Princeton tokamak heats up the race for fusion power

A 60-million-degree plasma brings science closer to an unlimited source of power

By EDWARD EDELSON

PRINCETON, N.J.

It's an ordinary day at the Princeton Large Torus (PLT), one of the world's leading fusion-energy research centers. I'm in the control room, watching red numbers on a digital counter click backward in a countdown. At zero, images on video monitors bulge outward for an instant, as if to register the violence of the fusion reaction taking place in the PLT. A wall-to-wall bank of computers behind me records millions of bits of data from the reactions. The console operators prepare for the next run, due in 2½ minutes.

It's a scene I've witnessed often in some 15 years of covering the effort to harness fusion energy for peaceful purposes. But there's a big difference this time, and the difference, believe it or not, is represented by nothing more than a hole in the ground at this Princeton University facility.

Break-even fusion

I leave the PLT control room and stroll across a field to watch workmen in an excavation over a hundred yards square. Right now, there's nothing in the excavation but a huge, oddly shaped concrete foundation. But this is the site of the Tokamak Fusion Test Reactor (TFTR), the next generation of fusion research machines. And this construction site is the start of a scientific dream come true—a dream that could haul humanity into a new era of energy riches.

The TFTR will not be an ordinary fusion research device. For some 30 years, physicists have been trying to achieve break-even fusion energy—to get out more energy than they put in. The TFTR seems likely to reach that goal in the early 1980's. When that happens, scientists will have proved that fusion power is scientifically feasible. The next step will be to construct a fusion reactor that generates electricity.

But there are still major problems to be overcome before our homes are lighted by fusion power. These are problems of politics, economics, and engineering, however—not of basic science. For the first time, the almost infinite power source of the stars seems to be within the grasp of mankind.

Using that power source is simple in principle but astoundingly difficult in practice. It starts with the familiar Einstein formula $E = mc^2$, which means that a little matter can be transformed into an enormous amount of energy. One energy-releasing technique involves fission, splitting very heavy atoms—the energy source in today's nuclear reactors. A more effective method is with fusion, squeezing together light atoms to release even more energy.

Fission energy became practical first because very heavy atoms such as uranium-235 split spontaneously. By contrast, light atoms such as hydrogen resist being fused. In nature, hydrogen atoms fuse only in the extreme temperatures and densities that exist in the cores of stars. On earth, we've fused hydrogen atoms only by using a fission bomb to set off the violently uncontrolled fusion reactions of the hydrogen bomb.

Lawson criterion

To build a fusion reactor, physicists must first strip away the outer electrons of hydrogen atoms to produce the hot, seething gas called plasma. Then they must heat that plasma and contain it long enough for fusion to occur. They must achieve a temperature of about 100 million degrees C in a plasma with about 10^{14} (that's a one followed by 14 zeros) to 10^{15} particles per cubic centimeter (about 10,000 times thinner than air) for a time span between a tenth of a second and a full second. Physicists call this combination of density, temperature, and confinement time the "Lawson criterion."

Fusion energy is a glittering prize because it could be both safe and inexhaustible. Fuel is no problem. A fusion reactor probably will use deuterium, a hydrogen isotope with one proton and one neutron, and tritium, which has one proton and two neutrons. The oceans contain enough deuterium to meet humanity's needs for thousands of centuries, and a fusion reactor could easily be engineered to breed more tritium than it uses. As for safety, plasma in a fusion reactor would cool down automatically if the magnetic-confinement system failed, and the nuclear reaction would stop.

The basic problem in fusion research can be simply stated: Containing a plasma is a damned sight more difficult than physicists origi-

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nally thought. You can't hold plasma in anything solid, because it cools instantly when it touches a wall. The major effort in fusion research has been to build a magnetic "bottle" that will hold the plasma.

I saw how tough that challenge can be when I visited Princeton five years ago. Workmen were just building the Princeton Large Torus, fabricating 18 huge coils, each weighing 11,000 pounds, to produce the PLT's main magnetic field. Two other sets of coils produce other magnetic fields. All of this magnetic energy is needed to contain just one milligram of plasma for a split second in a torus—a doughnut-shape tube—36 inches across.

Temperature breakthrough?

This time I came to the PLT at Princeton University's Forrestal Campus because physicists had just achieved the highest temperature yet produced in this kind of fusion machine. It was widely described in news reports as a major breakthrough. Frankly, I was skeptical. Time and again in the past, I've seen premature stories about "significant breakthroughs" that turned out to be nothing of the sort.

But as I talked to the people who built the PLT and are building the TFTR, I learned that the temperature record is indeed significant. It is one more goal that fusion scientists set for themselves and reached on schedule. After many years during which disappointment was the rule, fusion researchers now routinely reach goals on schedule. "The key scientific issues of fusion energy have been resolved," says Anne Davies, who heads the Department of Energy's tokamak research effort.

I did most of my learning at Princeton from Shoichi Yoshikawa, who about 10 years ago got the basic idea that made the PLT possible. Yoshikawa's idea is based on a major advance made in the Soviet Union. Researchers in both countries worked for a long time on torus-shaped fusion machines with frustrating results. Physicists could not make a toroidal magnetic field to keep the plasma stable long enough.

Americans had endless problems with our version of the torus, called a stellerator. The stellerator has two magnetic fields, one within the other, to contain the plasma. But the Russians had made an important advance. The late Lev Artsimovich used a transformer to produce a current in the plasma itself. This current produced its own magnetic field, which helped contain the plasma. They called the machine a *tokamak*.

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>
> —Anne Davies, Dept. of Energy

Yoshikawa improved the basic tokamak. He designed a torus whose plasma-containing tube is fatter—and whose doughnut hole is smaller. Yoshikawa calculated that such a machine would have several advantages, including one that is brilliantly simple: A larger radius means particles take longer to leak out because they have a greater distance to travel.

Beam heating

Other new ideas were coming along. Five years ago, Marvin E. Gottlieb, head of the Princeton lab, told me about a new technique called neutral-beam heating that sounded promising.

Early magnetic-confinement machines used only ohmic heating, the same principle that makes your toaster toast. Run an electric current through a wire or a plasma and it gets hot. But ohmic heating isn't enough to put a plasma into the fusion temperature range. The neutral-beam idea, pioneered at Oak Ridge National Laboratory, is to heat the plasma further by shooting in a beam of hydrogen atoms. The atoms penetrate the magnetic field because they are electrically neutral. Inside the plasma, the atoms lose their electrons in collisions and become part of the plasma, adding heat in the process.

On this visit, Yoshikawa told me that the neutral-beam scheme had indeed worked, but not without some trouble. At first, the neutral beam just wouldn't give the expected heating effect. It developed that atoms in the beam were interacting with one another, reducing the beam's effectiveness. The solution: a nozzle with dozens of tiny openings, separating the atoms just enough to prevent interactions. "With one stroke, we got a hundredfold improvement in heating," Yoshikawa said.

The PLT has four neutral beams with a total of four megawatts of power. Neutral-beam heating allowed the PLT to set its temperature record, Yoshikawa told me. With all the neutral beams going and the machine adjusted for maximum temperature, PLT achieved several runs at 60 million degrees C.

To reach the Lawson criterion and break-even fusion, all that is needed is greater plasma density

Major U.S. tokamak machines and their goals

Alcator (MIT): Using extremely intense fields, Alcator produces very high-density plasmas. It is designed, in part, to test the possibility of building small fusion reactors. It also serves as a test bed for the use of radio waves to raise plasma temperature to the fusion range.

Doublet III (General Atomic): It is designed to study plasmas that do not have a circular cross section. Earlier versions of Doublet had elliptical and D-shape plasmas; the current model has a peanut-shape plasma. There are indications that such plasmas may be more stable than those with a circular cross section.

Poloidal Divertor Experiment (Princeton): PDX is designed to test the concept of removing impurities from the plasma by the use of special magnetic-field coils to divert the impurities to a collection chamber. Even a tiny amount of impurities can reduce the performance of a fusion machine drastically. A so-called "scrape-off" layer of plasma will be used as a protective shield against impurity atoms from the chamber walls. PDX is also evaluating the stability of a D-shape plasma.

Impurities Studies Experiment (Oak Ridge): Originally designed to study the effects of impurities and non-divertor techniques of removing impurities. ISX is now being used to study plasmas with a high "beta" (the ratio of plasma pressure to the pressure of the containing magnetic field). Efficiency goes up with increasing beta, but so does the difficulty of containing the plasma. ISX will operate with a beta of six to 10 percent, in the range expected in a fusion reactor.

Ormak (Oak Ridge): Designed to investigate neutral-beam heating and to study the interaction of the plasma with the containing wall, Ormak has also been used to study alternative ways of heating plasma, such as the use of radio waves.

and confinement time. The PLT won't do that. Indeed, none of the fusion machines now operating will reach the Lawson criterion. Each device is designed to investigate one or two different factors.

The TFTR will put a lot of different elements together to reach break-even energy output. For one thing, it will be significantly bigger than today's tokamaks. The first Princeton Symmetrical Tokamak contained a plasma with a cross section of 12 inches. The PLT's plasma has a 36-inch cross section. The TFTR plasma will be 86 inches across. In addition, the TFTR will have four neutral-beam injectors with a total power of 20 megawatts, five times that of the PLT.

Tritium confinement

Equally important, the TFTR will be built to work with the hydrogen isotopes expected to fuel the first power-producing fusion reactor: deuterium and tritium. Under the same confinement conditions, this combination has 100 times the energy of deuterium alon[illegible]e fuel used so far for plasma-containment studies. But tritium is the tricky element because it is highly radioactive (although short-lived). To make any fusion reactor safe, engineers will have to achieve near-perfect confinement of tritium, a cost factor not included in fusion test reactors. The TFTR is expected to provide excellent working practice in tritium containment.

The TFTR is in what amounts to a friendly international competition with similar machines, although it seems to lead the field slightly. A European consortium is planning a next-generation tokamak called JET (Joint European Torus), but squabbling about the site has delayed a start. JET will be built near Oxford, England, and is expected to come on line in 1983, a year or more after the TFTR's target date. The Japanese are building a machine called JT-60, which is also expected to reach energy break-even. But JT-60 will not use tritium in its plasma.

But the tokamak isn't the only horse in this race. There are also magnetic-mirror machines, which allow the plasma to slosh back and forth between two walls of magnetic force. The Department of Energy is planning a Mirror Fusion Test Facility, the next-generation mirror-machine counterpart of the TFTR, at Lawrence Livermore Laboratory in California.

Fusion test results are discussed by Princeton researchers Harold Eubank, Melvin Gottlieb, Harold Furth, and Wolfgang Stodiek (left to right) in the Princeton Large Torus control room. TV monitors show PLT in operation.

And there is also inertial confinement, a totally different concept more or less based on the hydrogen bomb. Using extremely powerful blasts of laser light, ion beams, or something similar, researchers are trying to implode tiny pellets of hydrogen, in effect creating an internal-combustion fusion engine [PS, Dec. '76].

But at the moment, the tokamak seems to hold center stage. And in the tokamak field, the Department of Energy's money is on the TFTR.

"All of this work is leading up to the TFTR," Anne Davies told me. "We really think of the PLT as a small-scale test of the TFTR. In the magnetic-confinement program, the TFTR is *the* next generation. It is where we try to get out as much energy as we put in."

I got an idea of how difficult that might be when I stepped into the huge room housing the PLT's generating equipment. Yoshikawa explained the intricate, power-hungry sequence of events that goes into a single PLT run. First, hydrogen gas is injected into the torus, kept at a near-perfect vacuum. Then the network of ohmic heating coils, which run parallel to the torus, is pulsed rapidly to break down the gas, creating the plasma. A huge DC pulse then flows into a third set of coils, the equilibrium field coils, which help contain the plasma by pushing it inward. All of this is to achieve a confinement of about 60 milliseconds.

Flywheel power

To power the coils, a 96-ton flywheel, run by a 700-hp engine, drops suddenly from 360 revolutions a second to 250 revolutions a second, putting that energy into a generator. The PLT has three such systems, so that some 200 runs can be made in a 16-hour work day. The TFTR will need five times as much power.

But what comes after the TFTR? At this moment, no one can say for sure, although almost everyone in the field is working furiously on the subject. So many options are open that every aspect of the machine's design, from the method it uses to achieve fusion to its purpose, is open to question. One school of thought holds that the tokamak, while a fine research tool, will never be able to serve as the core of a working fusion reactor.

Hydrogen production?

Another school is busy designing and costing fusion reactors built around tokamak cores. There is uncertainty about whether the machine will be used to generate electricity, to make hydrogen gas as a preview of the "hydrogen economy" that may result when oil and natural gas are very scarce, or to run a mixed fusion/fission cycle, regenerating fuel rods from current nuclear plants by irradiation.

One thing certain, in the words of Anne Davies, is that "TFTR will achieve not just a power break-even, but will be a net power producer, in terms of heat." And that's enormously significant, because it marks a new way of talking in fusion research. Until recently, fusion scientists talked about a moving target. Any given year, they would say that a working fusion reactor was 20 years in the future. But now, the 1995 target date that was being given five years ago for the first power-producing fusion reactor still holds. That means the basic scientific questions about fusion have largely been answered.

But it also means that tough questions of cost, size, and engineering for a fusion reactor can no longer be put off until the hazy future. Fusion researchers now are faced with a long list of practical questions: the question of capital costs (in dollars per kilowatt), the question of generating costs (in

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cents per kilowatt-hour), the question of maintenance costs (in dollars per year).

They're also faced with a series of ferocious technical problems. For example, most of a fusion reactor's energy will be in the form of highly energetic neutrons. The present plan is to trap those neutrons in a "blanket" that will become heated; the heat will be used to generate electricity. The big issue is to find materials that can stand up to intense fluxes of neutrons for long periods. The TFTR will serve as a test bed where materials and components can be exposed to conditions much like those in a real reactor.

The size of a reactor core is another tough problem. Big is bad because it means big (and expensive) magnetic coils. Small is bad because it means that a smaller area must absorb a heavier flux of neutrons. W. R. Parkins of Atomics International, a skeptic about the feasibility of fusion power, gives this assessment about the capabilities of the plasma-containing vessel at the core of a reactor:

"The vessel must maintain vacuum tightness, operate at elevated temperature, withstand repeated thermal cycles and stresses from external pressure and non-uniform temperature distributions, be corrosion-resistant to the primary coolant and its impurities, retain adequate mechanical properties and dimensional stability while subjected to intense radiation, and be available in large quantity at an economic price."

Fusion economics

It is entirely possible that all these requirements, and scores of others that apply to other parts of a fusion reactor, cannot be met at an economically competitive cost. It could turn out that mankind will not want endless supplies of power from fusion because something else—such as photovoltaic power from solar cells—is cheaper. That story will be told in the next decade or so. PS

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different tests

While Mr. Beardsley's thermosiphoning hot-water system ["Alternate-Energy Adventure," Sept.] is an excellent design, it may be misleading to claim that it will heat 70 gallons of water from a cold start to 160° by noon. The photo indicates that tests of the water temperature were made by bleeding a valve above the tank at the input from the collecting panel. Since thermosiphoning creates very little turbulence, hot water stratifies strongly. Thus, the temperature at the top of the tank is nearly always considerably hotter than the average tank temperature. Because of this, the surprisingly high estimate of 75-percent efficiency for the system

Corrections: In the September article, "Solar Siter Charts the Sunlight," the photo-credit line was inadvertently omitted. Our excellent photos were taken by Roger Goldstein.

In "Tile a Countertop" [Sept.], Wonder-Board, the concrete underlayment used, was described as waterproof. While the product is unaffected by water, it is not, strictly speaking, waterproof. Any area behind Wonder-Board that must be kept totally dry should be covered with a waterproof membrane.

In "What's New in Electronics" [Sept.], the brand name of the "No-Wire CB" antenna should have read Avanti Astro-Fantom, not *Ph*antom. PS