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Fusion test reactor hits 200-million-degree milestone

By 1980, scientists were sure enough of fusion to propose a commercial plant by the year 2000—but recent results are better than predicted even six months ago. Carol White reports.

Fusion scientists and engineers at the Department of Energy's Princeton Plasma Physics Laboratory have achieved a temperature of 200 million degrees (Celsius) in the Tokamak Fusion Test Reactor (TFTR), it was announced on Aug. 7. This is 10 times hotter than the center of the Sun and the highest temperature ever recorded in a laboratory.

"This marks a major milestone in progress toward the development of fusion energy," said Energy Secretary John S. Herrington. "The temperature achieved is in the range required for a fusion reactor. These promising results bring us closer to the goal of fusion energy." According to Dr. John Clarke, director of the Department of Energy's Office of Fusion Energy, which is responsible for the funding of the TFTR, we can have a practical fusion power reactor within 15 years.

Since the beginning of the Atomic Age, scientists have known that it would be possible to create in a reactor on Earth the process that powers the Sun and the stars, and for 30 years, there has been steady progress in understanding and doing this. Fusion reactions occur when the nuclei of the isotopes of hydrogen (deuterium and tritium) "fuse" to form a helium atom, releasing energy in the process.

By 1980, the scientific community felt assured enough of the promise of fusion research to push for U.S. legislation that would mandate a commercial fusion plant by the year 2000. The latest results, however, are better than predicted, even within the last six months. They are especially important because the high temperature achieved is coupled with improvements in the density of the plasma and the duration and strength of containment.

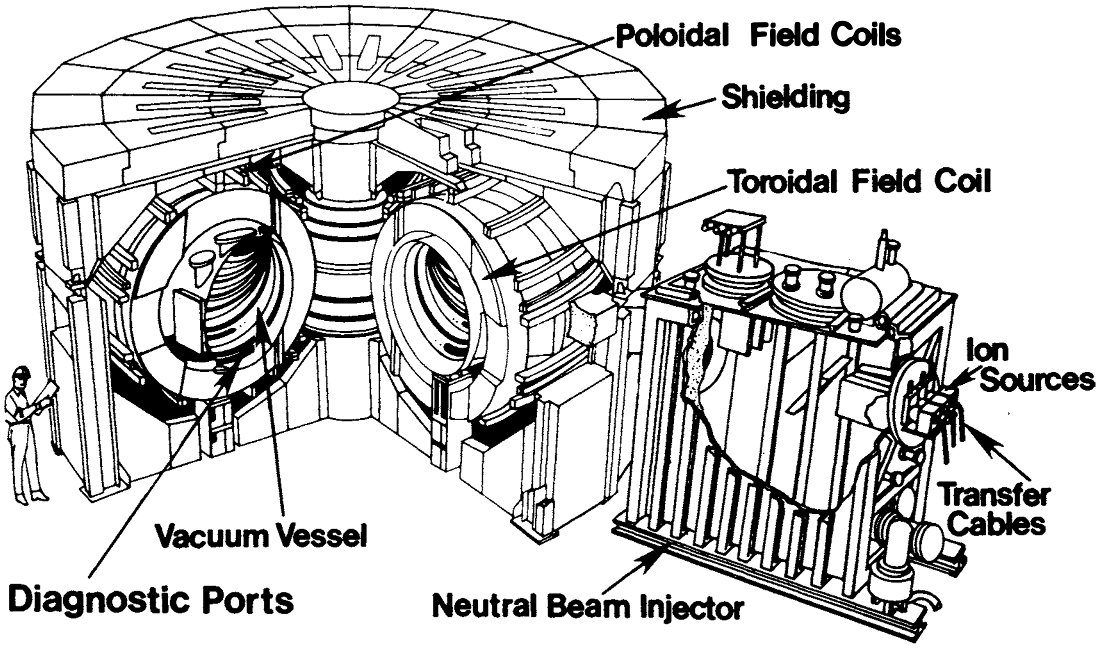
The fact that all of these developments are occurring simultaneously means that we are now indeed on the verge of a new industrial age—the plasma age.

The ability to obtain power generation from sea water (where the needed deuterium and tritium isotopes of hydrogen are found) is only a harbinger of an age in which mankind will have orders of magnitude higher energies at its disposal. By controlling high energy plasmas, mankind will be able to fulfil the alchemist's dream, transforming and creating the basic chemical elements at will by devices such as the fusion torch.

The immediate goal, predicted for next year, is energy break-even, which means that the release of energy from the fusion process exceeds the amount of energy needed to generate the process. TFTR is one of four major tokamak facilities in the world today, the others being located in the United Kingdom, Japan, and the Soviet Union. Similar results are expected in these as well.

In order to reach break-even in a fusion reactor, two separate conditions must be met: Both the plasma temperature and the quality of magnetic heat insulation must exceed threshold values. The problem with achieving nuclear fusion is that it is not sufficient to simply heat the fusion fuel to some required temperature. At the same time that it is being heated, the fuel must be kept concentrated and insulated against losing its temperature. The general approach to doing this that is being pursued at Princeton is that of magnetic confinement.

The TFTR consists of a doughnut shaped magnetic "bottle," which is used to trap and insulate hydrogen fusion fuel. At the high temperature—44 million degrees Celsius—required for fusion of the heavy isotopes of hydrogen to occur, the hydrogen gas is ionized. That is, the gas is a plasma, like



TFTR

Princeton Plasma Physics Lab

that in a neon light. Because plasma is highly responsive to electricity, it can be confined by the properly configured magnetic fields.

While the TFTR is no longer the largest in the world—the European Community's Joint European Torus (JET) at Culham, England is the largest in the world, and the Japanese JT-60 is next—the TFTR was the pioneer. When it was in the planning stage, it was probably the most sophisticated construction project in the world, a challenge to American engineering. For example, it had to be machined to a tolerance of 1/30,000th of an inch, a demand that only one U.S. company was capable of fulfilling at the time.

In 1974, the MIT Alcator Tokamak, built under the direction of Professor Bruno Coppi, essentially demonstrated that the confinement and insulation needed for break-even could be attained, and in 1978, the predecessor to the TFTR, the Princeton PLT Tokamak, attained a temperature of better than 60 million degrees Celsius—far in excess of the 44-million-degree minimum. Far more important, this experiment demonstrated a qualititative result, that fusion temperature plasma regimes could be stably confined (kept concentrated) with some degree of good insulation—what can also be termed energy confinement, and energy confinement time.

Ignition is the essential prerequisite for a practical fusion reactor. It is defined as the point at which the fusion plasma is able to maintain itself at fusion temperatures. That is, the fusion plasma first of all produces a large output of fusion energy. Second, the plasma absorbs enough of this fusion energy output to balance its own heat loss.

Much higher temperatures, plasma densities, and energy confinement times are required for fusion plasma ignition than for break-even. But an ignited fusion plasma provides the basis for a practical fusion reactor. In 1976, based upon his revolutionary Alcator results, Coppi proposed to leapfrog a break-even experiment and achieve full ignition, with a small Tokamak, but one built with the most intense magnetic field possible. His compact ignition designs were based on the results being obtained on the Alcator, including an enhanced confinement regime which has now, probably, been rediscovered by the TFTR.

At the time, Dr. Coppi was ignored. But today, after almost a decade of experimental confirmation of Dr. Coppi's projections, we have reached the point where his compact tokamak ignition proposals have been adopted as the chief focus of the U.S. magnetic fusion program.

The emergence of the enhanced confinement regime on the Princeton TFTR vastly increases the possibilities for the Western European JET tokamak to attain fusion ignition by 1990. JET is much larger than TFTR and has the capability of a much longer sustainment time. This could possibly be furthered by using radio frequency ramp-up to increase the sustainment time. This approach is based on a process in which radio waves can be used to generate electrical currents in tokamak plasmas.

Actual ignition experiments will provide the context in which a real science of the fusion process can be empirically developed for the first time. Based on our current knowledge, we know that ignition can lead to the development of practical fusion reactors within 15 years. But new processes which ignition may uncover, could lead to the development of self-sustained fusion systems and near-term realization of advanced-fuel direct-conversion fusion reactors.

TABLE 1

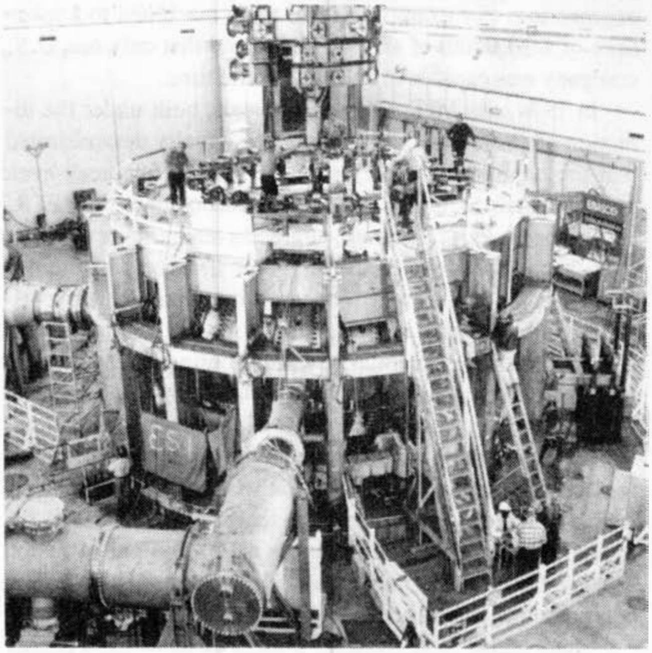
Progress on some major tokamaks

	TFTR Princeton	JET Culham, England	JT-60 Tokai, Japan	Alcator C MIT	Doublet III San Diego	ISX-B Oak Ridge
1. Date operational	12/82	6/83	4/85	4/78-11/86	1978-9/84	1978-84
2. **Highest combined density & confinement time,** $n\tau$ (seconds × nuclei/cm^3)(× 10^{13})	15	4-5	3-4	6	1.3	~0.07
3. **Ion temperature at highest** $n\tau$ (kiloelectron volts)	1.2	1.8	~1.5	1.7	2	—
4. Highest average electron density, n_e (electrons/cm^3) (× 10^{14})	3	0.8	0.5	15	1.2	1.5
5. Longest confinement time, τ (seconds)	0.75	0.8	0.4-0.5	.055	0.120	0.025
6. Highest ion temperature, T_i (kiloelectron volts)	18-20	7	—	2	6	1.6
7. Lowest impurity level, Z_{eff} (avg. atomic number)	high density ~1.0 low density 2.5-3	2-2.5	good	1.2	1.0	1.1
8. **Highest confinement quality,** β (%)	—	<1	—	1	4.6 4.0	2.6
9. **Toroidal field strength at highest confinement quality,** B_t (tesla)	—	—	—	10	0.6 1.3	0.8
10. Highest toroidal field strength used, B_t (tesla)	5.2	3.5-4	4.2	14	2.6	1.6
11. Highest current used, I (megamperes)	2.5	4.8	1.5	0.8	2	0.23
12. External heating, P (megawatts)						
neutral beam (deuterium)	12.5 now, 25 soon	~7	—	—	8	2.5
radio frequency	—	~7	—	1.6 absorbed	—	0.15
13. Major radius of torus, R (meters)	2.48	2.96	3.0	0.64	1.43	0.93
14. Plasma volume (cubic meters)	35	170	54	—	—	—

Fusion breakeven—and beyond—will soon be achieved by the "big three," TFTR, JET, and JT-60, and by the successor to the Alcator C. All of these machines have achieved the necessary Lawson product (combined density and confinement time, $n\tau$; the threshold is 3 × 10^{13} nuclei-seconds per cubic centimeter), as shown on line 2. None of them has simultaneously sustained the temperature of 93 million degrees Celsius (8 kiloelectron volts) that is the other threshold condition for breakeven, as shown on line 3.

The more than 200 million degrees Celsius (actually 18-20 kiloelectron volts) achieved by the TFTR in mid-July, a world record (see line 6) exceeds the threshold for breakeven and is suitable for an economical working reactor. But it was achieved at a significantly lower Lawson product (1 × 10^{13}).

Machines pursuing confinement quality, rather than breakeven, are GA Technologies' Doublet III and the ISX-B at Oak Ridge National Laboratory (see lines 8 and 9). Confinement quality, β, essential for an economical working reactor, is the ratio of the energy density of the plasma (density × temperature) to the strength of the magnetic field required to confine it. Beta of 6-10% is considered necessary for a working reactor. The highest β so far, 5.3%, was achieved on the Princeton Beta Experiment, PBX, not shown above, but described in the interview with Dr. Meade.



Princeton University's Tokamak Fusion Test Reactor (TFTR)

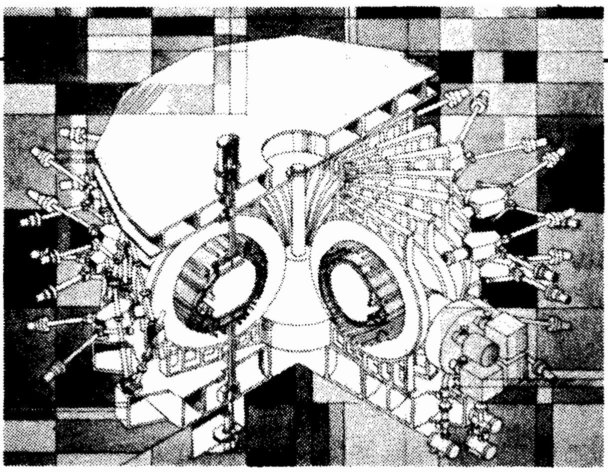
The status of the tokamak projects

The **TFTR**, built and operated at Princeton University for the Department of Energy, in mid-July achieved a new temperature record of 200 million degrees Celsius, 10 times hotter than the center of the Sun and the highest temperature ever recorded in a laboratory. "This marks a major milestone in progress toward the development of fusion energy," according to Energy Secretary John S. Herrington. "The temperature achieved is in the range required for a fusion reactor. These promising results bring us closer to the goal of fusion energy," he said.

JET is the Joint European Torus, a project of the European Community. It is by far the world's biggest tokamak in terms of the volume of plasma contained—and volume is important (see line 14 on Table 1). JET and the TFTR are the only tokamaks equipped to handle tritium—the deuterium-tritium combination is 200 times more reactive than deuterium-deuterium. Neither has yet achieved results adequate for introducing tritium.

JT-60 is the big Japanese tokamak, operational only since April 1985. The early results shown here are based on incomplete instrumentation and are only indicative, according to Dr. Curt Bolton of the Department of Energy Office of Fusion Energy. Neutral beam heating began this month, and its substantial contribution should be reflected in early results, Bolton says.

MIT's **Alcator C**, operated under contract with the Department of Energy, was designed to achieve break-even with a small, compact machine using very strong magnetic fields (Table 1 lines 2, 3 and 10). Alcator C will cease operating in November 1986, but may be reincarnated at Lawrence Livermore National Laboratory. The successor machine at MIT, the **Alcator C-Mod,** will have new toroidal and poloidal magnets and a new vacuum chamber. It has been designed to maintain a high Lawson product ($n\tau$) while achieving high temperatures with radio frequency heating. It is projected to achieve 5 kiloelectron volts while $n\tau = 1\text{-}2 \times 10^{14}$, according to Dr. Ron Parker of MIT's Plasma Fusion Center. That would still be below the threshold for full ignition. But C-Mod would serve as a half-scale prototype of the projected Compact Ignition Tokamak (CIT), having the same magnetic field as the eventual CIT, according to Parker.



The JT-60, a large tokamak designed by the Japanese Atomic Energy Research Institute.

Doublet III is GA Technologies' experiment in confinement quality (Table 1 line 8). It has already been succeeded by Doublet III-D (first plasma, February 1986), but it is too early for significant results. High betas (β), or the ratio of the outward pressure of the plasma to the field strength required to confine it, are expected this winter, once neutral beam heating is in place, says Dr. James Luxon, technical coordinator for the Doublet.

ISX-B, the Oak Ridge National Laboratory experiment in confinement efficiency, was shut down in 1984. Because of stingy funding, there is no successor tokamak planned. The lab is building a stellarator, the Advanced Toroidal Facility (ATF), that is expected to achieve high β at high temperatures in steady state operation, according to Dr. Michael Saltmarsh, head of the ORNL Confinement Projects Section. It will operate with plasma in March 1987, "but we will not have a clear picture of what it will do for about a year," Saltmarsh says.

ORNL's continuing major contribution to tokamak research is its development of neutral beam and pellet injection equipment—technologies as complex as the tokamak proper. The TFTR uses pellet injection built at ORNL, and Princeton's PBX device uses four ORNL neutral beam injectors.

The **Soviets** are still a major contributor to tokamak development—an approach they invented—while not at its forefront. Their current machine, the **T-10**, is roughly comparable to the Princeton Large Torus (PLT), a leading machine of the late 1970s. Work done with the T-10 on electron cyclotron heating (a form of radio frequency heating) has been unique.

The next Soviet tokamak is to be the T-15, according to Bolton at the Department of Energy. The T-15, he says, is the rough equivalent of the TFTR or JT-60, and construction is under way. "Two years ago, it was to come up in 1986; obviously, there have been delays," Bolton says.