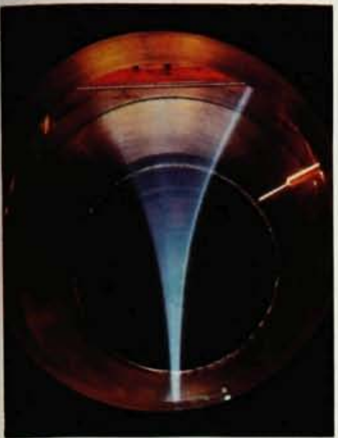
A glowing plasma fans out in the magnetic field of a "baseball" magnet at Lawrence Livermore Laboratory.



Plasmas and fluids

Plasma physics and fluid physics are large fields that are themselves divided into subdisciplines: Plasma physics is practiced by fusion and space researchers and applied to the development of novel particle accelerators and coherent-light sources, to isotope separation and to astrophysics; fluid physics is important to geophysics, biology, medicine, meteorology, combustion research and pollution control—as well as to plasma physics. The panel devotes one chapter each to fluid physics; general plasma physics, fusion plasmas, confinement and heating; and space and astrophysical plasmas. The highlights and recommendations of the panel report are numerous; space limitations permit only a relatively small number of these to be described below.

Fluids. Computers have had a particularly important influence on the development of fluid physics in the past decade. Problems that had previously defied theoretical analysis and experimental simulation, such as convection and circulation within the Sun and planetary atmospheres and the nonequilibrium flow surrounding the space shuttle orbiter on reentry, are now simulated numerically. Better aircraft wings, internal-combustion engines, fusion and fission devices and undersea naval vehicle components are now designed more quickly and less expensively with computers.

Powerful new computational tools as well as new experimental techniques have led to exciting improvements in the understanding of turbulent flows. On a large scale, turbulent and coherent dynamic fluid structures have been identified in the Earth's oceans and atmosphere and in the atmospheres of Jupiter and Venus. Eddy-resolving computer models have successfully simulated these atmospheres, giving a new view of laboratory turbulence and the general circulation, storms and weather of the atmosphere and deep ocean.

Fluid-dynamic modeling on a more human scale has led to basic knowledge of the cardiovascular, reproductive, and urinary systems as well as many of the internal organs of the body. The locomotion of organisms from single-ciliate cells to the hummingbird and the tuna is now better understood in terms of fluid-dynamic models. Principles of fluid physics have been vital to the design of artificial organs and tissues and the development of new clinical diagnostic methods.

A large problem that fluid physics must face is the limited direct support available for innovative or discretionary university education in fluid physics. Many areas of fluid physics are neglected by the university research community simply because of a complete absence of support. The panel believes that "this situation is a scientific and technological mistake, with the potential for grave economic consequences."

General plasma physics. Under this heading the panel includes research in basic plasma physics and its applications to problems other than thermonuclear fusion and space plasmas. Although basic plasma physics has direct applications to new technologies, it is often seen as incidental to the main objective. The panel feels that this is a mistake: Basic physics should be funded and developed along with new technology, because their futures are so closely intertwined.

The last ten years have seen the rapid development of extremely powerful high-voltage pulsed-power systems for the generation of intense beams of electrons, ions and photons. The particle beams produced by these machines, whose peak power sometimes reaches tens of terawatts, are so intense that the self-fields decisively influence their behavior; the beams are thus better studied under the rubric of plasma physics than accelerator or particle physics. Tremendous gains in the power of these machines have been made in the last decade; in the next decade emphasis will shift to increasing the repetition rate of these machines and developing new switches that can survive the huge powers they produce.

New particle-accelerator technologies using plasma phenomena are possible and have been investigated. These use the electric and magnetic fields of charged particles to accelerate and focus a beam of particles. Five different types of accelerators have been investigated in the past ten years: space-charge, wave, electron-ring, collective focusing, and laser-driven accelerators. The last type exploits the availability of high-power (more than 10^{14} W) laser beams, whose high fields could accelerate particles to the TeV range and beyond.

Fusion-plasma confinement and heating. Thermonuclear fusion is one of the very few options available to satisfy mankind's long-term energy needs.

Panel on the Physics of Plasmas and Fluids

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The PBFA-II light-ion driver at Sandia represents one of the approaches being taken to inertial-confinement fusion. It is capable of delivering 100 TW of power to implode a deuterium–tritium fuel pellet.

The basic requirements of a fusion power device have been understood since the early 1950s: A plasma must be heated to a high enough temperature and confined at a sufficient density to allow the relatively infrequent fusion reactions to occur. In the design of any fusion reactor one must make a tradeoff between density and energy confinement. Approaches to magnetically confined fusion fall into two major classes: those with 10^{14} particles/cm^3 and a confinement time of about 1 second (tokamaks, stellarators, mirrors) and those that have the potential for a much higher density, typically 10^{15} particles/cm^3, with a correspondingly reduced energy-confinement time of about one-tenth of a second (reversed-field pinches, compact toroids).

Plasma confinement in closed-field-line systems of the tokamak and stellarator type has steadily improved and tokamaks now occupy the dominant position in fusion research worldwide. The tokamak, which received its early development in the Soviet Union, has become the largest element in the US magnetic-fusion program. It has already achieved plasma parameters close to those required in a reactor. Indeed, experiments just coming into operation, the Tokamak Fusion Test Reactor at Princeton and the Joint European Torus in Europe, should produce more thermonuclear power than the power required to heat the plasma. Stellarators lag behind tokamaks in development by several years but stellarator plasmas are found to have characteristics comparable to those of tokamaks of similar size.

The present phase of toroidal research centers around facilities that are just now beginning or will soon begin operation. The new tokamaks—TFTR, JET, the Japanese device JT-60 and an upgrade of the Doublet III device called DIII-D—have plasmas of about a meter in minor radius, multi-mega-ampere current capability, pulse lengths of up to 10 seconds and tens of megawatts of auxiliary heating.

Fusion plasmas can also be magnetically confined in an open-ended cylinder by strengthening the magnetic fields at the ends of the cylinder to form magnetic mirrors. A major advance has been the development of tandem-mirror systems, in which mirror cells plug the ends of a large-volume ignited plasma. These systems were invented simultaneously in the United States and the Soviet Union and display significantly longer confinement times than single-cell mirror systems. The great design flexibility of mirror-confinement machines allows new ideas to be easily implemented.

Alternatives to tokamaks and mirror machines should also be pursued, the panel says, both as ends in themselves and for the light they can shed on the problem of magnetic confinement.

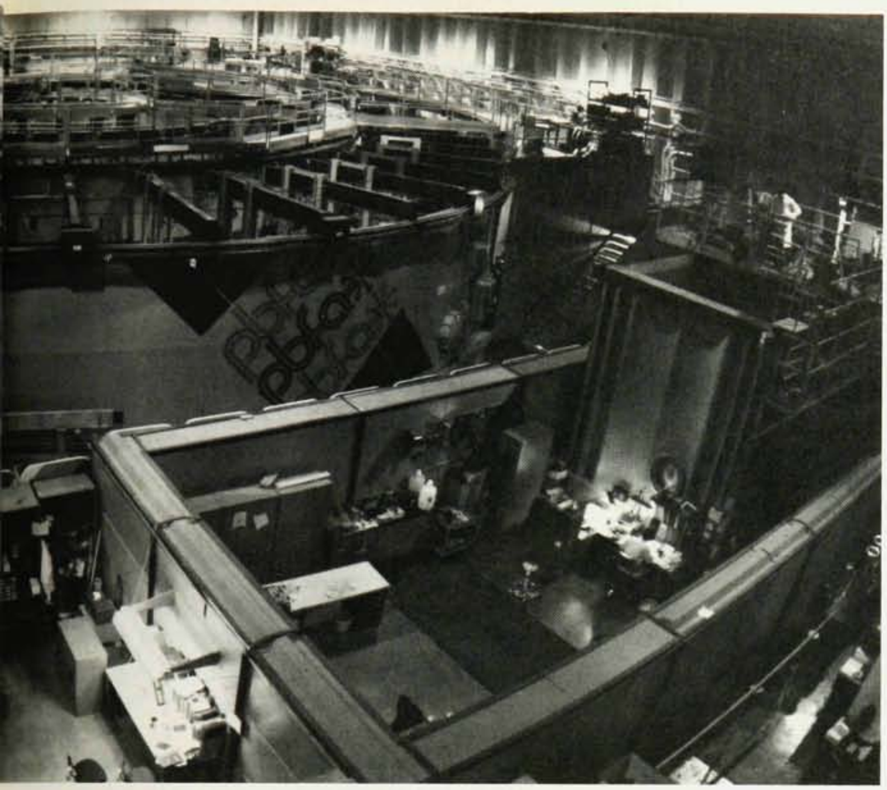
With regard to the future of magnetic-confinement fusion the panel recommends the construction of a "moderate-cost tokamak experimental facility" (the so-called Burning Core Experiment) to investigate properties of the ignited plasma state. Meanwhile, the US should maintain "a broad-base program in magnetic-confinement research, encompassing tokamaks, mirrors, stellarators, reversed-field pinches and compact toroids."

Inertial confinement. Inertial-confinement fusion involves the the use of laser or particle beams to compress a pellet made of deuterium and tritium to a density of 10^{25} particles/cm^3 and to heat it to a sufficient temperature to ignite a thermonuclear "burn" before it blows itself apart. Inertial-confinement-fusion research also has applications related to physics at high energy densities. Irradiation of plasmas by intense laser light opens up for study many nonlinear processes and enables one to investigate matter under pressures of tens to hundreds of megabars. The generation of highly ionized matter and of intense short pulses of x rays allows the study of atomic physics important to the development of x-ray lasers.

A neodymium glass laser driver has been used to implode targets to about 100 times ordinary liquid densities, which is within a factor of two of reactor requirements. Increasingly sophisticated plasma instrumentation and modeling codes have improved agreement between experiments and the theory of laser–target interaction.

Two very large driver facilities have recently been constructed in the United States: the Nova neodymium glass laser at Livermore and the PBFA-II light-ion-beam accelerator at Sandia. These and smaller facilities will be used to extend greatly our knowledge of the efficiency, symmetry and stability of pellet implosions. In addition heavy-ion drivers have been proposed and the search for efficient, shorter-wavelength lasers continues.

For inertial-confinement fusion the panel recommends striving to implode D–T targets to 1000 times liquid density, studying energy transport and fluid and plasma instabilities, and choosing and developing a cost-effective, multimegajoule driver design. "Timely execution of this strategy," they write, "will provide the basis for a



decision in the late 1980s on the next generation of experimental facilities."

Space plasmas. The solar system is the primary laboratory in which astrophysical plasma processes of great generality can be studied. By 1960, with the discovery by spacecraft of the Van Allen radiation belts and the solar wind, it was already clear that future understanding of the Earth and Sun would be expressed in terms of plasma physics. Plasma physics is also the key to understanding the generation of magnetic fields in planets, stars and galaxies; phenomena occurring in stellar atmospheres, in the interstellar and intergalactic media, in neutron-star magnetospheres, in active radio galaxies and in quasars; and the acceleration and transport of cosmic rays. The study of each of these subjects depends on and contributes to laboratory plasma physics. Each has traditionally been pursued independently. Only recently has there been a tendency to view them as a unified discipline.

In the past ten years the magnetospheres of Mercury, Venus, Jupiter and Saturn have been investigated with planetary probes. When the Voyager probes flew by Jupiter the data they beamed back to Earth established that Jupiter's rotation powers a radial outflow of heavy-ion plasma ejected by volcanic activity from the satellite Io.

Ten years from now the initial exploration of solar-system plasmas will have been nearly completed. The missions to comets Halley and Giacobini–Zinner will have provided the first measurements of any comet. The International Solar Polar Mission will have studied the solar wind and its effects on cosmic rays for the first time in three dimensions. A Voyager spacecraft will have taken the first *in situ* measurements of the magnetospheres of Uranus and Neptune. A Pioneer or Voyager spacecraft might have left the heliosphere and detected interstellar matter and galactic cosmic rays directly. The list of contemplated firsts could go on and on. Using the information from these probes, astrophysicists will complete in the decade to come the first generation of large-scale numerical models of space and astrophysical systems. These models will probably make plasma physics central to the interpretation of many astronomical observations and motivate new and different kinds of observations.

Not all important discoveries will come from planetary probes or computer models. Many laboratory experiments help develop basic theory and hence contribute indirectly to space and astrophysical research. The panel stresses this point: "Past experience indicates that laboratory experiments will continue to contribute to space and astrophysical plasma physics."

Theory provides the clearest expression of the unity underlying plasma physics in the laboratory, in the solar system and in the universe at large. Following the recommendations of the Committee on Solar and Space Physics of the Space Science Board (1980), NASA initiated the Solar–Terrestrial Theory Program, which has contributed to the new level of precision reached in solar-system-plasma research. The panel applauds the NASA program and writes, "We heartily recommend continuance of the excellent support that space plasma theory has received in the past 5 years and, especially, of the Solar–Terrestrial Theory Program." The Astronomy Survey Committee (1982) and the Theory Study Panel of the Space Science Board (1983) recommended independent research programs in astrophysical plasma, a judgment with which the plasmas and fluids panel agrees: "Theory and numerical modeling must both be strengthened in order that plasma physics play the central role in the interpretation of astronomical observations warranted by the fact that most of the universe is in a plasma state."

According to the panel, "Twenty years ago, imaginative drawings—cartoons—guided space plasma research." These were helpful, but our understanding has progressed to the point where more complex models of the entire magnetosphere of a planet are needed to understand the plasma processes that operate there. This is why large-scale numerical modeling is increasingly important. Unfortunately the largest computing facilities in the United States do not have space physics and astrophysics as institutional objectives. In some cases American researchers have had to travel to Europe or Japan to perform large-scale computations. In view of this, the panel recommends "a national computational program dedicated to basic plasma physics, space physics and astrophysics.... Such a program should ensure ready access to advanced computing on the basis of peer review."

—Bruce Schechter □