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The Quest for Fusion Energy

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The Quest for Fusion Energy

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Abstract

A brief history of the magnetic fusion program from the point of view of a stellarator enthusiast who worked at a major tokamak laboratory. The reason that success in the magnetic fusion energy program is essential is presented.

Key Words: magnetic fusion, stellarator, tokamak, history

Discussion

It is a pleasure to discuss the program that forms the major interest of the National Institute for Fusion Science. We, who have taken part in the fusion program, feel that success in this program is necessary and are particularly proud of the way that this effort has been characterized by international cooperation. Indeed, this meeting is being held as part of the Toki Conference, which includes a semi-annual Stellarator Workshop with participants from all over the world.

There is a real need for fusion energy. We cannot expect our fossil fuel reserves to last much more than 200 years; without breeding, fission resources will be depleted in a similar time; and solar and other renewable energy is so diffuse that it can at best take care of half of the world's needs. The possibility of global warming due to the greenhouse effect may make it necessary to cut back on fossil fuel relatively soon. There are difficulties involved in the preparation and transportation of fuel. The problem of waste disposal makes fusion energy the only possible long-term energy source.

The easiest fusion reaction would be the combining of two isotopes of hydrogen — tritium and deuterium — producing helium and neutrons. The energy that is carried by the neutrons can be used to heat steam and turn a turbine. This requires the confinement of a collection of particles, or a "plasma," at a temperature of about 100 million degrees, 10 times that of the sun. At this temperature the atoms are stripped into electrons and ions which move independently in electric and magnetic fields. These charged particles spiral around magnetic field lines, so that the collection of particles, or "plasma" can be confined if a magnetic field configuration can be found such that the field lines do not intersect a material wall.

The idea of getting energy from fusion was taken seriously in 1951 when a scientist named Ronald Richter in Argentina reported success. He turned out to be a fraud, but his work stimulated efforts in the Soviet Union, England and the United States. Lyman Spitzer in Princeton spent a skiing vacation thinking about the problem and devised the stellarator (Fig. 1). He used toroidal, or donut-shaped, fields where the magnetic field lines were confined away from the vacuum vessel containing the hot plasma. The magnetic field is produced by current in coils circling the donut. He twisted the torus into a pretzel so that the geometry causes the magnetic field lines to rotate around and form magnetic surfaces — the Figure-8 stellarator. This differs from the Russian tokamak and the English Z-pinch approach where the donut is flat and the twist is due to current in the plasma.

In 1954 it was suggested that instabilities could move some of the magnetic field lines outward and others inward allowing the plasma to escape. This led to the classical stellarator concept where helical windings carry current in opposite directions in adjacent coils are added to shear the field lines. In the early 1960's, it was recognized independently by a French group and by Uo at Kyoto that the same magnetic configuration could be achieved with a single set of helical windings, without any toroidal coils. Such a device, called a torsatron in the West and a heliotron in Japan, is much easier to build. The Large Helical Device, which will soon be operating at the National Institute for Fusion Science, is a heliotron and follows successful operation of others, including ATF at Oak Ridge and CHS in Nagoya. More recently, Furth and Yoshikawa at Princeton suggested a return to a system like the Figure-8 with a nonplanar axis but with a noncircular cross section, the heliac. Such devices are now operating in Canberra, Australia, and Madrid, Spain. Nührenberg in Germany pioneered the design of stellarators with nonplanar modular coils optimized for specific plasma properties. This led to the quasi-symmetric stellarator and helias concepts. Such a device is being built at the University of Wisconsin. Studies aimed at providing maximum plasma confinement and minimum toroidal current have led to the successful operation of W7-AS. They form the design basis for the W7-X Helias being built in Germany.

In the early 1950's The Soviet Union started its tokamak program and the English their Z-pinch one. The United States started its fusion effort, Project Sherwood, in 1952 with efforts on pinches at Los Alamos, magnetic mirrors (a somewhat different confinement scheme) at Livermore, and the stellarator at Princeton. All of the programs were secret because success would have led to a copious source of neutrons which would have had military use. It quickly became obvious that the development of fusion would be more difficult than had been expected, and all three efforts were completely declassified at the 1958 Second International Conference on Atomic Energy in Geneva. This led to close interaction of scientists and engineers from all over the world, a cooperation that existed throughout the cold war.

Spitzer proposed building four stellarator devices, Models A, B, C, and D. The Model A Stellarator was a small Figure-8 machine (Fig. 2) to show that the confinement idea worked; Model B was to demonstrate that plasma could be contained and heated in a vacuum vessel with a 5 cm diameter; Model C was to have a 20 cm diameter and be a quarter-scale pilot plant for Model D, which is what would be given as a reactor to industry. By the time of the 1958 Conference, Model A had been declared to be a success but Model B had experienced so many problems that several devices of approximately that size, including B-1, B-2, B-3, and B-64 (It was originally called B-8^2 but our Atomic Energy Commission considered the number "8" secret.) were being operated, and a new Model C was being constructed in the shape of a classical stellarator. England and Germany started stellarator programs immediately after the Conference, with the Soviet Union and Japan following not long afterwards. There was steady progress throughout the decade, but confinement was not as good as had been expected. The general attitude in the fusion community became (1) the stellarator didn't work, (2) it probably never would, and (3) even if it did, the configuration would be so complicated that nobody would want it.

Towards the end of the 1960's the Russians demonstrated that they could achieve high temperatures on their T-3 Tokamak. The United States, and most of the world, became infatuated with this approach and we quickly converted our Model C Stellarator into the ST Tokamak and confirmed the T-3 results. Progress came rapidly with the construction of larger and larger devices. I, and many other researchers, became convinced that fusion would work in 1978 when we obtained high temperatures on the PLT Tokamak, well above where some particularly damaging instabilities had been predicted theoretically. They were seen but did not damage the confinement significantly. Three large tokamaks were constructed in the 1980's, TFTR in Princeton (Fig. 3), JET in the European Community at Culham, England, and JT-60 in Naka, Japan. TFTR operated successfully and safely with a Deuterium-Tritium plasma but was recently decommissioned as part of the United States budget cutting. JET has just started to use this fuel combination and they will already obtained better results than we did. JT-60 showed that they would have achieved "breakeven," where the amount of power out equals the amount used for creation and heating, if they had used a D-T plasma,. The successes of these programs led the four major political powers, the United States, Japan, the Soviet Union, and the European Community, to carry through a design study for ITER, the International Tokamak Experimental Reactor (Fig. 4). Preliminary design is complete, leading to a large device at an estimated cost of a thousand billion yen. A decision as to its future should be made next year, but budget difficulties have led both the United States and Russia to say that they can not pay their shares. It will be interesting to see what happens; my guess and hope is that it will go ahead as a somewhat less ambitious device on a longer time scale than originally planned and will be built in Japan.

The fact that we are all here is proof that the stellarator concept is still very much alive. In the early 1980's, the German group showed that they could operate a stellarator with essentially no toroidal current, and that confinement improved when they approached this zero-current limit. This was quickly substantiated by the group in Kyoto. Professor Grieger and his collaborators did a good job of advertising their success and stellarator efforts were rejuvenated and established at many of the world laboratories, unfortunately not including Princeton. At present, I think that the two most exciting experiments are the German W7-AS and Japanese CHS ones. The Australian and Spanish programs are now beginning interesting experiments with the heliac concept. These devices have considerable flexibility and should provide an improved understanding of the effect of modifying the configuration schemes. The LHD Heliotron (Fig. 5), should commense operation at NIFS next March. This will be the most exciting fusion experiment in the world for many years. Our understanding of the behavior of the α-particles produced in deuterium - tritium plasmas that we obtained from the TFTR and JET experiments can be extrapolated to stellarator physics. Thus, LHD will not have to use tritium but will be able to concentrate on more basic physics considerations. The Germans are establishing a new Laboratory up near the Baltic Sea to build the W7-X Helias (Fig. 6), based on an elaborate plasma parameter optimization program. The techniques employed in its design should lead to its obtaining especially good plasma parameters. Both LHD and W7-X will have superconducting coils and significant heating systems, so that they should successfully explore the parameter space that is necessary for reactor operation.

New ideas are continuously being suggested for the stellarator approach. Nührenberg at the Max-Planck Institut für Plasmaphysik in Garching and Garabedian, at New York University, independently developed a configuration with a figure-8 shape that posesses all of the good qualities of the tokamak. We, at Princeton, are exploring the possibility of building such a device and are presently studying an interesting design (Fig. 7). The Kyoto University group is building a related device and I understand that NIFS may even replace their CHS heliotron something based on this concept.

I've concentrated on magnetic fusion, where the plasma is confined at thermonuclear temperatures by magnetic fields. Other approaches are also being pursued. The development of high energy laser sources in the early 1970's provided the possibility of irradiating a small D-T pellet with sufficient energy that it could be compressed to about 1000 times the density of ordinary solids, being heated to such a high temperature that many fusion reactions take place before it blows itself apart. This has been studied extensively in the United States, France, and Japan, and much progress has been made. My collegues in this "inertial confinement" program expect a newly authorized facility in Livermore, California, to lead to "break even". Various other schemes utilizing high energy electron or ion beams are being studied. If they were to work, they could allow other fuels which produce no neutrons to be used. The problems in all of these approaches seem to me to be so difficult that I find them unattractive.

Tokamaks have demonstrated that adequate confinement can be achieved but stellarators are simpler and offer the way to avoid the major difficulties that tokamak designs must face. There are still some engineering problems for both stellarators and tokamaks but they can be solved.

The cost of energy using fusion will always be similar to, or even higher than, that of fission energy, but safety issues and the significant simplification of the waste disposal problem over that of any other energy source (Fig. 8) makes fusion most desirable. Much fuel must be supplied for both fossil and fission plants, and they produce large quantities of dangerous waste. The annual fuel needs for 1000 MW fossil plant, which is a typical size, would be 250 trains, each having 100 cars or coal, or 11 super tankers of oil, and it would produce 11 million tons of CO_2, 220 thousand tons of SO_2, and 30 thousand tons of NO_2. A fission plant would require one and a half rail cars of UO_2 and would produce 30 tons of high-level radioactive waste. A Toyota pickup truck could deliver the 400 pounds of deuterium and the 1300 pounds of Li_6 (to make tritium)for a fusion plant, and it would produce 900 pounds of helium, which is valuable. Solar energy is too diffuse, requiring 5000 acres of collectors, and irregular, needing major energy storage, to supply all of our needs. I think that fusion is the only possible long term energy source. I wish that we had been able to develop fusion earlier, so that we could keep China from developing a coal-burning economy, which will be bad for Japan's atmosphere.

We now use about 2000 Watts per person, The U.S. uses 10,000 Watts per person. With 5 billion people, this is 10 Trillion Watt Years. If we assume 10 billion people in the future, at 3000 Watts per person (one third of U.S.) this is 30 trillion Watt Years. This is a very conservative estimate.

Oil can give		300-400 TWyr,	(60 years plus tar sands and shale)
Natural gas		300-400 TWyr,	100 years
Coal		3000-6000 TWyr,	> 200 years
Uranium		3000-5000TWyr,	> 200 years
Solar			40-50%
Fusion	D-T		> 1 Million years
	D-D		> 10 Billion years

Perhaps a good way for me to end this talk is to use the paragraph with which I always closed my foreign trip reports. As you may have noted, I spent most of my life working for the Westinghouse Electric Corporation, a major supplier of nuclear power plants in America, and was assigned to work at Princeton University Plasma Physics Laboratory, the country's leading fusion laboratory. I don't think that my bosses at either place were pleased to see my prediction:

The next fission plant that will be built in America will be built by the French; the first fusion plant will be built by Hitachi!

Acknowledgments

This presentation was prepared to be presented as a public lecture to the citizens of Toki-City in a session of the joint 8'th International Toki Conference on Plasma Physics and Controlled Nuclear Fusion and the 11'th International Stellarator Conference. I must express my appreciation to the organizing committee for the honor of giving this talk, to K. Ichiguchi for his help in the preparation of my view graphs and for correcting my mistakes in his translation of the talk, and to all who were willing to listen to me.

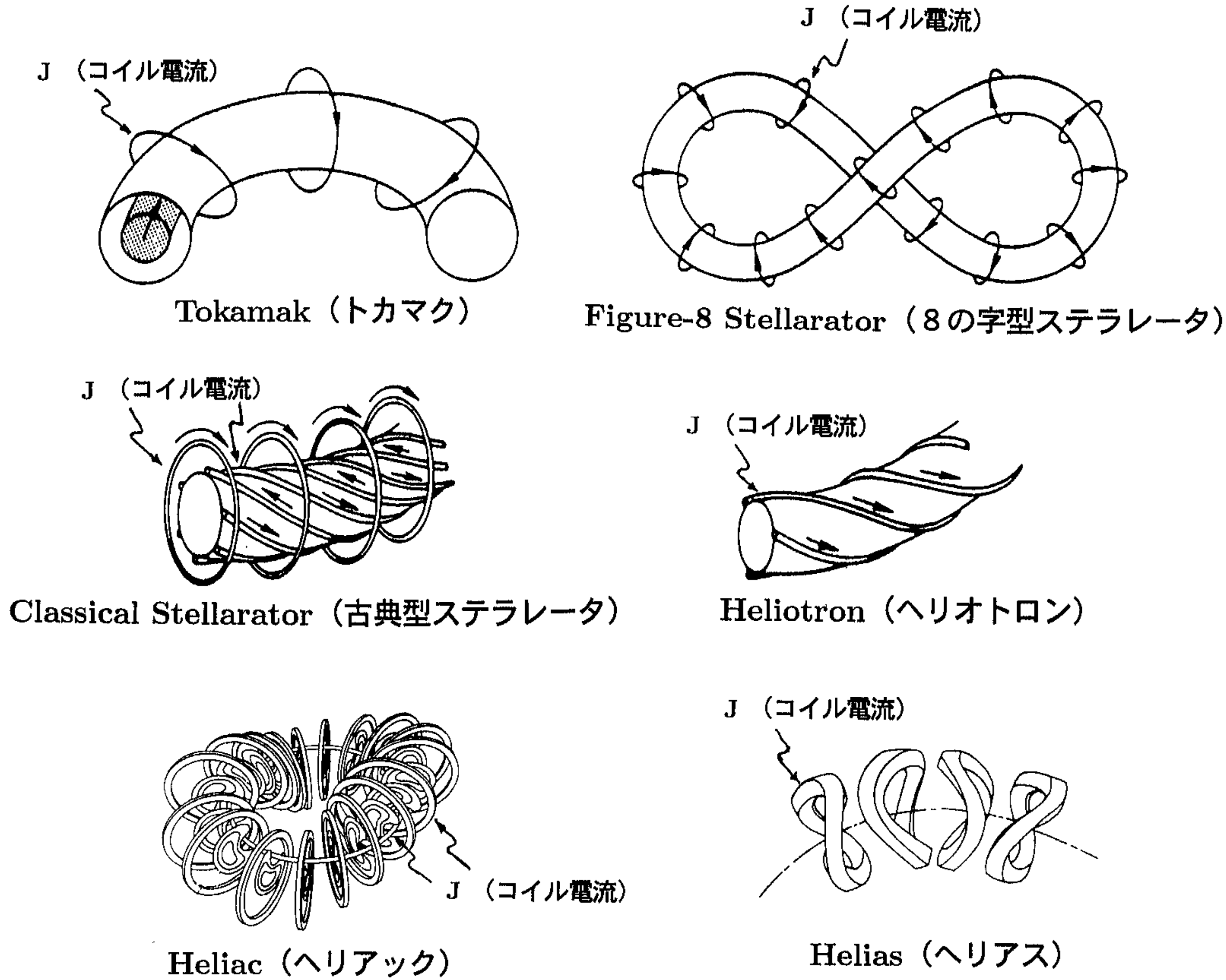

Fig. 1, Tokamak and Stellarator magnetic field configurations.

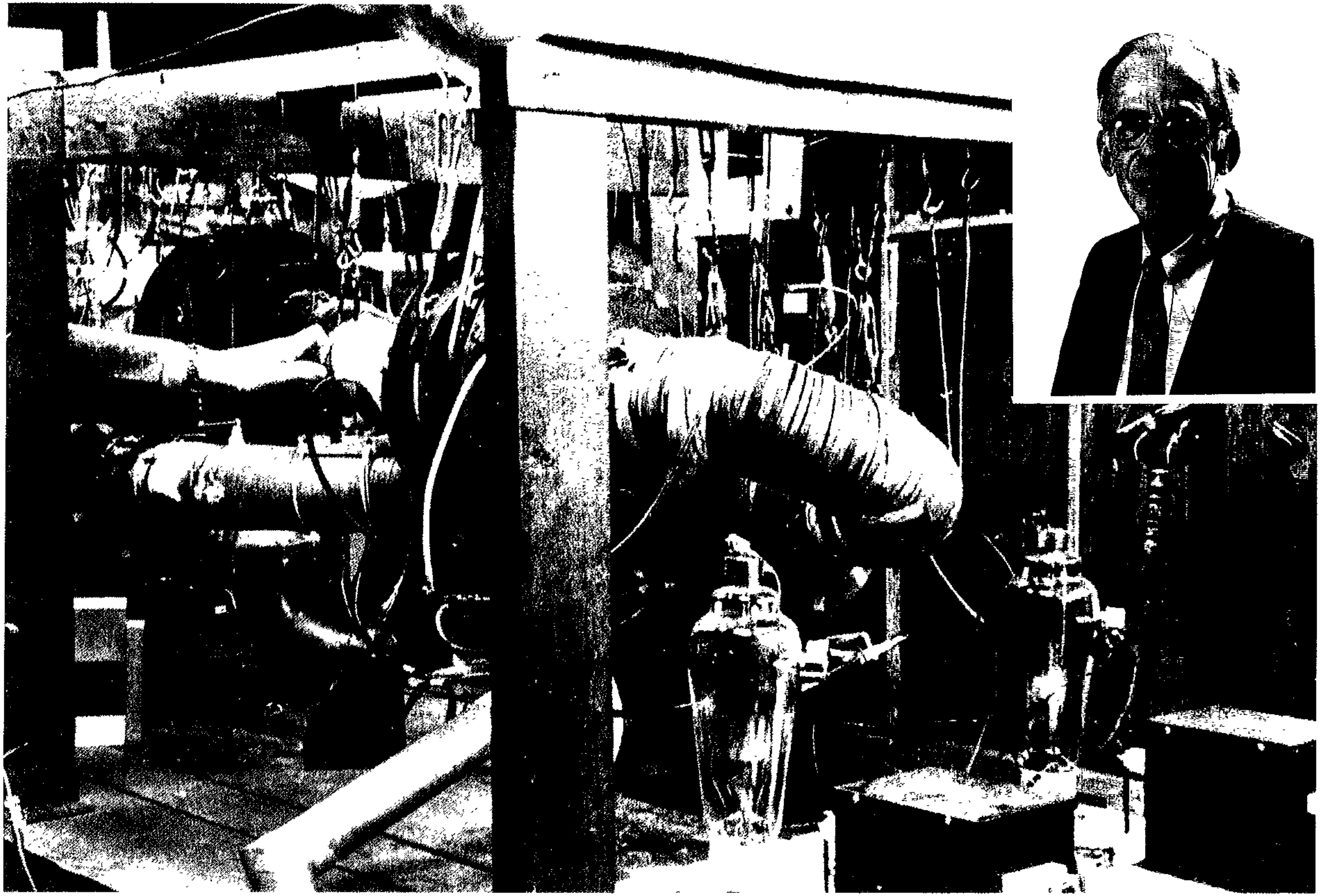

Fig. 2, Lyman Spitzer and the Model A Stellarator.

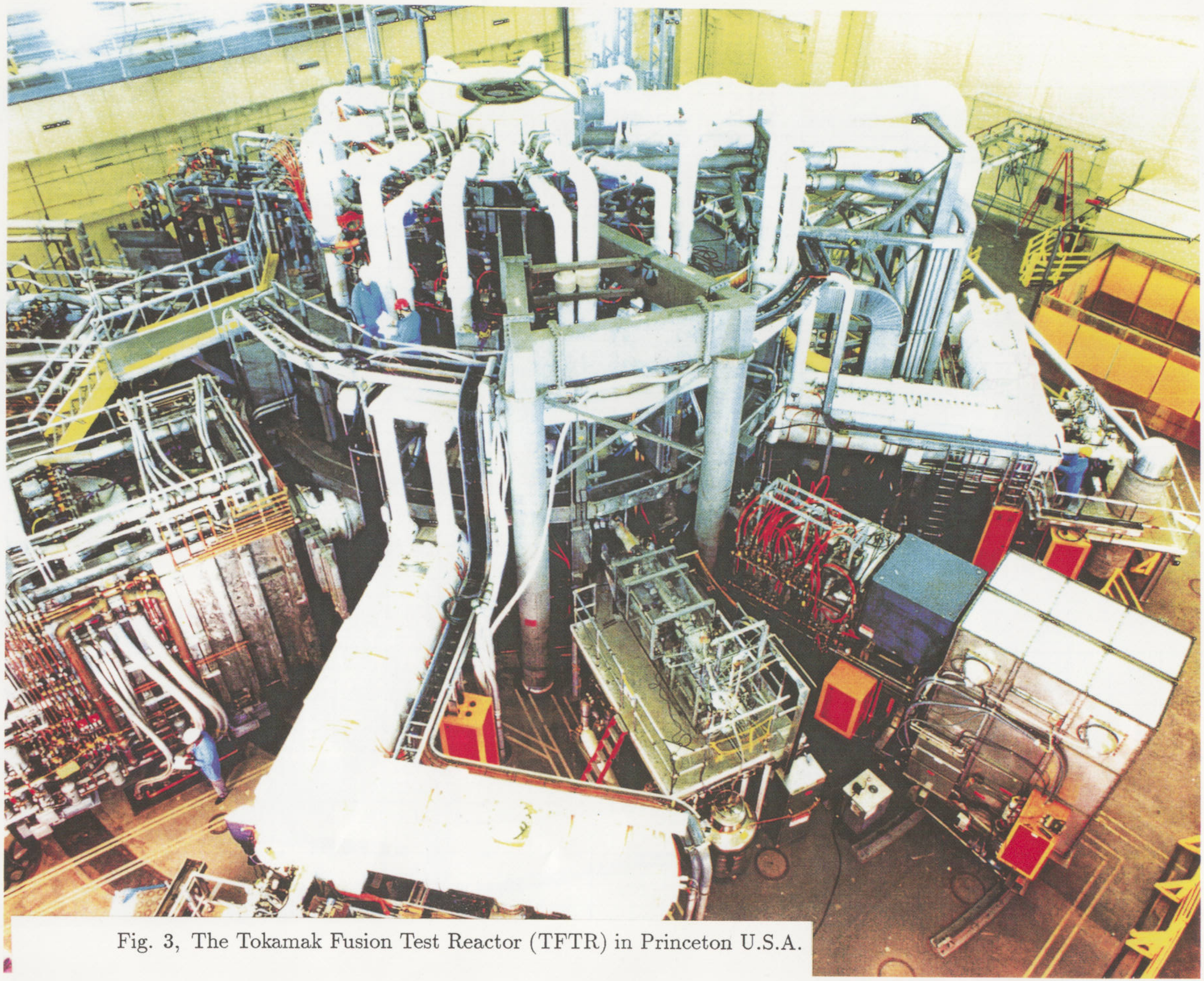

Fig. 3, The Tokamak Fusion Test Reactor (TFTR) in Princeton U.S.A.

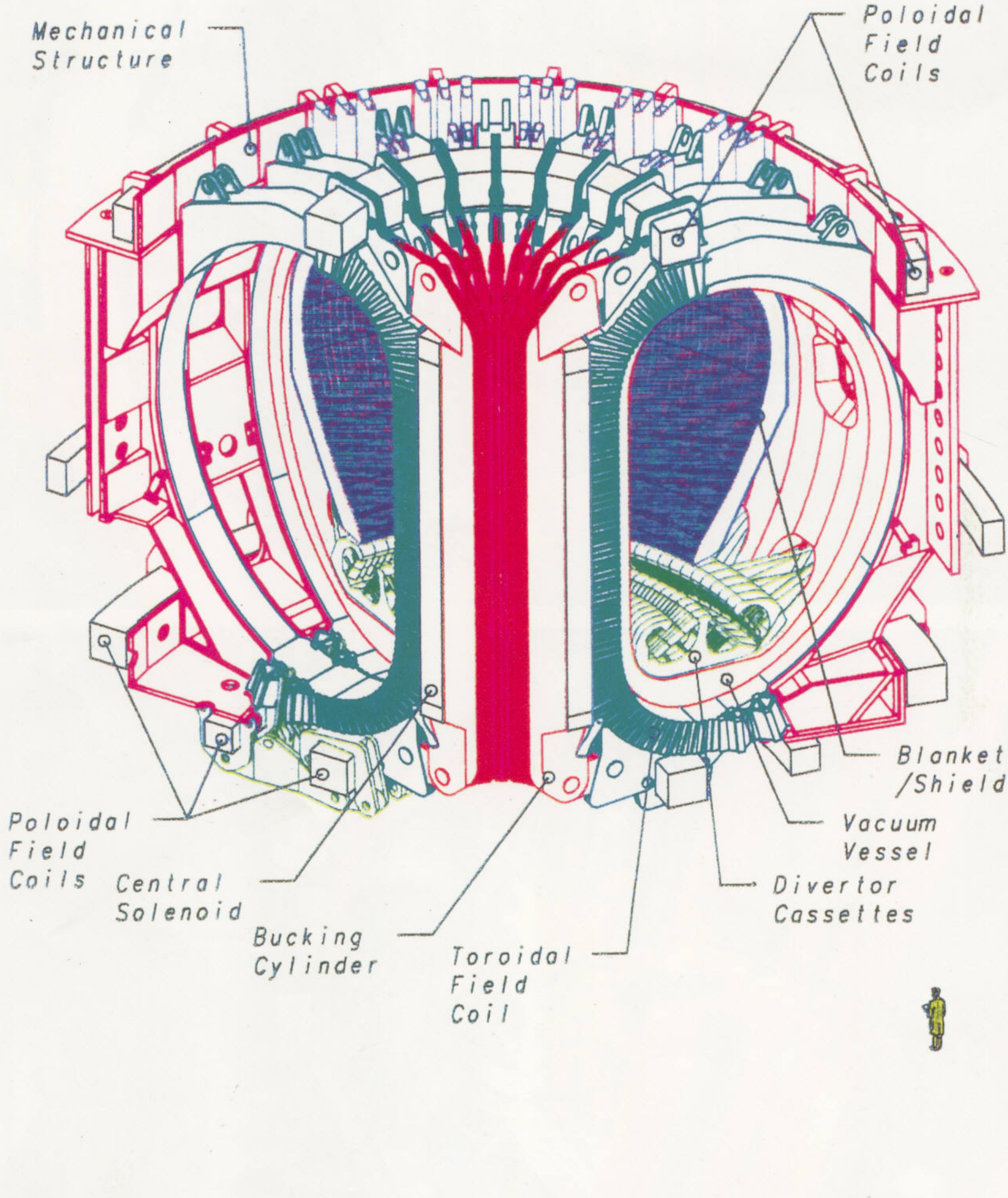

Fig. 4, The International Tokamak Experimental Reactor design.

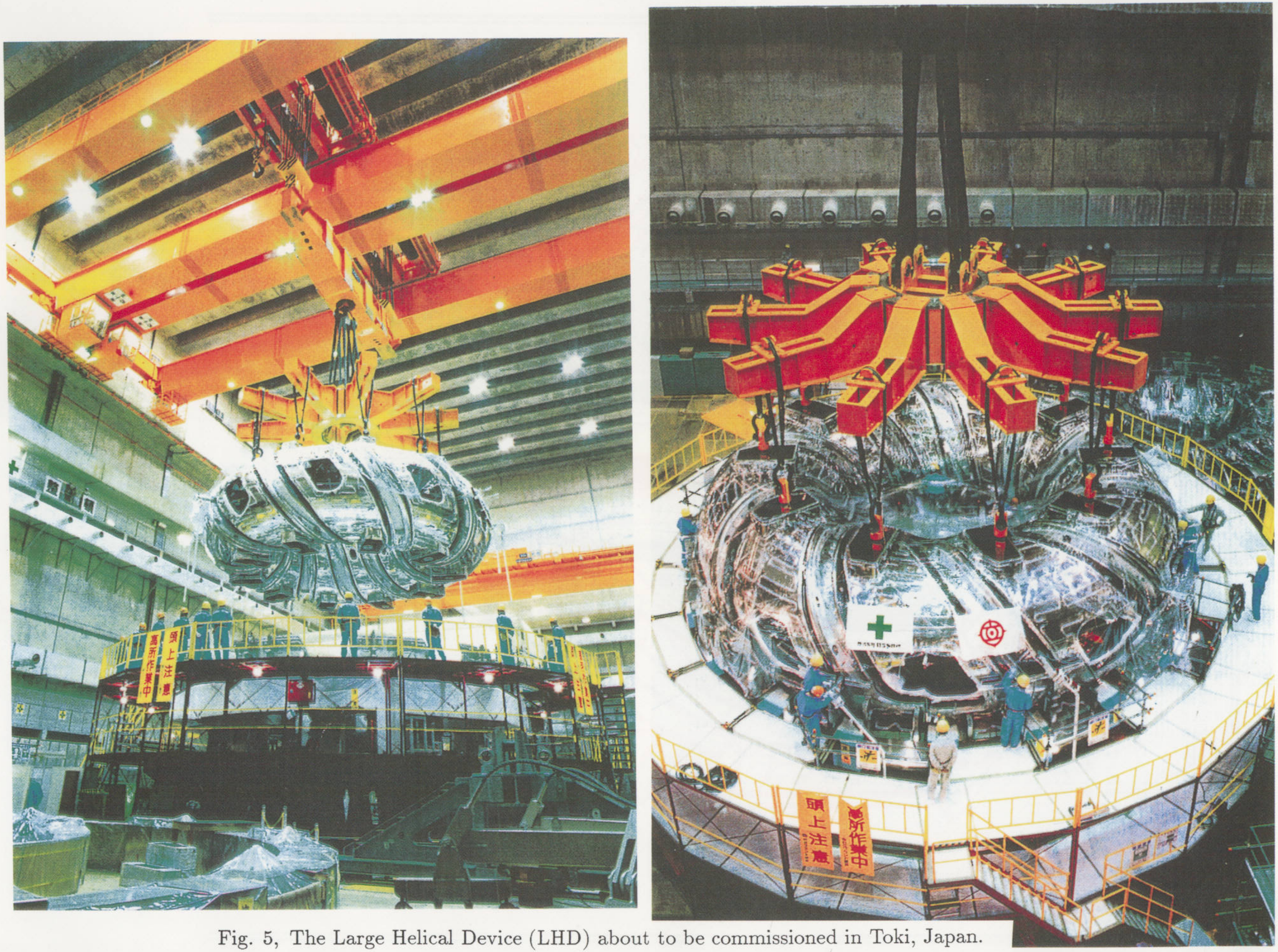

Fig. 5, The Large Helical Device (LHD) about to be commissioned in Toki, Japan.

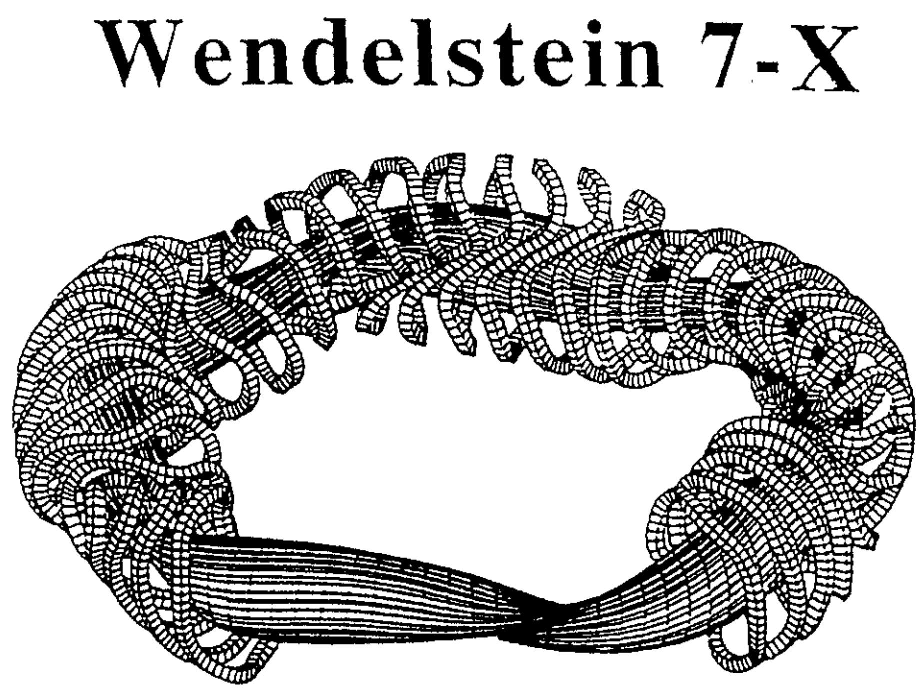

Fig. 6, Design of the Wendelstein 7-X (W7-X), which will be built in Greifswald, Germany.

QAS-BD

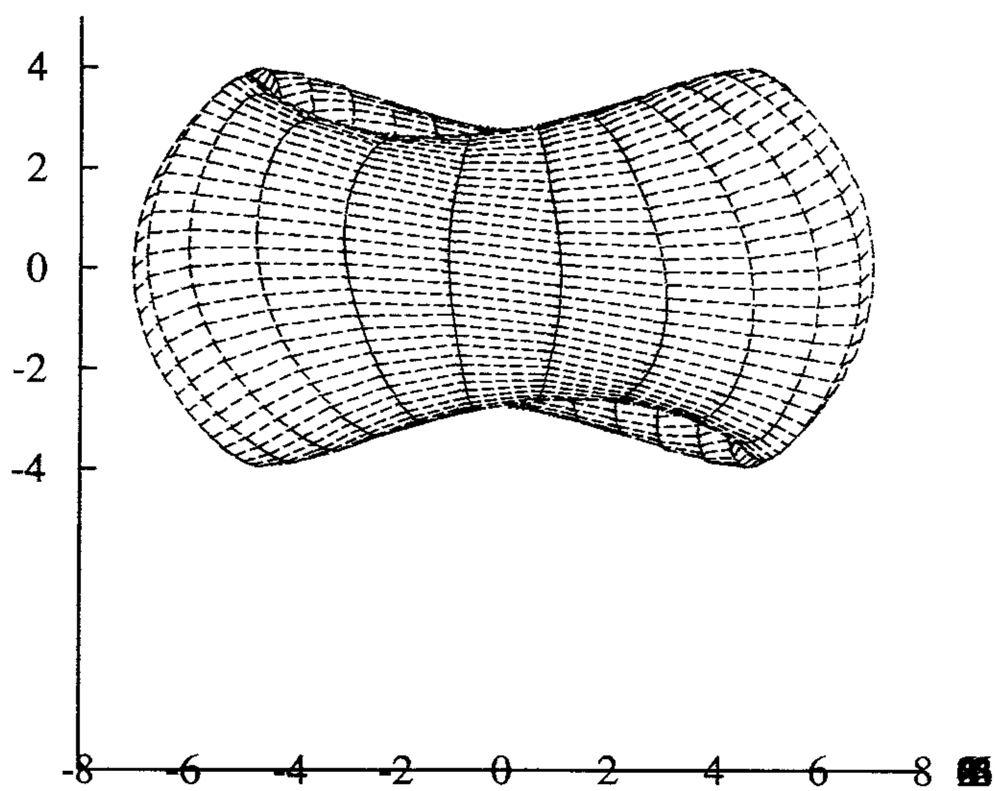

Fig. 7, The Bootstrap Current Driven Quasi-axisymmetric Stellarator being considered at Princeton.

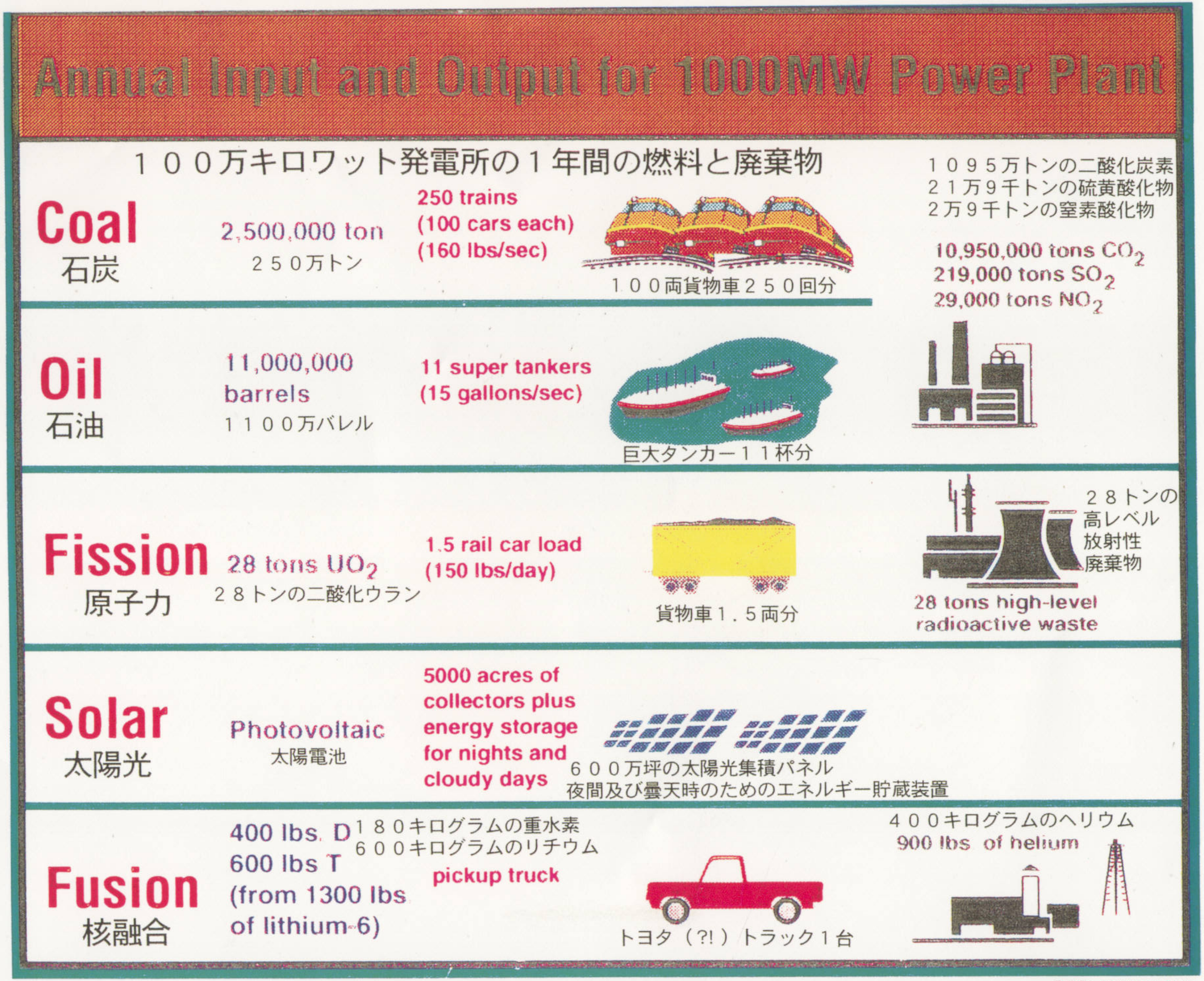

Fig. 8, Annual fuel requirements for and waste produced by a 1000MW power plant.

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