Compact Fusion: Small Is Beautiful

Smaller and cheaper reactors are emerging to challenge the front-running concepts; the utilities are all for it

The big money in magnetic fusion research is still in the so-called "mainline" technologies: the doughnut-shaped tokamak and the sausage-shaped tandem mirror. These are huge plasma physics machines, the most successful confinement devices developed to date. Before the decade is out, one or both of them will almost certainly achieve the long-sought goals of energy breakeven and plasma ignition.

Unfortunately, when utility executives contemplate scaling up one of these things into a working power reactor, they are deeply concerned. Both the tokamak and the tandem mirror are very large for the amount of energy they produce—the jargon is "low power density"—and conceptual designs for a power plant seem to imply a minimum output measured in gigawatts, and a minimum price ranging well into the multiple billions. In light of the unhappy history of fission power, most utilities would prefer to stick with coal, oil, and gas.

The point has not been lost on the fusion research community. For many in the field, the most exciting and intellectually challenging work being done today involves a set of devices known generically as compact reactors. Smaller and simpler than the mainlines, they embody intriguing new results in plasma theory—and should be much more in line with what the utilities will ultimately want to buy.

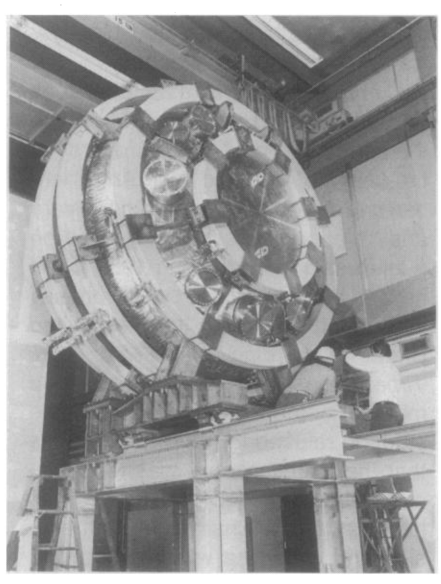
In fact, if the compact reactors are successful they could have a revolutionary impact on the whole fusion power strategy, says Peter H. Rose, president of Mathematical Sciences Northwest, Inc., in Bellevue, Washington, a company actively involved in the effort.

Instead of depending upon a few multi-billion-dollar experiments that are too expensive and complex to be used for unconventional ideas, he points out, the community could test a range of options in a series of hundred-million-dollar pilot plants. Instead of tying development exclusively to government funding because of the enormous costs, the Department of Energy (DOE) could make it attractive for private industry to come in early. And instead of utilities cutting their teeth on gigawatt pilot plants of uncertain reliability, they could phase in the smaller fusion plants gradually.

"If we had a fusion program that could prove what we are now proving, but at 1/10 the cost per step," says Rose, "fusion would be a hell of a lot easier to sell."

The DOE apparently agrees. For several years now it has maintained its compact reactor program at the $10 million to $20 million per year level in the face of strong pressure for cutbacks. Meanwhile, the Japanese have also mounted a vigorous effort in the field, with the Europeans and the Soviets not far behind. And private industry has indeed begun to come in, lured by the opportunity to gain in-house expertise (and perhaps a proprietary position) in the new technologies. In fact, among the best-funded projects is the RIGGATRON, a small-scale, high power density, "disposable" tokamak being developed by the INESCO company of La Jolla, California, entirely with private money—provided by Bob Guccione, founder of the *Penthouse/OMNI* magazine empire.

The emphasis on smaller reactors emerged in the mid-1970's, says Rose. The physicists were making great strides with the tokamak, but it was also becoming apparent to the utilities just how big and costly a tokamak power plant would be. A particularly vocal critic was Clinton Ashworth of Pacific Gas & Electric in San Francisco. "He pointed out what a terrible barrier this would be to getting any nongovernment support," says Rose. His prodding led the utilities' research arm, the Electric Power Research Institute in Palo Alto, California, to begin studies of less massive reactors.



The spheromak

Princeton Plasma Physics Laboratory's new large-scale spheromak, due for start-up by March 1983, should show substantial improvement in plasma containment over the prototype version.

Meanwhile, the DOE had already begun to rethink its own program. There had always been a small amount of money available for testing new and perhaps crazy ideas, says Rose. But the mainline approaches were doing well now, and people in the field were arguing that it was time to get rid of the deadwood. Focus efforts on devices that offered some clear advantage over the mainlines, they said. Thus the DOE, already under fire from the utilities, dropped several unpromising projects and in the late 1970's reoriented much of its advanced concepts program toward "compactness."

The challenge was (and is) formidable. STARFIRE, a conceptual design for a 1200-megawatt tokamak power plant produced in 1980 by Argonne National Laboratory, calls for a toroidal reactor nearly 30 meters across. The power plant as a whole would cost more than $2 billion in 1980 dollars, roughly twice as much as an equivalent light water fission reactor plant. The goal of the compact reactor effort is thus to cut capital costs at least by a factor of 2 and to cut the reactor size by a factor of many. In practice, that means finding reactors with much higher power density than anything the mainlines currently offer.

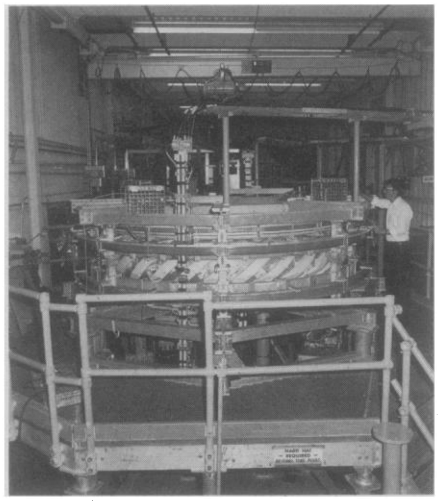
But that goes against all the experience of the fusion community. Improving a reactor's confinement properties almost invariably seems to involve making it bigger. In the words of one veteran, "fusion just doesn't like to operate at small sizes." For example, a small plasma has a large surface-to-volume ratio, which renders it hard to heat and quick to cool. A small reaction chamber likewise has walls lying close to the reaction, where they sputter impurities into the plasma and damp it even more. And as a purely practical matter, a small chamber enclosing a high-powered fusion reaction will have to endure an intense neutron bombardment and a high heat load, leading to a severe materials problem for the eventual designers of the power plant.

Nonetheless, a number of concepts have emerged. For example, since the 1950's there have been indications that a small, toroidal "smoke ring" of plasma might be remarkably stable: in principle, it could be a self-consistent system, with plasma currents spiraling around the ring and simultaneously generating the magnetic fields necessary to hold themselves on course. Such a ring is known in the trade as a "compact toroid." (Not to be confused with a "compact reactor." The nomenclature of fusion can be disconcerting.)

One form of compact toroid is the "field reversed configuration," which has the rough proportions of a napkin ring. Such a ring is easily formed by confining a cylindrical plasma within a conducting tube, then magnetically pinching off the ends. In fact, experiments date back to the 1950's. But early experiments were discouraging. The ring destroyed itself within microseconds. In the late 1970's, however, Soviet researchers were able to overcome the most spectacular instabilities, increasing the lifetime of the ring by a factor of 10 or more, and sparking renewed interest worldwide. Rose's company, Mathematical Sciences Northwest, for example, was commissioned by the Electric Power Research Institute to do a conceptual design for a field reversed reactor known as TRACT.

Meanwhile, in 1978, Marshall Rosenbluth of the Institute for Advanced Study in Princeton and Marie N. Bussac of the Ecole Polytechnique in Paris published model calculations implying that in a slightly different configuration the compact toroid could be very stable indeed. Its only misbehavior would be an easily controlled tendency to tilt. Since the new configuration looks a bit like a partially deflated basketball, it was dubbed the "spheromak."

Since 1980, spheromak plasma rings have been generated in at least three different ways in small test reactors at Princeton, Los Alamos, Livermore, and the University of Maryland. At Los Alamos, for example, the plasma was shot out of a coaxial gun, almost literally like blowing a smoke ring. The results seem to confirm the theory beautifully: the tilting modes indeed exist and can be controlled. Otherwise the plasma ring is stable, with losses coming primarily



OHTE

Built entirely with private capital, OHTE is a joint venture of GA Technologies in San Diego and Phillips Petroleum. The reactor was originated by GA vice president Tihiro Ohkawa, and its name is a bilingual pun: OHTE stands for ohmically heated test reactor, but in Japanese it is also the chess player's cry of "check."

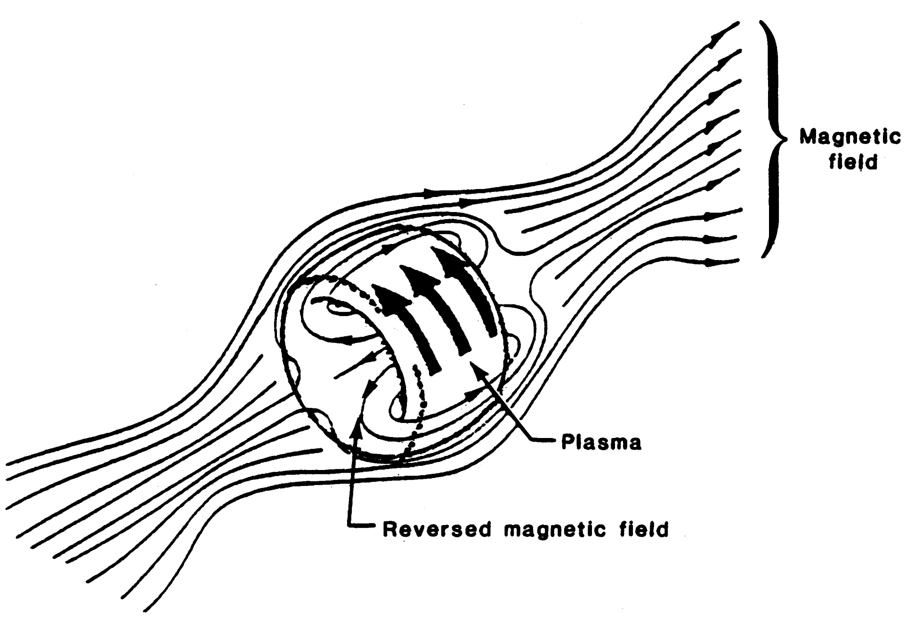
from impurities sputtered off the walls. Larger scale tests are being planned.

In terms of plasma confinement, the performance of the compact toroids so far has been modest. On the other hand, they are still in a relatively primitive state, especially when compared to the mainline reactors. What gets people excited is their eventual implication for power plant design.

One major complicating factor in the tokamak, for example, is the massive, current-carrying core that runs through the center of the doughnut and generates magnetic fields needed to hold the plasma in place. The compact toroids would eliminate the core entirely, leading to smaller, simpler reactors that would be much easier to maintain.

Heating the tokamak plasma is also a complex business, involving injections of electromagnetic energy at radio frequencies, or high energy beams of neutral deuterium and tritium fuel. With compact toroids, however, it might be possible to do away with all that. The plasmas can be quite dense, and it therefore may be possible to drive them all the way to ignition by the much simpler method of ohmic heating. This is the same principle that animates an incandescent light bulb: induce a current in the plasma and its electrical resistance will dissipate the energy of the current as heat.

Finally, the compact toroids promise a marked improvement over the tokamak's inefficient use of magnetic field. For a given external field strength, in other words, the compact toroids produce a hotter, denser plasma—essentially because the plasma is producing most of the field by itself. The field efficiency is measured by a parameter known as beta, the ratio of plasma thermal energy to magnetic field energy. In present tokamaks the highest beta to date is 4 percent; in the compact toroid devices, beta is typically 10 or 15 percent and has exceeded 50 percent. Thus, the potential is there for a high power density with a minimum investment in magnets.



A compact toroid

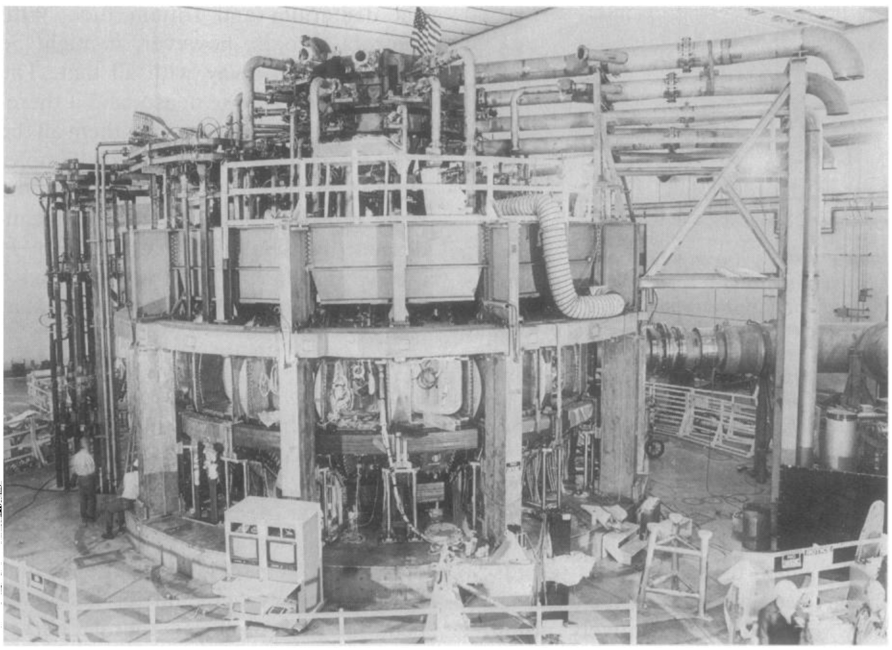
In principle the system is self-consistent: electric currents flowing around the ring generate magnetic fields which stabilize the ring. The compact toroid illustrated here is known as the field reversed configuration.

Many of these same potential advantages are seen in the second major class of compact reactors, the reversed field pinch (RFP) devices. (Nomenclature again: a "reversed field pinch" has nothing to do with the "field reversed configuration" mentioned above.) The concept actually dates back to the early 1960's, with important theoretical input on plasma stability in 1974 from J. B. Taylor of Culham Laboratory in Great Britain. But only in recent years have physicists overcome some of the technical problems involved in demonstrating the principle.

Like a tokamak, the RFP is a toroidal system with field coils running through the center. But like the compact toroid devices, the RFP generates most of its own confining field internally. (The plasma currents are such that the toroidal component of the magnetic field actually reverses direction near the walls; thus the name of the system.)

This gives the RFP one of its great potential advantages as a power reactor. A tokamak plant will have to have superconducting coils, lest it use up all the power it produces just in overcoming resistance losses. But this means building a cryogenic system that can handle massive amounts of liquid helium, together with thick layers of shielding to preserve the superconductors from the heat of the plasma. The RFP plasma, by contrast, generates most of its own field. This means that the external windings carry a much lower current and can be made of copper at room temperature. With the cryogenics and the shielding thus eliminated, the wall thickness of an RFP reactor could be shrunk to half a meter, instead of the tokamak's 1.5 meters.

This alone would cut the costs considerably, without even talking about high power density. But the RFP also shares the compact toroids' advantage of having high beta—at least 20 percent and perhaps much higher—and the possibility of purely ohmic heating. Thus it seems to be an extremely attractive candidate for a compact reactor. During the last few years, in fact, Robert Krakowski and his colleagues have begun to verify its potential with some very encouraging results with the ZT-40 device in Los Alamos. More recently, the General Atomic Company of San Diego (now GA Technologies) has sunk $5 million into building its own version, called OHTE: ohmically heated toroidal experiment. Phillips Petroleum is contributing an additional $10 million to operate it for 3 years.



The Tokamak Fusion Test Reactor

Located at the Princeton Plasma Physics Laboratory, the TFTR is currently the most advanced tokamak in the world. It achieved its first plasma in December 1982. By the end of the decade, it should achieve both scientific breakeven and a plasma ignition.

Such private sector interest is becoming increasingly apparent in the compact reactor field, largely because the effort seems to offer a relatively inexpensive entrée into the fusion world, with its potentially huge payoffs.

It is in much that spirit that the INESCO company and its backer, Bob Guccione, view the RIGGATRON reactor of physicist Robert Bussard.

In all of fusion research, there is nothing quite like the RIGGATRON. (The name comes from the Riggs National Bank of Washington, D.C., one of the first to lend money on the project.) It would essentially be a small, simplified tokamak with high beta, high power density, and copper coils. No attempt would be made to protect the reactor core from neutrons. About once a month, as components reach the end of their useful lifetime—for example, as neutron damage raises the resistivity of the copper to unacceptable levels—the whole core would simply be lifted out, thrown away, and replaced by a new one, rather like changing a light bulb.

In the INESCO scheme a working power plant would consist of perhaps a half-dozen RIGGATRON modules, to allow for continuous service during changeover. The reactor cores would be mass-produced for an estimated $250,000 and, since the activation products of copper are relatively benign and short-lived, the used cores would be stored on site for a few decades and then either recycled or junked.

The approach is controversial, to say the least, but Bussard and his team are highly regarded in the field. Their reference design—which has been favorably reviewed by an outside panel of experts—is complete, and the company is now searching for a site to begin construction. The plan is to build five experimental devices at $2.5 million apiece to test out variations of the reactor parameters.

"Under all the scaling laws for tokamaks, these things should ignite," says an INESCO spokesman. Unless those laws change in the new regime, he says, the viability of the concept should be demonstrated by 1987—well ahead of DOE's schedule for demonstrating ignition in tokamaks. INESCO will then be ready to move on to a commercial power plant in the 1990's.

Do the compact reactors foretell the end of tokamaks and tandem mirrors? Perhaps, but not likely. Many fusion researchers expect to see more of a convergence than a revolution. As the alternates strive for energy breakeven and ignition, they too will grow bigger. But as researchers on the mainlines have begun to feel the competition, they are already working on ways to slow the growth of their devices.

"Compactness is a *design* concept that can be applied to mainlines as well," says Stephen O. Dean of Fusion Power Associates. "The result may not be as small and as cheap as utilities would like. But I expect to get something in the middle."—**M. MITCHELL WALDROP**