for 50 to 100 years without the total rebuilding of the city's infrastructure. The cities will consist of one or several pairs of nuclear reactors, around which the most technologically advanced industry and agriculture will be clustered.

Over the next one to two generations, increasing numbers of Third World peasants will become technology-proud, American-style farmers, and will be fully integrated into industrial production. The first step is to bring the skilled and semiskilled indigenous population of the Third World into the most massive city-building effort in world history. Along with on-the-job training that will take place *in the process of working with engineers and technicians* from the advanced sector, work schedules will be planned to allow on-site classroom educational programs.

The second step will be to employ younger adults in the new jobs created as industry in the nuplex comes on line. Increasing numbers of people displaced through the mechanization of agriculture will be available for education and training, and then placement in the growing industry and agriculture-related activities of the new cities. By the turn of the century, only about 10 percent of the developing sector population should be involved in agriculture, as productivity in regions that are now deserts reaches the level of California's Imperial Valley.

About Appropriate Technology

The level of technology appropriate for any society depends upon the goals of that society. The goal of Mexico, India, and nations of the Middle East and Africa is to eliminate the very notion of the Third World by the end of this century.

The zero-growth faction, which includes institutions like the World Bank and the International Monetary Fund, insists that bringing the Third World up to a high-technology level is not possible. First, they say, the collapsing industrial sector cannot afford to develop the Third World; and second, industrialization and technology are somehow unnatural and therefore inappropriate for the more simple lifestyles of the Third World. The appropriate technology that this faction puts forward is symbolized by the pick and shovel.

If we want to bring the entire population of the world into the 21st century, nuplexes are the only technology appropriate to accomplish the task.

BASIC NUPLEX DESIGN

The nuplex concept is the integration of a centralized energy and power supply with other industries for a symbiotic relationship. For example, all electrical generation plants produce both electricity and waste heat, which are used most economically when in close proximity to production and agriculture.

Any form of fuel could be used for agroindustrial complexes; and some fossil-fuel-based energy centers have been built in the United States and abroad. The advantage of using nuclear reactors is the ability to put them anywhere—regardless of the region's endowment of natural resources—and that nuclear energy is cheaper than most fossil-fuel-based systems.

With the commercialization of the breeder reactor, a more energy-dense form of power will be generated and fuel will be reproducible on site. With the full deployment of thermonuclear fusion going into the 21st century, all limitations in terms of resources and energy production will be removed.

Every nuplex will be a unique configuration of basic modular industrial and nuclear technologies. While the complexes are still fission based, the mix of industrial and agricultural activities will depend upon the availability of raw materials in each specific region.

Great economy is clearly gained by sharing transport, storage, and processing facilities, which are used in all aspects of production, Also, having an assured and nearby energy supply allows the scaling up of manufacture and raw materials processing so that economies of scale are realized, even though the initial capital cost may be greater. Detailed cost-analysis studies done in the late 1960s demonstrated that savings from centralization and shared infrastructure more than compensated for the cost of hauling raw materials a greater distance to the nuplexes.

In addition, the clustering of the reactors lowers the overall cost of energy, since fuel handling, processing, and reprocessing facilities are shared. The effects of reactor down-time, planned or not, can be minimized by the redundancy in the energy source achieved by clustering and by the ready availability of skilled manpower for troubleshooting and rapid repair.

Transportation canals can be built to lace the industrial area to facilitate the movement of raw materials and semifinished goods from one part of the nuplex to another. The industrial area can be as large as 5 to 10 square miles. Linking excess energy from one nuplex center to the next would create an electrical transmission grid covering whole regions where no power is now available.

A generalized nuplex center, for example of 10 reactors of different types, could produce about 15 GW (gigawatts, or 1,000 megawatts each) of electrical power. This would provide power for industry and could support a city of at least 5 million. These plants also produce the equivalent of about 10 GW of waste heat and steam. This resource, now considered thermal pollution, is a crucial energy source for both agricultural and industrial processing.

Even after extracting steam for electrical generation and for use in steam turbine waste in industry, approximately 25 GW of thermal energy is contained in the power plant effluent at between 80 and 100 degrees F. This hot water and steam is ideal for fish farming and aquaculture, as well as for providing hot water and district heating for the city.

The Oak Ridge Studies

All the advantages and promise of world development represented by nuclear-centered industry and cities were recognized by the scientists and statesmen who formulated President Eisenhower's 1953 Atoms for Peace program. By the late 1960s, the scientific community began to work on making that promise a reality.

The growth of nuclear power in the United States took many people by surprise. In fact, the Atomic Energy Commission during the 1960s made yearly upward revisions in its projections for nuclear power usage up through 1980.

By 1967, with a 10-year proven track record in commercial fission, a group of scientists and engineers under the direction of Alvin M. Weinberg at Oak Ridge National Laboratory and Glen Seaborg at the Atomic Energy Commission undertook a series of detailed studies to plan the building of nuplexes in the Third World and industrial West.

The purpose and motivation of the Oak Ridge studies was made perfectly clear:

> [Nuclear-centered, agroindustrial complexes] would provide developing countries a means of combating the imminent food shortages as well as providing a means of "leapfrogging" in their development.*
>
> The time has come when the energy derived from nuclear energy can be looked upon very seriously as a key for releasing indigenous agriculture from the bondage imposed by the necessity of securing fuel, fertilizer, and power for tillage all directly from the land without energy resources from outside. . . . Such inputs could free these people from Malthusian limitations hitherto imposed upon their indigenous food supply. . . .

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* *Nuclear Energy Centers: Industrial and Agro-Industrial Complexes*, ORNL 4290. Oak Ridge National Laboratory, November 1968. This report, the first in a series of seven studies, describes the basic technologies, design, and economic justification for nuplexes.

Twenty years of U.S. aid to various countries since World War II has had some great successes, but many times has failed to achieve technological advances in proportion to the money spent. The reason for failure may in some instances be that power resources are not readily available for agricultural improvement . . . . The present study was conducted to determine whether nuclear energy has now become cheap enough that nuclear energy inputs can be within the economic reach of near-starving people for agriculture and associated agricultural industries. . . .*

The full-time team of 16 scientists, engineers, economists, and agricultural experts examined the full range of industrial and agricultural technologies available or conceptualized for the 15-year period following their studies (1967-1970). They agreed that the nuplex would have to be prepared for the introduction of revolutionary new techniques at least every 15 years.

They examined potential global sitings for the nuplexes, and worked closely with the Atomic Energy Commission of India, with Mexico, and with other developing-nation governments. Scarcely a year after the 1967 Middle East war, the Oak Ridge team recommended that a nuplex encompassing parts of the Sinai and Negev deserts would encourage historically hostile nations to work together for mutual benefit and development. This approach and a thoroughly detailed analysis and feasibility study provided important back-up to the Nixon administration's Rogers Plan for peace through economic cooperation in the Middle East.

The results of the series of Oak Ridge studies concluded the following: that nuclear-centered, agroindustrial complexes would be technically and economically feasible for the developing and advanced sectors; that the mid-1980s commercialization of the breeder reactor would permit an even wider range of energy-intensive technologies to become economical; that nuplex building would provide sufficient return on investment to be an attractive investment both for Third World governments and private industry; and that the needed skilled labor force in the developing countries could be developed by the process of constructing the nuplex itself coupled with intensive training and education.

Although little of the cost analysis from the Oak Ridge studies is applicable today—because of escalation in capital and energy prices since the late 1960s—the mixes and ranges of industrial and agricultural technologies under examination are quite valuable starting points for the nuplexes of the 1980s. Unfortunately, due to the stagnation of advanced sector industrial development, virtually the same technologies that were on the drawing boards 10 years ago are still there today.

The value of the Oak Ridge studies is that their starting point was to answer the question: "How can we most quickly bring the developing countries up to the standard of living of the advanced sector?" Agricultural productivity projections for India were based on yields and capital inputs in the Imperial Valley in California. Chemical, raw materials processing, and iron and steelmaking technologies were evaluated on the basis of the most promising advances then being considered by the industrial giants in the West and Japan. In addition, the prospect of a cheapening source of electrical power would open up the possibility of substituting electricity for fossil fuels in basic raw materials processing.

THE THREE NUPLEX TYPES

In most cases, the first nuplexes built in the Third World will be primarily *agricultural*, with the industry based on providing needed fertilizers inputs and, in cases where desalination is required, processing minerals taken from seawater. In regions where there are ore bodies such as iron, copper, aluminum, and other metals, a second type of nuplex will incorporate *primary metals processing and semifabrication*.

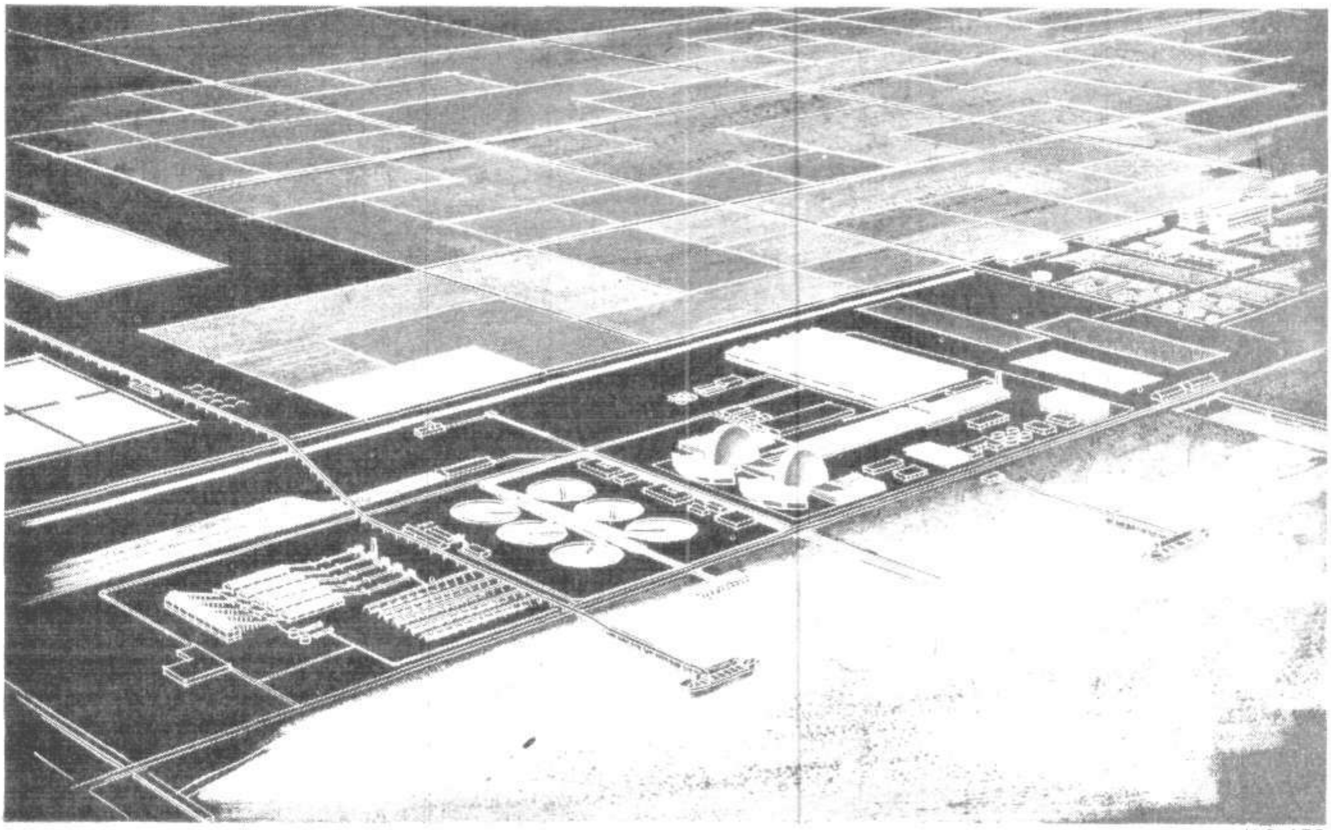
Before any large-scale nuplex building is feasible, however, a third type of nuplex, *industrial complexes for mass-production of nuplexes*, must be built in the United States, Europe, and Japan. At the present time, only Japan has the capability to fabricate large-scale equipment in its modern, computerized, and fully automated shipyards. The Soviet assembly-line nuclear-plant production facility, Atommash, should provide needed engineering experience; the Soviet program of city-building in Siberia is the only nuplex-type of city building attempted during this century. Soviet scientists and engineers will thus be essential in a worldwide city-building effort.

The U.S. capability to mass-produce floating plants, including nuclear reactors, cement plants, and miniature electric-generating stations, will prepare a coastal region for the construction of the permanent industrial, agricultural and urban infrastructure. These plants will provide ready energy and construction materials where virtually nothing now exists.

At the same time, gigantic nuclear-centered, heavy-industry complexes will be built in the U.S. heartland of the Greak Lakes Basin, stretching from Pittsburgh, Pennsylvania to Milwaukee, Wisconsin and incorporating the Canadian Golden Horseshoe to Cincinnati, Ohio. These basic-industry nuplexes will require little city building in the advanced sector, but will serve as the centers for mass-production of nuclear reactors, steam turbines, steelmaking machinery, multiton machine tools, and machinery for other heavy industry and most light industry for Third World nuplexes.

Another species of advanced sector nuplex would be for primary metals processing and fabrication in total integration with the chemical industry. Current, on-the-board technologies for steel production—such as the Jordan process, direct reduction of iron ore, plasma arc specialty steelmaking, and other processes—will be brought to

* Perry R. Stout, *Potential Agricultural Production from Nuclear-Powered Agro-Industrial Complexes Designed for the Upper Indo-Gangetic Plain*. ORNL 4292, Oak Ridge National Laboratory, November 1968.


U.S. AEC

This artist's model of a nuclear-powered agroindustrial complex was part of the AEC nuplex study at Oak Ridge National Laboratory. The nuplex could produce up to 1 billion gallons of fresh water per day and more than 2,000 megawatts of electricity. The adjacent 300,000-acre "food factory" was projected to feed 6 million persons.

commercialization and will provide feedstocks for the chemical industry attached to it, which will in turn produce fertilizer, liquid fuels such as methanol, and other vital chemical products.

In all cases, however, industrial activities will be clustered by activity around the heart of the nuplex itself, the nuclear reactors, so as to maximize utilization of the direct electrical output from that source as well as of waste heat and other energy by-products. Moreover, as more advanced nuclear technologies come on line over the next three decades, the overall technological level of industrial activity in the nuplex will advance. The implications of such advances for the first nuplex model, the agroindustrial complex, are outlined below in a discussion of desalination and irrigation technologies. The next article in this series will discuss the implications of raising the technological capabilities of the steelmaking nuplex to meet the increasing energy density throughput of the first, second, and third decade power sources.

Desalination Methods

The most important input for agricultural development in coastal, desert, and other underdeveloped areas is water. For some regions, such as eastern India, Puerto Rico, and other rainy regions, existing natural underground aquifers can be developed for irrigation. The main requirement is electricity to pump water from aquifer storage to cultivated fields. In terms of economics, the irrigation of large-scale areas for wheat and cereal production is perfectly feasible.*

At present levels of technology, conventional desalination using either multistage flash distillation or reverse osmosis is too expensive to be used, in terms of capital and energy, except for high-value crops such as tomatoes and citrus fruits. In the second decade of nuplex building, desalination technologies, such as the atomizing desalination process, will become feasible, especially as nuclear breeder development brings down the cost of electricity. With advanced desalination techniques, the irrigation of fields for all crops will become economically feasible.

Desalination will be required to meet the fresh water needs of the nuplex-centered city and will be used for high-value crops. The waste minerals in seawater will be the basic raw materials for various chemical processes and fertilizer, as summarized in Table 1. Many of the agro-related chemical processes for the agricultural nuplexes developed in the Oak Ridge studies depend upon the ready electrolysis of water to free hydrogen.

* R. Philip Hammond, *Nuclear-Industrial Complexes*, LASL-57950C, Los Alamos Scientific Laboratory, 1974.

Figure 1
SCHEMATIC FLOWSHEET FOR A NUPLEX
PRODUCING ALUMINUM, MAGNESIUM, IRON, AND STEEL

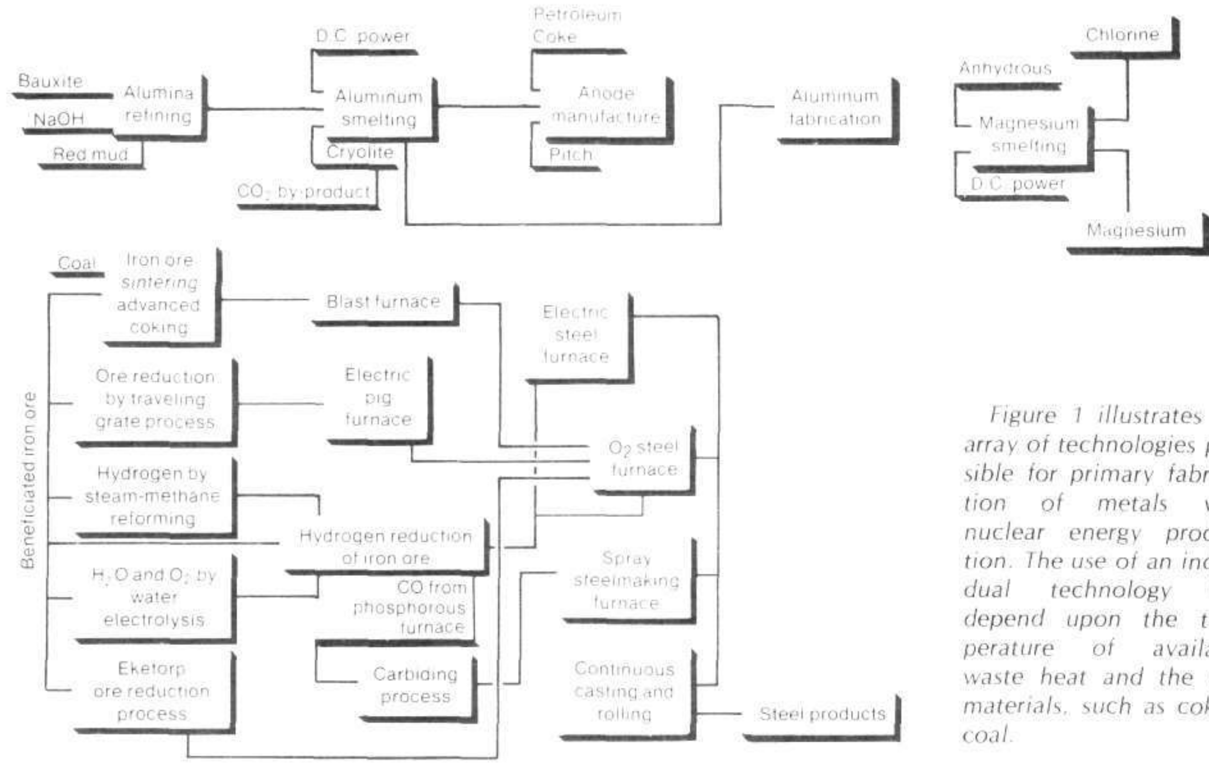


Figure 1 illustrates the array of technologies possible for primary fabrication of metals with nuclear energy production. The use of an individual technology will depend upon the temperature of available waste heat and the raw materials, such as coking coal.

Table
INDUSTRIAL PROCESSING IN THE AGRICULTURE-CENTERED NUPLEX

	RAW MATERIALS	MAJOR PROCESS	PRODUCT
Semifinished	Water, air	Electrolysis of water for hydrogen	Ammonia
Semifinished	Phosphate, rock coke, silica	Electric	Phosphorous
Semifinished	Extract from seawater	Crystalization from brine	Potassium chloride
Semifinished	Seawater	Electrolysis of saturated brine	Pretreatment of seawater for evaporators
Finished		Synthesis of ammonia and air	Ammonium nitrate
Finished		Synthesis of ammonia and carbon dioxide	Urea
Finished	Phosphate rock, calcium carbonate, ammonia	Acidulation with nitric acid and treatment with carbon dioxide and ammonia	Nitric phosphate

The table shows an array of technologies in an agriculture-centered nuplex. Because of the proximity to electrical generation, the minerals and metals that are now unused byproducts of desalted water can be processed into vitally needed fertilizer.

Source:
Oak Ridge National Laboratory

Techniques now under investigation in West German laboratories have the potential to use a thermally assisted electrolysis process that would produce hydrogen economically. In addition to being a feedstock for chemical processing, hydrogen is an excellent clean and high-temperature fuel that can substitute for fossil fuels in many industrial areas, and new techniques would make it competitive with natural gas.

In addition to using the waste heat from the nuclear plants for multistage flash distillation desalination and for chemical processing, the agro-based nuplex will use the 80 to 100-degree F. power plant effluent for cheap protein production through aquaculture. Shellfish, now a delicacy, can be raised directly in the cooling ponds at the power plant site. Growth rates for shrimp, lobster, clams, and all sorts of fin fish have been doubled by the use of heated water.*

In regions of the world where significant bodies of natural ores exist, the nuplex will be geared to primary metals processing and, in the second nuplex decade, will be provided with fabrication facilities. Waste heat from more advanced, higher temperature gas reactors (described below) and breeder reactors can then be used in some of the second stage metals processes.

Figure 1 schematically shows the flowsheet for the production of aluminum, magnesium, iron, and steel in a primary metals processing nuplex. The figure indicates the range of potential technologies available until fusion is brought on line as a commercial energy source.

NUCLEAR-INDUSTRIAL TECHNOLOGY

At the present time, U.S. industry uses about 40 percent of the total world energy produced; of this, almost 17 percent is process steam. Among the most energy-intensive industrial processes, pulp and paper, chemicals, petroleum, rubber, and primary metals use 75 percent of the industrial steam generated. The most electrical energy-intensive industries—aluminum, caustic chlorine, electrolytic hydrogen, and electric furnace steelmaking—will benefit directly from configurations of nuclear reactors.

Industrial steam consumers will derive increasing benefit as nuclear technology itself is developed, and as higher process steam temperatures become available. In the first nuplex decade, however, before these higher process temperatures are available, the conventional light water reactor will provide the energy. The heat from fission reactions is now typically used to heat a working fluid to between 500 and 600 degrees F. At that temperature, the steam is used to generate electricity from conventional high-pressure turbines at about 220 to 280 degrees F. The turbine condenser discharge water is about 85 to 120 degrees F.

In the paper, chemical, rubber, and agricultural industries, steam ranging from 100 to 450 degrees F. is needed and can be adequately supplied by light water reactors. This eliminates the need for each manufacturing facility to build fossil-fuel-based boilers to produce industrial steam. It has been calculated that even if the steam supplied by the nuclear plant had to travel up to 10 miles (which is unnecessary with integrated processing), it would still be cheaper to supply steam from a central power source.

The Breeder

The nuplex decade of the 1990s will see the large-scale deployment of breeder technology. The liquid metal fast breeder reactor, which is being developed in Europe, Japan, and the Soviet Union, brings delivered heat from the power plant up to between 900 and 1,100 degrees F. This is due to the threefold to fivefold increase in power density inside the reactor. In addition to extending the possible range of integrated industrial processes based on waste heat, the main value of the liquid metal fast breeder is that it generates its own fuel and can provide a ready supply of nuclear fuel to all other power plants within the nuplex and throughout the region.

In their detailed studies of reactor technology, the team at Oak Ridge estimated that the lowered electrical cost from breeder reactors would bring certain processes, like electrolysis of hydrogen and electric furnaces for phosphate rock processing, into commercial feasibility. By 1985, the French government and industry will have a 1,200-MW electric (3,000 MW thermal) breeder, the Superphenix, on line.

On the verge of commercialization both in the United States and in Western Europe is the *high-temperature, gas-cooled reactor* (HTGR), which will bring fission technology up to temperature ranges at which process heat for most industry can be provided almost entirely from the power source itself. HTGRs provide both a cheaper electrical source and higher quality waste heat. (The HTGR will be discussed in detail in a subsequent article in this series on nuclear steelmaking.)

Two of these HGTRs are the U.S. graphite core reactor and the West German pebble bed reactor. Both can take full advantage of high-temperature, high-pressure turbines, can efficiently convert thorium to a fissile fuel, and can produce industrial process heat in the range of 1,700 to 2,000 degrees F. The helium coolant used also lowers the water requirements for the nuclear complex.

The graphite prototype reactor has been operational since 1974 in the U.S. delivering helium temperatures up to 1,360 degrees F. The West Germans have had a working pebble bed reactor since 1973, with a helium outlet temperature of 1,740 degrees F., and a commercial reactor with a 2,000 degree F. potential is under construction. The West German reactor uses balls of thorium-uranium compound for fuel, which are dropped in the top of the vessel at the rate of between 3,000 and 4,000 per day.

An equal number of fuel "pebbles" are removed from the bottom of the reactor vessel, thereby providing a continuous fuel supply. This eliminates the normal down-time required to remove spent fuel rods and replace them with fresh fuel.

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* M. Olszewski, *The Potential Use of Power Plant Reject Heat in Commercial Aquaculture*, ORNL/TM-5663, Oak Ridge National Laboratory, January 1977.

It has been estimated that one 1,000-MW reactor could supply the electrical and steam needs for the largest existing chemical plants. This means dedicating about 300 MW to the processing plant, leaving the rest to other users, and supplying 4 million pounds per hour of steam at pressures ranging from 200 to 600 psi (pounds per square inch).

Similarly, a 500,000-barrel-per-day petroleum refinery, slightly larger than any now in operation, requires 4,000 MW thermal to operate. Of this energy, about half is in the form of steam; the rest is needed as higher temperature process heat and electricity. One large HTGR, providing steam at 650 to 1,250 psi and heat at 1,200 degrees F. would fill this energy requirement.

In the primary metals industries, of which iron and steel production account for 65 percent of the energy consumption, the coking process demands temperatures in the 1,300 to 1,750 degree F. range. Even higher temperatures are required for higher quality coke. These temperatures can be achieved by the HTGR and can be substituted for the oil and gas currently used as fuel for coking.

Pig iron production requires an air blast of about 1,600 degrees F. which is within the HTGR range. The demand for process steam in other downstream metals production—in the 300-degree range—will be supplied by light water reactors. Nonelectric steelmaking technologies, variations on the basic oxygen furnace, require heat over 2,000 degrees F. As described in the steelmaking article, this will continue to be provided by fossil fuels until fusion becomes commercially feasible.

The large heat users of the chemical industries, acetylene, ammonia, and methanol production, are ideal for HTGR-centered nuplexes. Half of the energy in acetylene production goes into naptha cracking at 1,800 degrees F.; the remainder is used in the form of steam at 750 degrees F. and 600 psi. Both ammonia and methanol production depend upon the steam reforming of methane under current technologies and can use other hydrocarbon feedstocks at temperatures of 1,000-1,500 degrees F.

Distillation, cracking, and reforming of petroleum products requires steam and heat in the 150 to 1,000 degrees F. range, while pulping and paper drying use cooled steam from HTGRs or conventional reactors at 200 to 350 degrees F.

The Fusion Nuplex

At the point that fusion reactors produce electricity from seawater, all direct-electrical processes become possible. The use of the fusion plasma itself will transform the resource base of the world economy by making large amounts of high energy-charged particles—neutrons and gamma rays— and electromagnetic radiation available.

Although there will be significant revolutions in technology with the large-scale use of fission and breeder reactors, the advent of fusion will require "unplugging" the modular industrial nuplex plants and replacing them with whole new facilities. The original design of the nuplex city will take into account the need for these periodic technological advances in reactors and plants so as to minimize disruption in the functioning of the entire nuplex. Floating plants can also be used to complement energy requirements during periods of technology transition, as they will be used in the initial phases of nuplex construction.

The commercialization of advanced fuel-cycle fusion reactors (deuterium-deuterium fuel) will produce charged particles, rather than mainly neutrons, which can be converted directly to electric power through magnetohydrodynamics (MHD) eliminating the steam turbine cycle completely. By the MHD process conversion efficiency can be brought from 30 to 35 percent to nearly 100 percent. The combination of seawater for fuel with the high energy density of the fusion reaction will make electricity available at a small fraction of today's cost.

A high-temperature stream of the fusion plasma will be diverted for use in the *plasma torch,* a concept that has been under investigation since 1969.* The fusion torch, in which the ionized plasma is raised to temperatures at which materials are decomposed into their constituent atoms, will open the door to a host of efficient industrial processes: the direct production of primary metals; synthetic fuel production, particularly hydrogen and methanol; chemonuclear production of basic industrial chemical compounds such as carbon monoxide, hydrogen peroxide, ethylene, formaldehyde, and nitrogen dioxide; photochemical reactions in general; ozone production; large-scale desalination of water; and elemental reprocessing of waste matter, recycling it.

A Revolution in Mining

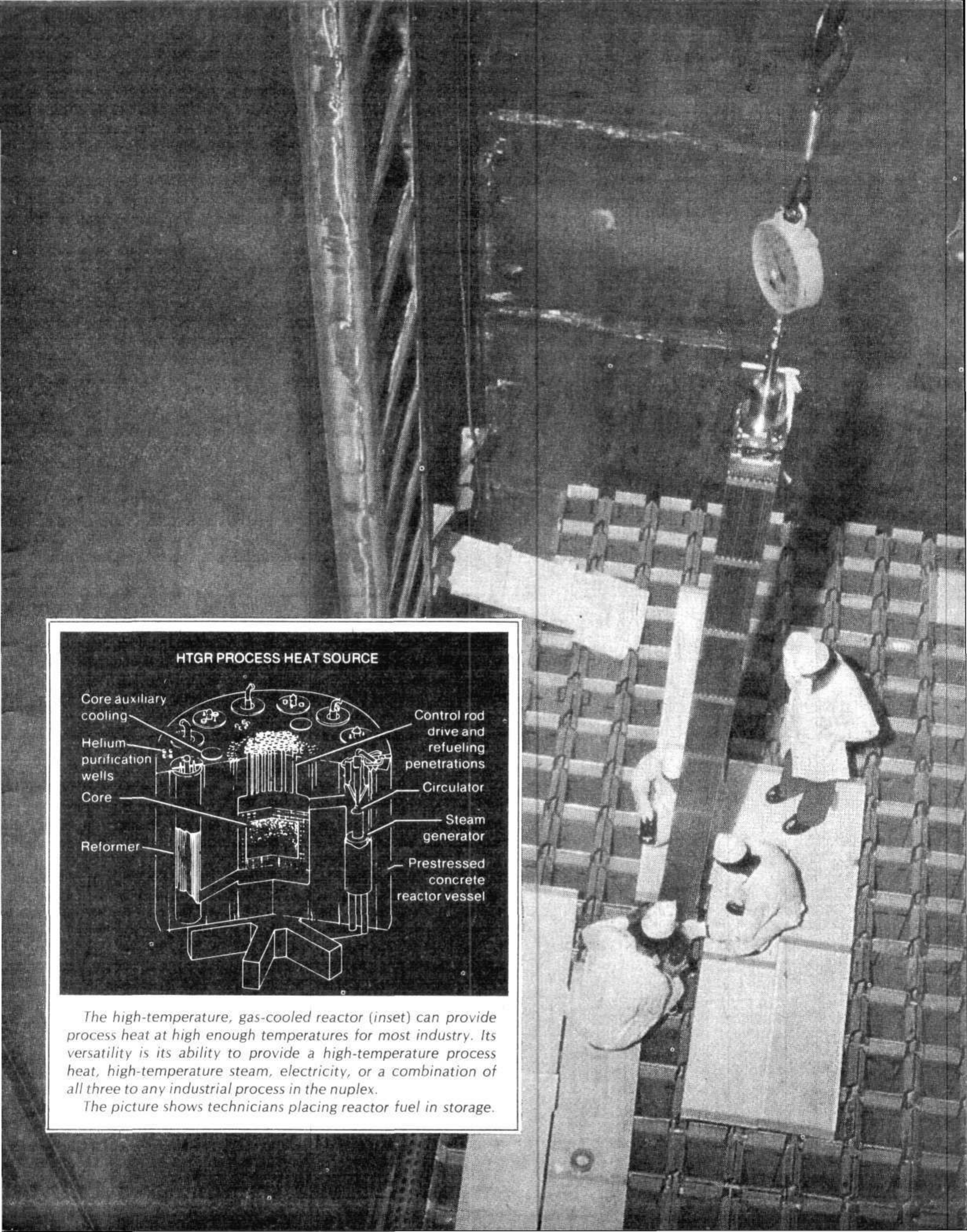
Yet another proposal is the separation of basic atomic species from ores and other materials vaporized by direct plasma interactions, by means of rotating plasmas. With this energy source, basic materials processing and manufacture would no longer be limited to concentrated ore bodies. Whole sections of earth can be processed by the fusion torch, and *all* mineral resources could be extracted at the same time, whether or not they are present in large concentrations. At some future date, it will be entirely feasible to consider taking any area of rock, dirt, or sand, running it through the torch and extracting a variety of metals. Also possible will be closing the materials waste cycle by reprocessing all wastes using the fusion torch, and turning them back into useful industrial raw materials.

All of the costly mechanical-processing industries will be replaced by fusion torch processing, eliminating materials-intensive and labor-intensive industry. Along with full automation, electromagnetic manipulation of materials will eliminate the mechanical metals-processing technology in use today, and will revolutionize the mass-production of machinery.

Marsha Freeman directs FEF industrial research and Dr. John Schoonover coordinates FEF campus work.

The next installment in the nuplex series will describe nuclear steelmaking.

* B. J. Eastlund and W. C. Gough, *The Fusion Torch: Closing the Cycle from Use to Re-Use.* U.S. Atomic Energy Commission Report, WASH 1132, May 1969. More recent work on the fusion torch has been done by Z. Sabri in her Ph.D. dissertation at the University of Wisconsin in 1972.



The high-temperature, gas-cooled reactor (inset) can provide process heat at high enough temperatures for most industry. Its versatility is its ability to provide a high-temperature process heat, high-temperature steam, electricity, or a combination of all three to any industrial process in the nuplex.

The picture shows technicians placing reactor fuel in storage.

Research

Soviet T-11 Breaks Beta Barrier

The small, Soviet T-11 tokamak has tied down the last scientific parameter required for commercial fusion power production by tokamaks—plasma beta.

At the International Atomic Energy Agency fusion meeting in Innsbruck, Austria in August, the T-11 research team reported reaching plasma betas of between 2 and 4 percent. Plasma beta is the measure of how efficiently the magnetic fields are used to confine and insulate fusion plasmas. A plasma beta of 4 percent had been projected as the minimal beta needed for economical tokamak power reactors.

After the Princeton PLT tokamak reached fusion ignition temperatures last July and the Massachusetts Institute of Technology's Alcator tokamak achieved necessary confinement levels earlier in the year, the beta parameter was the only remaining scientific barrier for commercializing tokamaks. As one of the Princeton PLT directors commented, if the Princeton PLT had not reached its spectacular temperatures just before the IAEA meeting, the Soviet T-11 would have been the center of attention at Innsbruck.

Economical Tokamaks in Sight

Further experiments on the T-11 and on several U.S. tokamaks—the ISX-B at Oak Ridge, the PLT at Princeton, and the General Atomic's Doublet III—probably will greatly extend this initial result to plasma betas between 10 and 20 percent in the next months.

The expected breakthroughs in plasma beta hold great promise for making very economical tokamaks. The cost of generating the magnetic field is a substantial part of the total cost of a tokamak reactor. The cost of power production from a tokamak, in fact, is inversely proportional to the square of the plasma beta.

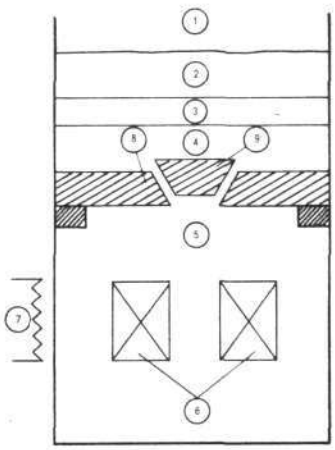
Proposed Ban

An inconclusive study in which a specific cancer-prone breed of rat was fed high dosages of nitrites is being used by the Food and Drug Administration (FDA) and the U.S. Department of Agriculture to push for a phaseout of nitrites because the substance allegedly caused cancer in rats.

A ban on nitrites would be exceedingly hazardous. Nitrites are used as a preservative in bacon, ham, and luncheon meats to prevent botulism food poisoning in cooked and partially cooked animal protein products. Without nitrites, two-thirds of the pork and one-tenth of the beef marketed either would have to be kept totally frozen or be taken off the market, to prevent possible epidemics of botulism.

The FDA-funded nitrite study, carried out by Paul Newberne at the Massachusetts Institute of Technology, is one of a series of carcinogen experiments in which the assumptions and logic behind the experiment are fraudulent.

HOW THE SUPERCOOLANT WORKS



This simplified drawing of the refrigeration apparatus demonstrates the principle of the system designed by the French fusion group. Area 1 is under atmospheric pressure; area 2 is normal helium, which boils at 4.2° K; Area 3 is a thin layer of helium that acts as a transition to area 4, which is helium at the critical temperature for superfluidity of 2.16° K. Area 5 is the lower bath of superfluid helium at 1.8°K, which bathes the superconducting magnet, labeled 6. Area 7 is part of the cooling system to maintain the temperature. Area 8 is an insulation barrier with a hole in it, plugged by the movable stopper, labeled 9.

Any fluctuations in the temperature of the magnets are quickly evened out by the extraordinary heat conduction of the superfluid helium.

Advanced Technology

French Use Superfluidity In Fusion

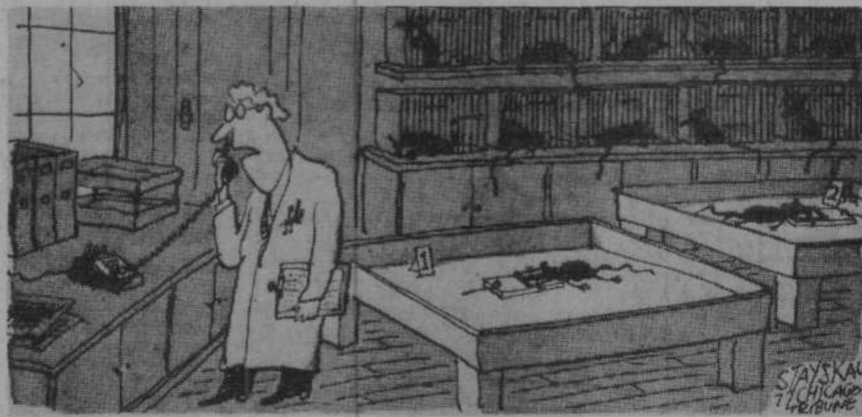
Researchers at the French fusion research center have announced the discovery of the first practical application of superfluidity, the well-known but mysterious property of supercooled liquid helium that enables it to flow and conduct heat with no resistance (zero viscosity).

on Nitrites Based on Shoddy Science

Such experiments assume that the ingestion of an abnormally large dosage of an industrial product, such as nitrites, in a specially bred cancer-prone strain of various lower species is a reasonable index of that product's carcinogenic capacity under normal consumption in human society. This logic ignores the well-known metabolic threshold effect, in which a biochemical that is essential at normal dosage levels may become a lethal poison at abnormally high dosages. (For a full discussion of this point, see "There Is No Cancer Epidemic," *Fusion*, August 1978.)

Cancer-Prone Rats

In the much publicized nitrite study, high nitrite dosages were fed to a specially bred strain of rat—the Charles River Sprague-Dawley rat—that is known for its abnormally high incidence of mammary tumors; in other words, for being cancer prone. Previous testing of nitrites on other strains of rats and other animal species, carried out for the past 10 years, has demonstrated no relationship between cancer and nitrite consumption in normal rats, mice and other species.



"Hello, FDA? . . . I'd like to report research that directly links cheese with death in rats."

Furthermore, a large group of these Charles River Sprague-Dawley rats in the study were fed an abnormal, semisynthetic diet; yet, diet differences were ignored in the final statistical analysis of the nitrite-cancer relationship. In addition, the study showed that *both nitrite-fed and non-nitrite-fed rats had an abnormally high incidence of cancer.*

The normal human gastrointestinal tract is totally different from that of a rat. In humans, only 2 percent of the nitrites to which the body is continually exposed come from processed meats. More than 97 percent of nitrite exposure comes from nitrites created during the normal digestive process in

Continued on page 54

Pierre Roubeau of the Center for Nuclear Studies in Saclay, France has developed a technique that uses the extraordinary heat-conducting properties of superfluid helium to stabilize and regulate the huge, superconducting magnets in magnetic confinement fusion experiments. Roubeau's technique was reported in the Aug. 9. issue of *Le Monde*, the French daily.

Supercooling the Hot Spots

This discovery by the French nuclear group brings together two of the most striking physical phenomena in physics. the resistanceless flow of electricity in superconductors and the resistanceless flow in superfluids.*

Superconducting magnets use the superconducting property of various alloys to generate large and concentrated magnetic fields with the high currents carried by the superconductor. However, these magnets have suffered from a serious problem in the past. The superconductivity of the magnet coils is subject to instabilities in which a small perturbation in the superconducting property, a "hot spot," for example, can result in a rapid and catastrophic loss of superconductivity for the magnet as a whole.

The French technique uses superfluid helium to prevent such an instability from destroying a superconducting magnet. The same properties that give superfluid helium its bizarre mechanical property of resistanceless flow also result in its remarkable thermodynamic ability to disperse heat at the speed of sound. Heat waves travel through the superfluid helium at 70 feet per second, cooling off any local accumulations of heat almost instantaneously.

Roubeau's idea, shown in the figure, is to use superfluid helium as the refrigerant for the superconducting magnet. This superfluid helium would be coupled to a larger bath of very cold, but not yet superfluid helium that would act as a heat sink for heat from the magnet. A fine capillary would connect the refrigerant to the reservoir of normal helium, allowing the superfluid phase to function both as a bulk coolant and as an emergency heat conductor for any "hot spots." The technique uses a much smaller overall expenditure of energy for refrigeration than in currently operating superconducting magnets.

As the French announcement points out, the immediate and exciting application for the invention is the cooling and control of the superconducting magnet used in fusion experiments.

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* For a review of the subject, see "The Physical Significance of Superfluidity" by Dr. Morris Levitt in the March 1978 *Fusion*.

Continued from page 53

the gastrointestinal tract. These nitrites are continually produced by normal microbial action on undigested proteins, dead cells sluffed off from the lining of the gastrointestinal tract, and various nitric compounds found in the intestines as a byproduct of digestion. Another 1 percent or so of nitrite exposure in humans comes from nitrites in water and vegetable products.

The nitrite ban proposed by the FDA and the USDA would thus eliminate only 2 percent of the alleged cancer risk associated with nitrites. This is hardly a sane tradeoff for the anticipated large increase in botulism and botulism deaths that would accompany a nitrite ban, particularly among the elderly and the poor who consume a greater proportion of precooked and processed meats.

Early Photosynthesis Indicated

Recent discoveries by Dr. Carl Woese of the University of Illinois indicate that photosynthesis may have evolved much earlier than previously thought.

Woese has identified a salt-water photosynthesis microorganism, *Halobacterium halobium*, as a close relative of the methanogens, which he classifies as ancient bacteria or *archeobacteria*. His previous work indicated that the methanogens are as evolutionarily distant from the so-called true bacteria as the bacteria are from the eucaryotes (organisms whose cells have a nucleus) and that the methanogens appear to predate the true bacteria evolutionarily. Woese's present findings, therefore, suggest that photosynthesis also may have appeared with the archeobacteria, which implies the very early evolution of photosynthesis.

The technique Woese uses to classify organisms is the comparison of the biochemical composition of ribosomal RNA (r-RNA). The more similar the r-RNA of two organisms, the closer they are related evolutionarily. In this case, Woese found that the r-RNA of the halophiles is as close to the r-RNA of the methanogens as the two main types of methanogens are to each other. (For more details on Woese's work, see "The Origins of Life" in the June 1978 *Fusion*.)

The early evolution of photosynthesis would be consistent with Woese's hypothesis that the origin of life never went through a completely heterotrophic stage in which the main source of energy for the primitive organisms was feeding on the detritus of the so-called primitive soup of accumulated organic molecules. Woese postulates instead that virtually from the beginning of microscopic life, there was some form of active energy capture by the organisms.

Woese is now attempting to find more remnants of what seems to have been an entire self-sustaining archeoecology that existed during the first several hundred million years of the earth's history. The rapid evolution of this archeoecology after the formation of the earth demonstrates the powerful effect of nonlinear forces in the evolution of the biosphere.

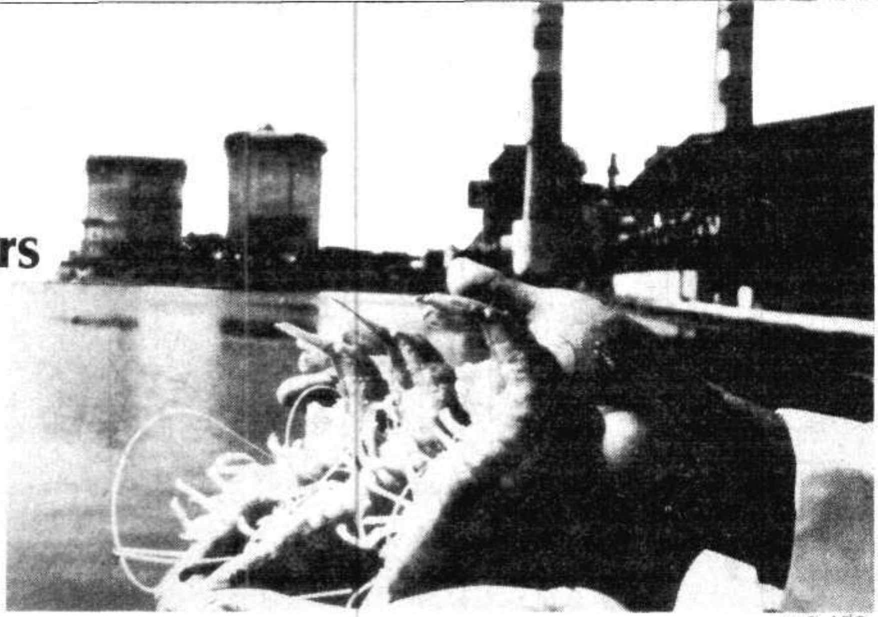
DNA Research May Lead to Self-Feeding Plant

A new gene manipulation technique has been discovered that could pave the way for creating plants that have increased protein content and that even manufacture their own fertilizer.

Biologists in Belgium have used a natural system of bacteria-plant gene exchange to insert genes into plants. This is the first case of genetic recom-

Waste Heat Spurs Seafood Growth

A number of speakers at the National Shellfisheries Association's 70th annual conference in late July favorably reviewed the potential for using waste heat from nuclear reactors or conventional power plants to increase the growth rate and extend growth periods of seafood produced through aquaculture. The speakers said that fish or shellfish grow considerably faster—four to five times faster in many cases—with aquaculture techniques that use waste heat than under natural conditions.



U.S. AEC

Five-inch white shrimp like these are harvested all year round in the warm-water ponds of Florida Power and Light's Turkey Point nuclear power plant.

U.S. Behind in Aquaculture

Recent studies by the National Academy of Sciences and other organizations have shown that aquaculture currently supplies an average of 10 percent of total worldwide fish production but only 3 percent of U.S. production. Some areas of Southeast Asia use aquaculture to supply 40 percent of their fish production.

Legislation to set up a national aquaculture development plan for the United States has already passed the House of Representatives and is pending in the Senate. The proposed law, the National Aquaculture Organic Act of 1978, would provide funds for important research in aquaculture technique, guaranteed loans for aquaculture facilities, and funds for insurance against some operational losses.

Uranium Processed From Fertilizer

A new process for extracting uranium from phosphoric acid, a feedstock for the production of phosphate-based fertilizers, has been developed by the International Minerals and Chemical Corporation. Experts estimate that the new process could double the world's uranium supply.

The company will use the process in a new $50 million plant scheduled for completion in late 1979. The new IMC plant, which will be constructed adjacent to the company's New Wales phosphate chemicals complex in central Florida, is designed to extract 750,000 pounds of uranium a year from about 840,000 tons of phosphoric acid. Once the uranium is removed, the phosphoric acid will continue to be used to produce phosphate-based fertilizers.

IMC engineers estimate that when the yellowcake (uranium oxide) is upgraded to nuclear fuel, it could provide year-round energy for three 800-megawatt nuclear power plants, enough to supply power for a city of 1.5 million.

An IMC spokesman said that all phosphoric rock contains uranium as a trace element in varying concentration. There are large phosphate reserves in Morocco, which are especially rich in uranium, he said.

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binant research in which a gene was put into the functioning genome of a eucaryotic organism (the advanced organisms including animals and plants whose cells contain a nucleus that houses gene-containing chromosomes). Previously, genes had been exchanged between bacteria or taken from a eucaryote and put into a bacterium.

Marc van Montague and Jeffrey Schell of the University of Ghent in Belgium used species of agrobacteria that cause crown gall tumors in almond, peach, and rose plants. Under natural conditions, the bacteria cause the tumors by inserting genes into the plant cells via a plasmid, a piece of bacterial DNA.

In addition to causing the tumor growth, the plasmid also contains genes for the production of rare amino acids that are then produced by the plant tumor cells. These amino acids, such as opine, are used by the agrobacteria as a necessary nutrient; that is, the bacteria induce the plant cells to produce substances that the bacteria need in order to live. The researchers isolated a gene for antibiotic resistance from another species of bacteria, inserted it into the agrobacteria plasmid, infected plants with the agrobacteria, and subsequently found evidence of the gene in the plant tumor cells.

This experimental result opens the way for inserting other genes into plants, such as genes related to food quality (high protein content, etc.), to nitrogen fixation by the plant, and so on.

To demonstrate the ultimate usefulness of the procedure, the researchers removed tumor cells following the gene transplant and grew them in tissue culture to produce entirely new plants without tumors that maintained the transplanted gene.

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milestone in the group's five-year history, Levitt said. In the past few months, the FEF has become internationally recognized as a leading authority in the fusion field. To its credit are several international conferences; a major role in putting the latest fusion breakthroughs on the front pages of the world press; the publication of the fastest growing scientific magazine in the country, *Fusion*, which now has a circulation of 42,000; and the achievement of an annual income rate of $250,000.

After describing the FEF's progress in some detail, Levitt laid out the foundation's goals for the immediate future. "We must make fusion the centerpiece of the more general fight for world development," Levitt said, "and make the Fusion Energy Foundation the spark for a broad burnwave of progress."

A $1 Million Plan

What this will require was presented in a just-issued 35-page FEF report titled "Review and Prospectus 1977-1979," in which the FEF documents its impressive array of accomplishments in research, public education, and publishing and outlines a $1 million plan for expansion. Goals include funding promising advanced research in plasma physics, establishing a fellowship program, upgrading the magazine, publishing a book on fusion, and putting the staff on salary.

As Levitt spelled out, the FEF, which has tax-exempt status, intends to raise $750,000 above its current income from individual, corporate, and foundation sources and from increased publication sales. At present, 86 percent of the FEF income comes from sales and subscriptions to its monthly magazine, *Fusion*, and quarterly journal, the *International Journal of Fusion Energy*.

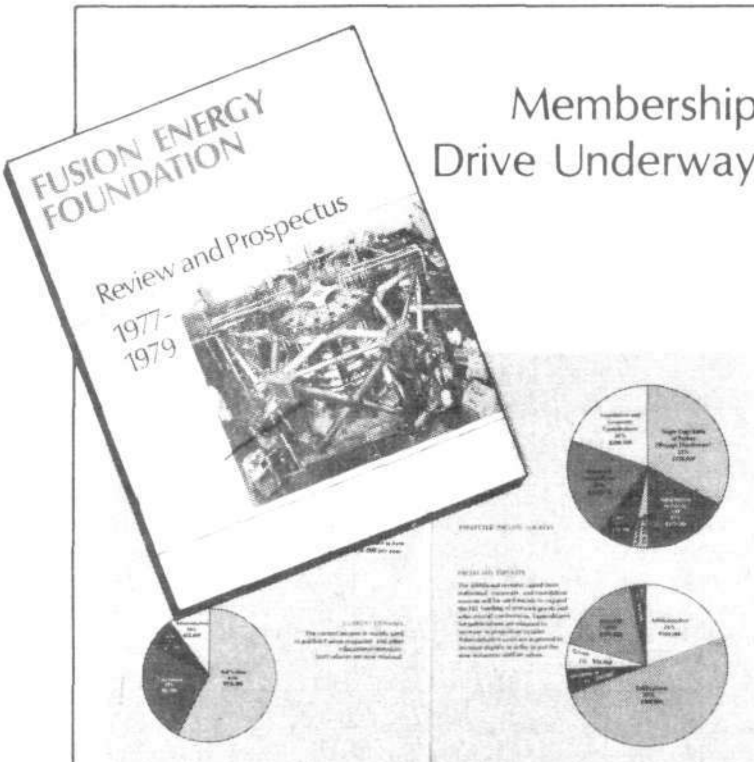
In the "Review and Prospectus," acting board chairman Hall made it clear where this money should come from. "Since the FEF was granted tax-exempt status in April 1978, we have set fundraising from the corporate sector as a top priority. ... After discussion among the FEF directors and trustees, many of whom have long experience and outstanding records of accomplishment in our nation's top R & D and scientific programs, we made the commitment as individuals and as the leadership of the FEF to raise funds from the private sector that will 'match' funds from other sources."

In Levitt's concluding remarks, he noted that fusion had the potential to solve the energy crisis, the dollar crisis, and the world economic crisis. "For this reason, support from the corporate sector for the FEF to meet its goals is really a litmus test of where that sector lines up —on the side of progress, or on the side of destruction."

It is in this context that businessmen and others have to view the attack on the FEF in the Oct. 2 issue of *Business Week*, which ridicules the FEF as a small group with nothing new to say, Levitt noted. "We plead guilty to that charge. One has to know the best of the old in order to develop the science and technology of the future."

The FEF meeting concluded with the decision to add William Hall to the board of directors. The expanded board then mandated immediate efforts to implement the fundraising project and to recruit a review committee of top scientists to evaluate research for purposes of funding by the FEF and other agencies.

—*Marjorie Hecht and Dr. Steven Bardwell*



Membership Drive Underway

As part of the new fundraising drive, the FEF board of trustees plans to initiate a membership drive to bring foundation members and supporters into the fight for advanced science in the United States. Starting in November, FEF members will receive a monthly newsletter, called *Fusionotes*, with inside information on energy news, FEF events, and campus club activities.

Regional membership meetings are also planned to coordinate local fundraising and to involve members in educational and organizing activities. Luncheon meetings for reports and discussion of the latest scientific advances are one of the main activities under consideration.

The FEF is preparing a questionnaire for members, asking them if they wish to participate in a chapter organization and what sort of activities they are interested in. Also, a revised membership schedule establishing new membership categories and privileges is in preparation.

Members will receive a copy of the FEF "Review and Prospectus 1977-1979," as well as edited transcripts of the two-day annual FEF meeting reported here.

Plasma Physics: The Frontier of Scientific Research

At every point in history when man was confronted with the necessity for a revolution in technology, it was also necessary for man to make a revolution in scientific and philosophical understanding. The advent of the fusion age is no exception.

The development of fusion energy will profoundly change every aspect of our material existence; simultaneously it requires and provides the means for a new understanding of the universe. For theoretical and practical reasons, the science of fusion—plasma physics—is now the frontier of scientific research.

This issue features a primer on this fusion science, presenting the basics of plasma physics for the layman from a conceptual foundation that will challenge even the most jaded plasma physicist. For when the experimental results of plasma physics are fully considered, they imply that phenomena in the physical universe are self-ordering, almost lifelike in development—an implication that jolts the very foundation of modern physics.

From a practical standpoint, plasma physics has equally momentous effects. As the article on nuplex technology shows, the study of plasma physics is the key to a new world, a world of virtually unlimited material abundance and a universe characterized by the same necessity for progress and development that characterizes man.

The front cover is a color density rendition of a solar flare photographed in 1973 from the U.S. Skylab space station in earth orbit. Below is a schematic drawing of the plasma layers that surround the earth. The solar wind, the plasma expelled by the sun, is on the left; the solid lines indicate the interaction of the earth's magnetic field wtih the plasma layers; distances are marked in units of the earth's radius.

Cover design and illustration by Christopher Sloan; photograph courtesy of the National Aeronautics and Space Administration.