The demise of a full-scale ITER, a giant experimental reactor project, and the promise of alternative approaches prompt a congressional call for a divided field to set its priorities

Competition Heats Up on the Road to Fusion

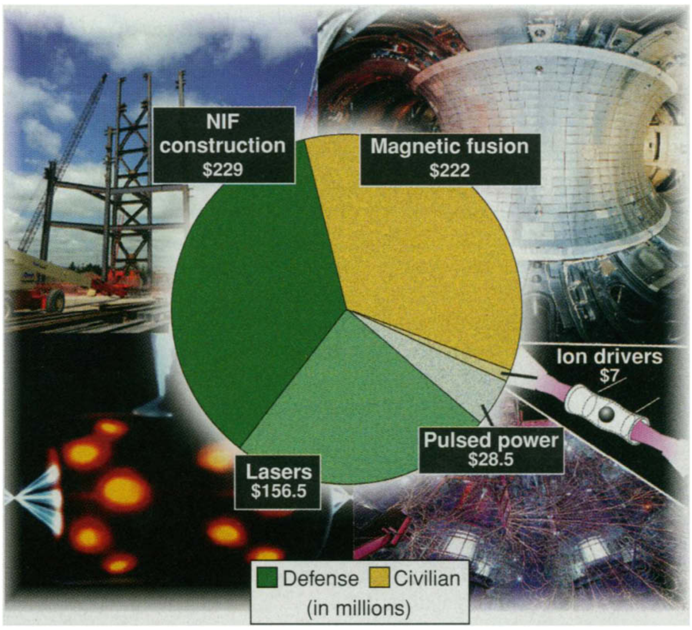
Dividing your forces during battle is a risky maneuver. Yet that is what U.S. researchers and their government funders have long been doing in one of the most daunting scientific and technical campaigns ever: trying to replicate on Earth the power that fuels the sun. One arm of this effort aims at providing safe, clean, and cheap electric power sometime in the next century by caging a hot ionized gas in a magnetic field. The other arm focuses on the physics of nuclear weapons by creating tiny explosions in pellets of fuel crushed by lasers or other methods. That two-pronged effort paid off for a generation in the form of breakthrough science. But with the demise of a project to build a vast magnetic fusion reactor and a surge of activity in the military fusion effort, there is a push for the two approaches to fight for supremacy.

Last month the U.S. Congress asked the Department of Energy (DOE) and the fusion community to review the government's entire \$650 million fusion research program and set priorities. The results could shape the direction of fusion research for decades to come, and it could ultimately lead to a unified strategy for fusion power that would test, compare, and perhaps even combine technologies from both arms of the current effort.

The review strikes fear in the hearts of some fusion researchers, who expect it to intensify competition for limited funds. But others welcome the effort, which both the House and Senate backed in the 1999 DOE spending bill. "I think we basically need a physical—a complete checkup," says Dale Meade, head of advanced fusion concepts at the Princeton Plasma Physics Laboratory. Adds Gerold Yonas, vice president for pulsed-power technologies at Sandia National Laboratories in Albuquerque, New Mexico, "It's time for us to review and rethink fusion—we're all in this together. In the long run we are all better off figuring out a way to make a credible demonstration of fusion power."

The review will reexamine a division blessed by a 1990 blue-ribbon panel that identified distinct goals for magnetic fusion and inertial confinement fusion, which relies on lasers, particle beams, or pulses of current. Magnetic fusion, funded as part of DOE's civilian energy research effort, is meant to work toward a commercial power plant. Inertial confinement fusion, funded mainly by the department's nuclear weapons program, is designed to support national security objectives.

Now, however, the centerpiece of the magnetic fusion program, a \$10 billion international project called the International Thermonuclear Experimental Reactor (ITER), appears to be dead (*Science*, 2 January, p. 20). Political and technical problems drained congressional support from the project, and many scientists have also turned away from it. At a recent meeting in Madison, Wisconsin, magnetic fusion researchers discussed the prospects for a cheaper version called "ITER Lite," now being studied by the international partners. The researchers also considered an alternative approach based on a series of smaller machines that could be hosted by several nations and called for a sweeping review of magnetic fusion science. At the same time, technical breakthroughs in pulsed power at Sandia and construction of a massive \$1.2 billion new laser facility at Lawrence Livermore National Laboratory in California have raised the profile of inertial confinement research.



The faces of fusion. DOE's fusion research budget is divided among (clockwise from upper left): construction of NIF and other projects, tokamaks like Princeton's, ion-driver work at Lawrence Berkeley, Sandia's Z-machine, and lasers like Nova at Livermore.

SOURCE: ENERGY DEPARTMENT PHOTOS (CLOCKWISE FROM TOP LEFT): LLNL, PPPL, UNIV. OF CALIFORNIA/LLNL/DOE, R. MONTOYA/SANDIA, LLNL

These developments prompted lawmakers like Senator Pete Domenici (R–NM), who chairs the Senate DOE spending panel, to take another look at the diverse fusion program. With each approach clamoring for more dollars to fund research and build expensive facilities, some lawmakers see the split between military and civilian programs as an unwanted relic of the Cold War. "Fusion is divided into separate areas, but to politicians the dollars are going toward the same goal," says one congressional staffer. Domenici's bill calls for a review of both civilian and defense technologies "prior to making decisions about next steps toward fusion energy." The House version echoes that request.

Burning desire

The magnetic fusion community's troubles were highlighted last month when Representative John McDade (R–PA), who chairs the House panel that funds DOE, asked the department not to sign an international agreement extending the ITER collaboration. His panel also refused to provide the \$11 million the Administration had requested in 1999 to continue U.S. work on the project, which includes Japanese, European, and Russian participation.

Now the community is scrambling to lay out a long-term plan for the future. At Madison, Michael Mauel of Columbia University, president of the University Fusion Association, which represents academic researchers, outlined a proposal—which he said has been encouraged by DOE—to emulate astrophysics and particle physics and hold intensive retreats to hash out fieldwide priorities. Such an approach "leaves a lot of blood on the floor," warned Robert Rosner, a University of Chicago astrophysicist who was invited to explain the process. But once the arguments are over, he said, the field "heals itself" and presents a unified voice to lawmakers.

A series of technical presentations offered a preview of battles to come. A large contingent favored breaking the ITER mission into smaller, less costly experiments that could be scattered around the globe (see sidebars). One cluster would study technology. The second would explore innovative and relatively diminutive machines that, like ITER, would cage plasma in a doughnut-shaped chamber called a tokamak. But while ITER was meant to be closer to a complete fusion reactor, the main goal of the smaller machines would be to study the physics of a short fusion burn—perhaps 10 seconds during which a plasma would produce much more power than was used to heat it. Such a plasma might even ignite, meaning the burn would continue when the heating source is turned off. "Better, cheaper, faster fusion—that's a theme I think we ought to get behind," said Richard Siemon of Los Alamos National Laboratory in New Mexico, summing up a widespread feeling.

But the reaction from those who still favor large projects was harsh. "The stupid man's approach to ignition" was how Charles Baker, the U.S. ITER Home Team Leader, characterized the smaller-is-better philosophy. Baker, an engineering professor at the University of California, San Diego, said that only lengthy burns of hundreds of seconds could illuminate the way a real power plant would work. Baker now supports ITER Lite—a roughly half-price version of the original with suitably reduced goals (*Science*, 8 May, p. 818)—and he found some allies among the international contingent.

Mitsuru Kikuchi of the Japan Atomic Energy Research Institute told a reporter that "we would not be interested" in a global, modular program of many modest devices. Although the U.S. and European programs are focused primarily on plasma science, Japanese researchers are generally more interested in technology—technology not addressed by the smaller ignition devices. On the other hand, a source within the European fusion program expressed support for "lower cost versions of ITER" as well as "alternative solutions."

By the end of the weeklong meeting, the multiple-machine option had emerged as the favorite. "Most of the people were surprised that the community could come together as it did," says Columbia University plasma physicist Gerald Navratil, who summarized reports from several breakout groups. Most resounding of all, said Navratil, was a con-

Korea Brings U.S. Design to Life

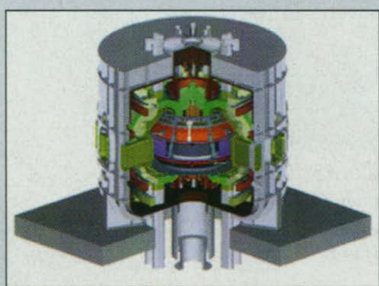
SEOUL—Researchers at the Princeton Plasma Physics Laboratory (PPPL) felt a mixture of pride and regret last fall when South Korean officials began ground preparations for the Korea Superconducting Tokamak Advanced Research (KSTAR) facility. The pride was for their role in preparing Korean scientists to take a big step toward understanding a key element in fusion reactions. And the regret was for one that got away: KSTAR is a scaled-down version of the $750 million Tokamak Physics Experiment (TPX), a fusion research facility slated for PPPL that the U.S. Congress killed in 1995 in an economy move.

Despite the country's worst economic crisis in more than 40 years, the Korean government is backing KSTAR because it believes the project will stimulate industrial R&D at the same time that it catapults Korea into the front ranks of fusion science. That's an attitude not widely held among politicians in the United States, where cuts are forcing officials to perform triage on a range of possible experiments (see main text).

"The project gives Korea's science and technology sector a chance to catch up with [wealthier] countries for a comparatively small amount of money," says Lee Gyung-su, project coordinator at the Korea Basic Science Institute in Taejon, KSTAR's home some 150 kilometers south of the capital. Work on KSTAR itself will begin this fall, and Lee says that its completion in 2002 will not only boost Korea's fusion program but also demonstrate that the country has the ability to manufacture advanced research devices.

KSTAR is designed to focus on techniques that "allow tokamaks to operate continually and at high performance," says PPPL's George Neilson, physics coordinator for the U.S. team that has been working for the past 3 years on the KSTAR design. It "is getting at a set of issues [that will] make the tokamak a better product."

The key to achieving that steady-state goal lies in understanding the behavior of superheated plasmas—ionized particles at temperatures of millions of degrees—and minimizing the turbulence that robs a tokamak of its ability to confine heat. The plasma, which is created by the inductive current pulse and sustained by longer lasting sources like radio-frequency waves, is confined magnetically, and a more compact plasma will allow scientists to build less expensive, smaller tokamaks. KSTAR's goal is to confine the plasma for 300 seconds, "almost an eternity for tokamaks," says Lee.



PPPL

A STAR is born. A cross section of Korea's tokamak, KSTAR.

Longer pulses also lend themselves to superconducting magnets that don't heat up like conventional magnets and which, in theory, can run indefinitely. Superconducting materials have already been used in some stellarators, another torus-shaped machine that uses external coils rather than the inductive plasma current to apply a necessary twist to the magnetic fields. Building these magnets will be one of KSTAR's biggest challenges, and officials hope that the project's industrial partners will apply the knowledge gained to a range of commercial products.

Because KSTAR is not designed to achieve ignition, it will use hydrogen and deuterium as fuel instead of the more potent mixture of deuterium and tritium. That combination reduces the amount of shielding needed to protect users from radioactivity. The scaled-down version of TPX also comes with a smaller pricetag, an important consideration given the country's current economic woes. Indeed, a government review this spring gave high marks to the project, delaying only the construction of three auxiliary heating systems and some diagnostics. The cuts, which won't interfere with early experiments, are expected to trim 20% from the $300 million cost of the baseline machine.

At that price, Korean officials think KSTAR is worth it. "There's a nice time window" in which KSTAR will be the only major advanced superconducting tokamak of its kind, says Lee. "For small money compared to what [others] spent, we can suddenly leap into major nation fusion research [status]. We can be in equal partnership." —MICHAEL BAKER

Michael Baker is a free-lance writer in Seoul.

sensus that the next step should feature burning plasmas—which could include ITER Lite or the smaller devices.

Whichever path is chosen, several scientists emphasized that ITER and tokamaks should not overshadow other innovative magnetic concepts that could lead in the long run to more attractive reactors. These concepts, which include a hybrid approach that crushes the plasma, as in inertial confinement, while bottling up the hot particles with magnetic fields, "are really exciting and are bringing young scientists into the field," said Mauel. "These are the things we've been doing in the non-ITER part of the program for years."

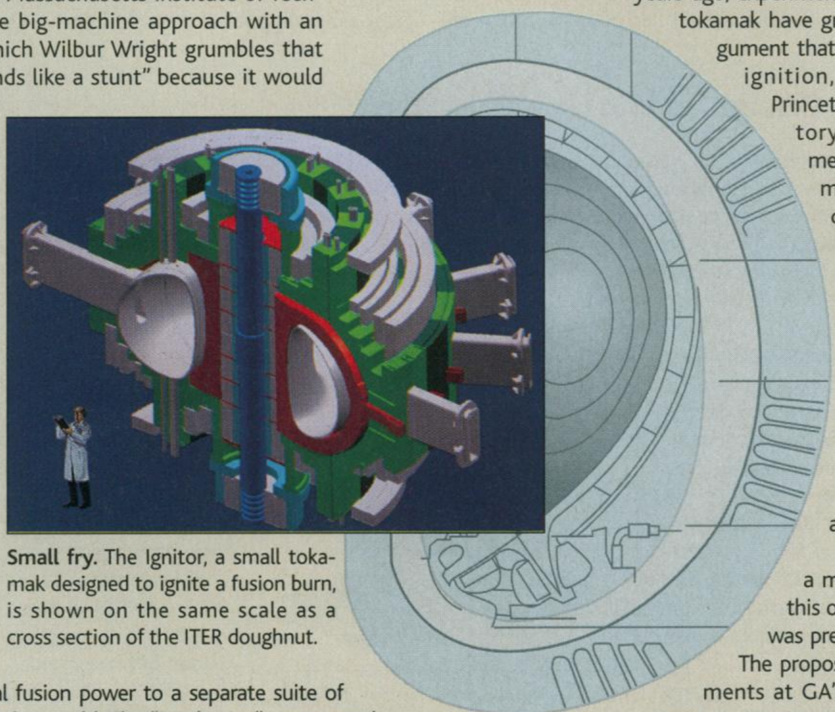
Real gain

While the magnetic community stumbles toward a long-term approach, newer types of fusion are striding ahead with bold plans. Construction is well under way at Livermore's National Ignition Facility (NIF), which will focus nearly 200 laser beams on a single target and will serve as a key facility for DOE's stockpile stewardship effort to maintain nuclear weapons without underground testing. Lab laser chief Mike Campbell already has an extensive wish list; on top of the $90 million the lab now spends on laser fusion, he says that some $35 million to $40 million annually will be needed through 2003 to prepare experiments on NIF.

Magnetic Fusion Researchers Think Small

Magnetic fusion needs to take a page from the Wright Brothers, say some fusion researchers. They are arguing for small and cheap "burning plasma" experiments—the Kitty Hawk flights of fusion energy—in place of the massive, costly reactors that have been the mainstay of the government's fusion program, such as the defunct International Thermonuclear Experimental Reactor or even the scaled-down incarnation called ITER Lite.

At a recent fusion meeting in Madison, Wisconsin (see main text), Earl Marmar of the Massachusetts Institute of Technology (MIT) spoofed the big-machine approach with an imaginary dialogue in which Wilbur Wright grumbles that the proposed flight "sounds like a stunt" because it would not demonstrate practical mass transportation. He tells Orville that a delay is in order while they address materials issues. "Wood and cloth will never make it," he frets. "In 10 to 20 years we'll be ready to build a single integrated step on the path to the jumbo jet."



Small fry. The Ignitor, a small tokamak designed to ignite a fusion burn, is shown on the same scale as a cross section of the ITER doughnut.

SOURCE: C. R. FRASCATI / IGNITOR PROJECT SOURCE: JAERI

But Orville's approach won big at the Madison meeting. Participants described a range of small experiments that would focus on the physics of an energy-producing fusion plasma, leaving the technology needed for practical fusion power to a separate suite of devices scattered around the world. The "jumbo jet"—an actual power plant—would be considered much later. "I believe the technology is going to change tremendously in the next 50 years," says Tim Luce of General Atomics (GA) in San Diego. "The physics is not going to change. So let's study the physics." Agrees Gerald Navratil of Columbia University, one of the meeting's organizers, "The overwhelming consensus was that the exploration of a burning plasma really was the primary priority."

A majority of the researchers, said Navratil, favored the multimachine approach. Like their outsized cousins, these smaller devices would be tokamaks, doughnut-shaped vessels threaded with magnetic fields that confine hot plasma. The devices would create those magnetic fields with electrical currents in chilled copper coils, rather than the bulky and expensive superconductors of ITER. Copper coils can deliver much more powerful fields than superconductors can—albeit for shorter periods.

Copper-coil devices rely on these high fields, rather than sheer size, to confine the plasma at densities and temperatures high enough for it to ignite. As a result, these machines can be dramatically smaller than ITER. The Ignitor, a project led by MIT's Bruno Coppi, will produce a field more than twice as strong as ITER's and shrink the doughnut width by a factor of 6, to 2.6 meters (see graphic). Coppi estimates that the project, parts of which are already being built in Italy with funding from the government there, could cost as little as $200 million—a factor of 50 less than ITER.

Since Coppi began work on the high-field concept more than 20 years ago, experiments on MIT's Alcator C-Mod tokamak have greatly strengthened the argument that such devices could reach ignition, say Dale Meade of the Princeton Plasma Physics Laboratory and others. The experiments have shown good plasma confinement at the high densities and fields that would be needed. Meade's own concept, called BPX-AT, would be slightly larger than Ignitor at 4 meters across and have somewhat lower fields, but would be based on similar principles. "Bruno deserves the credit for initiating research in this area," says Meade.

Yet another concept for a modest-sized ignition device, this one not based on high fields, was presented in Madison by Luce. The proposal relies, in part, on experiments at GA's DIII-D tokamak that attempt to create many of the same "dimensionless parameters"—such as the ratio of the hot plasma's pressure to that of the confining magnetic field—that an ignition device might have. Because the experiments also show, in an indirect fashion, that plasma confinement rapidly improves if these parameters are held constant while such a machine is scaled up, Luce concludes that a tokamak about the size of the Joint European Tokamak in the United Kingdom, some 6 meters across, could ignite.

These machines can't produce all of the fusion conditions that would be needed for a practical reactor, such as very long ignition pulses. But proponents say they could reproduce the essential physics. "The analogy with the Wright Brothers is very good," says Meade. The Kitty Hawk flight "is analogous to lighting this plasma and having it heat itself up and coming back down. The next step," he adds with a chuckle, "was to go once around the field and land."

–J.G.

That figure would rise to $80 million to $100 million annually through 2010, he estimates, followed by a couple of billion dollars for a next-generation NIF.

Even if NIF reaches its goal of igniting a fusion target, no one argues that the approach could lead directly to a commercial fusion power plant. NIF's glass lasers, for example, are acceptable for defense purposes but impractical for a power plant because of their cost and low efficiency. While NIF would demonstrate controlled ignition, another technology, heavy-ion drivers, could take the place of the lasers in a future machine. These particle accelerators, which could prove far more efficient and flexible than lasers, are under development at Lawrence Berkeley National Laboratory in California as part of the department's civilian fusion effort. The funding, however, is modest—about $7 million a year.

Meanwhile, pulsed-power advocates at Sandia hope to advance their own long-term plan in light of recent breakthroughs in that technology. The method, whose energy applications are just starting to be explored, would crush fuel pellets with x-rays emitted from a plasma imploding after an array of wires is vaporized by a jolt of current. Although the concept has received much less study and funding than Livermore's approach, Sandia officials say pulsed power could prove far cheaper than lasers or ions, and they want to build a $400 million facility called the X-1 to prove it. "We have a reasonable prospect to produce real energy gain," says Yonas.

But Campbell and Yonas will have trouble squeezing additional money out of the stockpile stewardship program, despite its massive $4-billion-a-year budget. Vic Reis, who heads DOE's defense programs, warns that any fusion efforts funded by his office must also help to keep the nuclear stockpile safe: "We can't do science for science's sake." Adds David Crandall, who heads DOE's inertial confinement program: "The budget process over here is at least as fierce as it is on the [civilian] fusion energy side. Finding a few million dollars more over here is no easier."

Some magnetic fusion researchers worry that behind the congressional request for a review is a move to shift money into inertial confinement programs at their expense. And civilian fusion program officials are quick to note that there's no money to spare in magnetic fusion. Given her tight budget, says Anne Davies, head of DOE's civilian fusion program, "they don't *want* to be over here." Congressional aides deny such an intent. The idea, says one, is "to keep doing basic research on each technology until we are confident enough to choose one direction." And inertial confinement researchers insist that greater cooperation among the various technologies would benefit all sides. "My goal is not to erode the program—it already has been eroded—but to build it up," says Campbell. Adds Yonas: "You don't compete to kill each other, but for the better idea."

DOE officials are now making plans for the review, which likely would be conducted by a panel of researchers from within and outside the fusion community. They hope to have it ready by December, in time to offer guidance to Congress as it considers the 2000 budget. "I'm not going to prejudge where we will come down," says outgoing DOE Secretary Federico Peña. But one outcome could be a single fusion office, speculate some congressional aides and researchers, adding that such a change would not be easy given the long-standing separation between fusion researchers.

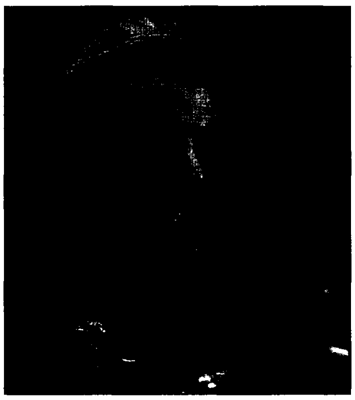
What seems certain is that the very process of a review will force all the players in the fusion drama—laser, pulsed-power, ion-driver, and magnetic researchers alike—to interact more closely. Both Davies and Crandall say there has been progress in building bridges between the cultures. But a great deal more blood may be shed before the fusion communities can become one. —**ANDREW LAWLER AND JAMES GLANZ**

BIOLOGICAL WEAPONS

Arms Control Enters the Biology Lab

An enforcement protocol of the bioweapons convention, now under negotiation, could affect some biotech firms and academic microbiologists

Some biotechnology companies and academic biology labs could soon find themselves caught in the highly charged world of arms control. Facilities and labs that handle potentially worrisome types of biological agents could be required to file reports detailing the materials they possess and submit to regular inspections. The reason: Negotiations that resumed last week in Geneva may finally put some teeth into the Biological and Toxin Weapons Convention (BTWC), an arms control agreement that is currently based entirely on trust; it has no mechanism to check whether signatories are complying.



BRAD MARKEL / GAMMA LIAISON

"The [convention] needs enforcement teeth if we are to have confidence it is being respected."

—Madeleine Albright

Although the convention was negotiated in 1972, verification was not considered a high priority until recently, largely because few military experts considered biological weapons to be a major threat. But revelations about the extent of the former Soviet Union's biological weapons program, and recent discoveries by United Nations inspectors of Iraq's widespread efforts, have injected a sense of urgency into the discussions. Both the European Union and the Clinton Administration are now pushing for a compliance protocol to be negotiated for the BTWC by the end of this year. And, in a speech last month, U.S. Secretary of State Madeleine Albright underlined the message: "The [biological weapons convention] needs enforcement teeth if we are to have confidence it is being respected around the world." Tibor Toth, the Hungarian ambassador chairing the talks in Geneva, told a meeting of industrialists, diplomats, and academics in Vienna in May, "It is not now a question of whether but of when and how."

That prospect has come as a wake-up call to biotech industry and microbiology researchers worldwide. Industry trade organizations, particularly in the United States, have long been aware of the issue, but individual companies and institutions are only now realizing they soon may become involved. "Until recently," says Brad Roberts from the Institute of Defense Analysis in Washington, D.C., "the U.S. [biotech and pharmaceutical] industry hoped this issue would just go away."

The negotiations that reopened last week in Geneva will determine how extensive and intrusive the verification provisions are likely to be. Some of the 158 countries that have