The international history of fusion energy research

Suppose it were possible to solve the energy crisis for all time. Imagine that there existed a kind of energy system that is inexhaustible, cheap, without radiation or environmental hazard, and capable of producing energy for human use in all forms. This energy system is limitless, because its fuel comes from ordinary water; it is so efficient that it can produce more energy from one gallon of ordinary seawater than now comes from 300 gallons of gasoline. It works in such a way that it can be used to break down useless materials into their basic elements, and recombine them into useful materials of all kinds.

Having such an energy system would be like bringing the sun down to earth, to provide abundant energy for millions of years—electrical, thermal, hydrogen—and a limitless resource base.

It's not a daydream. The world scientific community is now certain that fusion power can be achieved before the end of this century. When both Houses of Congress passed by near-unanimous votes the legislation that Congressman McCormack introduced to commit the United States to that goal, they were expressing the unqualified confidence of experts.

"The scientific laws, the physical laws, underlying the process are now sufficiently well known that even the skeptical, conservative scientists are willing to say yes, it's no longer a question of scientific feasibility," reports Edwin E. Kintner, Fusion Director at the Department of Energy. "That is a very profound conclusion: man on the face of the earth can create the energy of the sun and the stars."

As Charles B. Stevens of the Fusion Energy Foundation expressed it, "There are no scientific or technological barriers to a commercial demonstration of fusion power during the 1990s."

Of course, new theoretical and technological advances will continue to be made. Fusion represents the frontier of science. Fusion is the power of the sun, a large fusion power reactor in which the nuclei of atoms are fused as they are pressed together by the force of the sun's gravity. On Earth, the same process must be achieved using the same ionized gas called plasma that makes up the sun—but without benefit of such gravitational force.

Plasma must be heated to very high temperatures, yet it must be simultaneously confined—using magnetic fields, or the inertial force of powerful beams like lasers. In the latter case, it must be compressed to extreme density. Fusion requires meeting all three conditions: when **temperature** is great enough, and the product of **density** times **confinement time** large enough, the nuclei of atoms fuse together, forming heavier new atoms and releasing enormous amounts of energy.

Among the developments in the past few years that gave rise to scientists' confidence are the following:

Scientists at Princeton, working on a tokamak—a magnetic confinement device developed by the Soviet Union, whose name refers to charged magnetic fields, achieved **temperatures** of 80 million degrees, well above those required for fusion reactions, and far hotter than the sun.

Scientists at Oak Ridge National Laboratory achieved the highest recorded "beta," a measure of the **efficiency** with which magnetic fields achieve **confinement** of plasma, while also maintaining **densities** high enough for fusion reactions.

Scientists at Massachusetts Institute of Technology, working on a device called an Alcator (a small tokamak), were able to **confine** hot plasma at high **density** just long enough to produce the conditions equivalent to energy **breakeven**—producing as much energy as was used in operating the device.

These and other scientific breakthroughs were translated into political action by a variety of forces. Among key developments were the following:

- A growing debate developed among scientific, industrial, and military policymakers as it became clear that Carter administration policies on energy and the economy were leaving an open field to Soviet preeminence, particularly in nuclear technology. The Soviets are known to be engaged in several lines of advanced research with implications for major weapons breakthroughs. The breakthroughs at Princeton, Oak Ridge, and elsewhere, however, had given the United States a significant lead in magnetic fusion research.

- A report by Chicago Prof. Isaak Wirszup on Soviet scientific education served to highlight how badly American technical and scientific education has fallen off since the winding down of the NASA space program; a serious fusion development program, with its large requirement for scientific manpower training, is the obvious focal point for reversing this situation.
- Industrial and engineering firms with an interest in the fusion area combined with scientists like Dr. Stephen O. Dean, former head of the government's fusion confinement division, to form Fusion Power Associates, a private consortium to promote the development of fusion power.
- The Fusion Energy Foundation, formed in 1974, grew in a few years to become the largest nonprofessional scientific organization in the entire nation, with 14,000 members and paid circulation for its magazine, *Fusion*, approaching 200,000—a large proportion of subscribers among scientific, industrial, and political leadership layers.
- Three prestigious panels established to report to the President or Congress, the Foster, Hirsch, and Buchsbaum committees, each recommended a significant expansion of the nation's magnetic confinement program.
- Dr. Stephen Dean testified in favor of a greatly expanded fusion program at the 1980 Democratic Party platform hearings. Dr. Morris Levitt, the Fusion Energy Foundation's executive director, testified before the Buchsbaum panel and the Democratic Party's platform committee, recommending an "Apollo-style" fusion effort on the scale of NASA's moon-shot program.

The result was Congressman McCormack's legislation, which got 159 cosponsors and went through the House of Representatives by an overwhelming 365-7 vote. Sen. Paul Tsongas then signed up 23 cosponsors, and the Senate sent the bill to the President by a voice vote.

The history of the program

In 1953, the Soviet Union developed the world's first H-bomb—an *uncontrolled* fusion device—which was soon thereafter developed in the United States. As early as 1950, I. V. Kurchatov, director of the Soviet weapons development program, convinced Soviet leaders that significant resources had to be devoted to the development of *controlled* fusion energy, which he called "the second atomic problem of the 20th century." Work began on the same problem in the United States, at the urging of Dr. Edward Teller and others.

In its early stages, fusion research was almost wholly classified, kept top secret. But because of the very advanced nature of the theoretical physics involved in fusion, many scientists in both East and West, believed that, as Kurchatov expressed it, "complete frankness among scientists of the various countries occupied with research on controlled thermonuclear reactions" was essential.

A turning point came in 1956, when Kurchatov, addressing the British Harwell physics conference, presented the full experimental and theoretical details of Soviet fusion research to a startled audience of Western scientists. A similar unilateral "declassification" came a few months later, when Soviet academician L. A. Artsimovich made a presentation to an audience in Stockholm. Within six months, significant parts of the U.S. program were also declassified and made public. At the same time, the program in the West was accelerated, on the basis of the new information exchange that resulted from Kurchatov and Artsimovich's presentations.

The tokamak

Among the information that came to light were data pertaining to the key Soviet fusion program, the tokamak. In the late 1940s, Soviet scientist Sakharov proposed that fusion plasma could be contained in a doughnut-shaped magnetic bottle. In this geometry, an electrical current could be induced in the plasma to transform the circular magnetic field into helical spirals winding around within the doughnut.

After initially poor experimental results due to the presence of impurities in the plasma, the decade-long Soviet tokamak research effort under Artsimovich achieved a major breakthrough in plasma heating in 1969.

Soviet reports of the tokamak results were initially treated with skepticism in the West. But a team of British scientists invited to the U.S.S.R. was able to use advanced laser diagnostic techniques not available to Soviet scientists, and found that the tokamak was generating even higher temperatures than the Soviets themselves had believed.

Another leading magnetic confinement program is the stellarator, a device similar to a tokamak. The stellarator was actually first developed by U.S. scientist Lyman Spitzer. The stellarator is also a doughnut-shaped magnetic bottle, but the helical twist in the magnetic field lines is not generated by inducing an electrical current internal to the plasma as in the tokamak. The tokamak's induced current is exhausted within one minute to one hour, therefore requiring a discontinuous or "pulsed" mode of operation; it must be shut down and started up again—the main tokamak drawback. The stellarator's current is generated externally, with a fixed secondary winding around the doughnut.

Difficulties prevented the construction of large-scale stellarators during the same period that tokamaks were being readily built; the United States discontinued its program in favor of a tokamak focus. The Soviet Union, however, maintained research work on the stellarator, whose advantage over the tokamak lies in the continuous mode of operation which an external current-generating source makes possible.

In 1974, a group of U.S. scientists from the major research laboratories went to the U.S.S.R. to examine the Soviets' latest stellarator work. They concluded that the Soviet model of the abandoned U.S. concept may be even more promising than the tokamak.

The Soviets today maintain the largest stellarator program in the world, and their persistence is beginning to reap rewards. A few months ago, West German scientists working on the stellarator reported experimental results as good or even better than those of the mainline tokamaks.

The recent breakthroughs

Perhaps the most important single element determining the pace of fusion research progress has been funding. In the United States, as budgets for fusion research began to increase under the Nixon and Ford administrations after 1969, results began to be reported with increasing frequency—each seemingly more significant than the previous ones. After the initial Soviet and U.S. breakthroughs of the 1969-73 period, the past seven years have seen spectacular progress in both magnetic and inertial confinement approaches.

In May 1975, KMS Fusion achieved the first confirmed laser-induced thermonuclear fusion. That July, magnetic fusion researchers at Lawrence Livermore Laboratory achieved temperatures of 140 million degrees Celsius on a magnetic mirror machine—a linear device with a magnetic force acting as "reflector" at each end. The same experiment showed that plasma confinement time increases with increasing temperature, called "classical scaling."

In October 1975, MIT's small Alcator tokamak broke through all hypothetical barriers to high densities by producing the cleanest (most free of impurities) plasma ever achieved in a tokamak. Just as Livermore showed classical scaling for confinement time and temperature, the MIT experiment simultaneously showed a different classical scaling: that confinement time increases with density.

In December 1975, the Soviet research team headed by L. Rudakov at the Kurchatov Institute in Moscow used the Angara electron beam to produce fusion for the first time.

The year 1976 saw an even more startling series of breakthroughs in rapid succession. In January, the MIT Alcator achieved the minimum density-and-confinement conditions needed for fusion, although below the temperatures required. One month later, Soviet Kurchatov scientists using the T-10 tokamak achieved the minimum confinement conditions needed for a hybrid fusion-fission power plant.

That March, materials researchers at Oak Ridge in Tennessee showed that #316 stainless steel could withstand fusion-generated environments within a reactor for up to 20 years, operating at approximately 350 degrees Celsius—resolving the most significant technological problem facing fusion reactor development.

In April 1976, Lawrence Livermore mirror machine researchers made breakthroughs related to plasma energy density that made their device a serious contender with the tokamak for the "first reactor" prize. In November, Oak Ridge's tokamak used neutral beam heating to achieve 20 million degrees Celsius without loss of plasma stability. French tokamak researchers reported similar results.

In December 1976, Rudakov's achievements at Kurchatov were duplicated at Sandia Laboratory in New Mexico by electron beam researchers who used a unique, new type of electron beam target.

In April 1977, Livermore scientists produced more than 1 billion fusion neutrons using the Argus glass laser, and the same month, Los Alamos researchers produced the first fusion reactions with a carbon dioxide gas laser. In July, Oak Ridge reported that the anomalous behavior of previous tokamak experiments had been due to tungsten impurities, and announced the development of new impurity control techniques for the tokamak. In August of that year, the Princeton Large Torus (PLT) tokamak duplicated the results of the Soviet T-10 device.

In September 1977 came a series of new developments—all in one month. First, laser fusion workers under N. Basov at Moscow's Lebedev Laboratory produced significant compression of pellet fusion targets and achieved a confinement of 500 trillion seconds-nuclei per cubic centimeter. Then, Sandia Labs in New Mexico demonstrated that an electron beam can be transported through a laser-generated plasma—key for reactor technology. Lawrence Livermore theorists developed new pellet target designs that permitted the glass laser to produce high energy gains.

In December 1977, the Livermore Shiva laser was completed and fired bursts of power up to 27 trillion watts—twice as good as originally specified.

During 1978, Los Alamos scientists were able to fire bursts of power on their carbon dioxide gas laser up to 20 trillion watts, also twice as good as originally specified. At Sandia in April, the Proto II electron beam achieved power levels of 8 trillion watts, the originally specified goal.

Then, in July 1978, the Princeton PLT tokamak used neutral beam heating to achieve 80 million degree temperatures, establishing that there is no temperature limit in tokamaks except that set by radiation. In the same month, Soviet researchers at Kurchatov were responsible for significant discoveries concerning tokamak startup.

The Princeton results in July were particularly significant for their impact on both the world scientific community and political leadership. Newspapers from New York, to Moscow, to Paris began to report that "The tokamak results from Princeton prove that thermonculear fusion is possible" (*Le Matin*, Aug. 16).

A remarkable record

In the year 1979, many significant breakthroughs occurred in materials development, superconducting magnets and materials, fuel processing and control, plasma heating technology, and special diagnostic, measuring and monitoring equipment for experiments. When all of it was reported at December 1979 congressional hearings on fusion, which featured members of the Hirsch panel set up in collaboration with Congressman McCormack's energy research subcommittee, it became clear that no industrial or technological project had registered a comparable record of achievement in a recent period. And the fusion program had stayed well within its stringent budget, meeting or beating its timetables despite inflation and animosity from as high as the office of the energy secretary.

The testimony of Dr. Paul J. Reardon, head of the Princeton tokamak program, at the December 1979 congressional hearings, removed any remaining basis for lingering doubts. Reardon stressed to the congressional audience that the U.S. fusion program has already gone most of the distance to reactor-level technology.

In the past 10 years, the U.S. fusion program has increased the plasma volume in tokamaks by a factor of more than 10. For a working reactor, only a fractional increase beyond this is needed. In terms of **energy gain**, determined by multiplying temperature and density-confinement time, Princeton's Tokamak Fusion Test Reactor, the first industrial-scale magnetic fusion project, has improved on previous accomplishments by a factor of 10,000! Only another factor of 10 is necessary.

Thus, recent progress has not only demonstrated the scientific principles, but has laid the basis for the actual development of the engineering technology to which the McCormack bill now commits the nation. All-important from the economic standpoint, changes have been developed in tokamak designs that have led to much smaller reactors with a significantly higher power density. As a result, the capital-budget costs have been brought down to a level that is, even now, approximately equivalent to those of nuclear fission plants of the same size. But unlike conventional nuclear plants, once built, a fusion reactor's basic costs are over—the fuel is virtually free.

The impact on U.S. industry

A large and continually growing involvement of industry in fusion research and technology development will be the result of government efforts to meet the goals of the McCormack fusion bill, said Stephen O. Dean in a recent interview. "All the engineering technology needed means getting programs going in the private sector," said Dean.

Stephen Dean was formerly director of the Department of Energy's fusion confinement programs. He now heads Fusion Power Associates, a consortium of industrial and engineering firms created to promote fusion development.

Today, the U.S. magnetic fusion program is by far the largest and most rapidly progressing advanced research effort in the country. Both small, advanced technology firms and large aerospace corporations are already essential components of the program. There is a great deal more involvement of industry that is less conspicuous, according to Dean, and during the next 10 years, in which the United States is to complete construction of a fusion engineering device, he forecasts the involvement of both small and large companies from a variety of industrial sectors, and the revival of many industrial research and development capabilities that are presently idle.

The special expertise of the nuclear industry, aerospace and electronics concerns, computer firms, all the way to milling and metallurgical companies, will be required to develop and build power systems, special materials, superconducting magnets, special diagnostic equipment and instrumentation, and other technologies whose need only becomes clear in the course of the program's development.

Moreover, as in the NASA program of the 1960s, most of the technologies required for the fusion program will have immediate application in other areas.

Industrial involvement in the fusion program is nothing new, reported Dean. The first stellarator device in the late 1950s was wholly built by Allis-Chalmers and RCA. United Technologies, predominantly an aerospace firm, just completed construction of a tokamak device at the University of Texas, and has the capability right now to "build a slew of tokamaks if there was a demand for them, here or abroad," he said. Similarly, the Tokamak