GOD'S

the u.s. needs energy the way a junkie needs skag—and someday fairly soon controlled thermonuclear fusion will give us the inexhaustible connection

article

By RICHARD RHODES

PAINTING BY ROGER BROWN

BIG FIX

AS FAR AS THE UNIVERSE is concerned, the energy crisis is a fraud. There is no energy crisis now, there never has been, and there never will be. Dislocations, yes: massive and destructive in the past, possibly more so in the future. But there never was any shortage of energy in the universe. We knew that all along, watching the sun rise and burn and set through all the millennia of the race's evolution and never once falter, never once go out. Was there anything earlier that we wanted? Excepting only ourselves, was there anything earlier that we knew?

The sun will save us?
No.
Yet it obsesses.
That huge, unquenchable source.
Then it will save us.
From ourselves?

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Controlled thermonuclear fusion, the ultimate source of inexhaustible energy, in the long run almost entirely pollution-free, toward which physicists have been talking and working since before the end of World War Two, is nearer this year to being realized in the laboratory than it has ever been. Last year, 1973, was a turning point, the year the leading physicists in the field decided that fusion was in fact possible and would eventually be practical. They told Congress so; they told journalists so; one of them, Dr. Harold P. Furth, of the Princeton Plasma Physics Laboratory, might as well speak here for them all: "There's really no doubt any longer about the fact that a fusion reactor is possible. One could even describe such a reactor, and one might be off a little bit on the size and cost, which are of course rather important, but one could describe a reactor with near-absolute certainty that some such thing in some size will in fact work."

How scientists reached this point, how their experiments have gone and how a reactor would work, and where that work may lead us, are facts worth knowing, because controlled thermonuclear fusion will change American life and the life of the world at least as much as its diabolic bastard kin, the hydrogen bomb, already has. Nothing afterward will ever again be quite the same. If that sounds ambiguous and even ominous, it is meant to. If power corrupts, it remains to be seen whether or not absolute power will corrupt absolutely.

From the beginning, then, heavy gold: The sun, the stars, the clouds between the stars, the northern lights, the glow inside a neon tube, the fireball of a hydrogen bomb, all are made of plasma, the fourth state of matter. Solid, liquid, gas, plasma. To make a plasma from hydrogen gas, you inject the gas into a vacuum chamber and heat it above 10,000 degrees centigrade. The electrons then separate from the nuclei, negative electrons from positive ions, and the gas becomes ionized: Plasma is ionized gas. Like ordinary gas, it can be heated by compression and cooled by expansion; like ordinary gas, it jostles about with no particular form and expands outward equally in all directions; but unlike ordinary gas, it conducts electricity and can be shaped and directed by magnetic fields.

Making a plasma is easy; you do so whenever you turn on a fluorescent light. Making a plasma do what the sun does—do better than the sun does, because the sun isn't very efficient—is hard. Ions, the nuclei of atoms stripped of their electrons and thus positively charged, repel one another with great force. To bring them together, that force must be overcome. For the heavy isotopes of hydrogen—deuterium and tritium—the temperature required to overcome the natural repellence of their ions is around 50,000,000 degrees centigrade. Above that temperature, deuterium and tritium atoms not only collide but sometimes fuse together and become helium ions. In the process of fusing, a little of their mass is converted into energy. The amount of energy released is enormous. $E = mc^2$, that great tonic chord of physical reality that Einstein struck so long ago, looks the soul of innocence until you spell out the numbers: Energy in ergs equals mass in grams multiplied by *the square of the speed of light* in centimeters per second. But the square of the speed of light in centimeters per second is 900,000,000,000,000,000,000. One gram of matter converted entirely into energy becomes 900 billion billion ergs. An erg isn't much; 9 x 10^{20} ergs is one hell of a lot.

Nuclear fusion on a modest scale was first accomplished on earth in 1952, when the United States set off a 21-ton monstrosity called Mike I on Elugelab, Eniwetok, in the South Pacific. The resulting explosion vaporized all 21 tons of Mike I and replaced Elugelab, a little strip of coral, with a hole a mile wide and 175 feet deep. Even before the United States developed the bomb that was called the Super in those early days and is called the hydrogen bomb today, some of the leading scientists at Los Alamos—men such as Enrico Fermi, Edward Teller, James Tuck—were tossing around ideas for a controlled-fusion machine. (Tuck, an Englishman, midnight-requisitioned some funds for the work from a program at MIT that was housed in the Hood Building; Tuck's boss suggested that Tuck was robbing Hood; the secret program to solve the world's energy needs forever was therefore named Project Sherwood. Physicists are celebrated for their wit, not their sense of humor.)

Controlled fusion never looked easy, but in those early days it at least looked straightforward. Mike I, like all hydrogen bombs so far, needed an atomic bomb to set it off. That's how its inventors got the millions of degrees they needed for fusion. Controlled fusion has to work without an atomic trigger. It has to work within some kind of container, but the plasma in which the fusion reactions take place cannot touch the walls of the container. Science writers like to say that the plasma can't touch the walls of the container because it would melt them. That isn't true. To be confinable at all, the plasmas used in controlled fusion must be kept at very low density—100,000 times lower than the density of the air we breathe. One one-hundred-thousandth atmospheric pressure is considered a pretty good vacuum in other lines of work.

So the plasma is the merest puff of gas, and at such low density it immediately cools off when it touches something solid. Fifty million degrees sounds like the ultimate conflagration, but you could stick your gold-plated Cross pen into a thermonuclear plasma and very little would happen to it. It might pit a little and it would radiate soft X rays like crazy, but the main thing it would do is make a cold hole in the plasma. A thermonuclear plasma gives off heat not in the usual sense we think of heat, heat we can feel, heat that burns us, but rather heat as energetic particles and fast neutrons, and those in turn can be used to make "real" heat that can turn turbines and generate electricity.

It seemed to those early explorers—and they had their brilliant counterparts in the Soviet Union, though neither side knew about the other yet, because the whole subject was top secret—that they had only to figure out a way to confine a plasma without allowing it to touch anything solid, and then to heat it up to thermonuclear temperatures, and then to keep it there long enough for the fusion reactions to build up to the point where they became self-sustaining, and that would be it. They thought they'd have a working reactor on the near side of 20 years. I don't mean to suggest that they were naïve, though on the face of it, it appears that they were, but only to suggest what was in fact true, that no one knew much about plasma physics in those days—despite the fact that the universe is almost all plasma. (Solids, liquids and gases are nearly as rare within its vast confines as human beings, who are composed of all three and no plasma at all, except briefly, when hit by lightning.)

Confinement was the most difficult of all the problems, and still is, though physicists now think they've nearly got it licked. Plasma, since it conducts electricity, is affected by magnetic fields just as metals are. It seemed reasonable, then, that a plasma could be confined within a magnetic field. The first experimental devices were simply tubes wrapped with coils of wire. When electricity was sent through the coils, it produced

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magnetic-field lines running the length of the tube. The electrons and ions of the plasma inside then aligned themselves along the field lines. Both electrons and ions move freely along magnetic lines of force. Left alone, the particles would have spun along the lines of force until they bumped into the ends of the tube and quenched out; but to forestall that result, the experimenters had added a few more turns of wire at the ends. Thus, the particles, as they approached the ends, faced a more powerful magnetic field than the field in the middle, and it turned most of them around. This kind of confinement device, which is called a magnetic mirror system, is still being studied at the Atomic Energy Commission's laboratory in Livermore, California, and it still shows promise of eventually producing a practical fusion reactor, though probably in the longer run rather than the shorter.

The mirror system didn't work as well as its inventors expected. As the plasma heated up, it wouldn't hold still. It kinked, it buckled, it bent, it shaped itself into fluted columns, and inevitably it broke loose, hit the walls of the tube and quenched out. But the major problem of mirror systems was leakage out the ends. Physicists hoped that such instabilities were unique to the mirror system, and some of them turned to other approaches. The lab at Princeton University, for example, designed a machine that had no ends, a hollow figure eight that was grandly named the stellarator, the star generator. But in 1954, at one of the frequent meetings of the Sherwood scientists, Teller, the irascible Hungarian who is credited with having invented the hydrogen bomb, argued chillingly that all the devices then being experimented with would also develop instabilities of one kind or another, and the physicists gloomily left the meeting more than a little sure that Teller was right; and after rechecking their previous results and running more experiments, they saw that he was. The Fifties weren't the best years for fusion research, nor the early Sixties, either. Graduate students began looking the other way. Only lately have they begun turning to plasma physics again.

But at least one crucial step was taken, in 1958, without which the program might be foundering still. Sherwood had been classified top secret because it was obvious that a fusion reactor would produce vast numbers of neutrons, neutrons that could be used, for example, to make plutonium for atomic bombs. In the late Forties, when the classification was applied, there weren't many nuclear reactors around and neutrons were hard to get. So rather than show other countries how they might make neutrons through controlled fusion—we were optimistic in those days, remember, that fusion was just around the corner—we kept our work secret. By the mid-Fifties, after the Soviets got the H-bomb, it was obvious that there were neutrons aplenty, and fusion research was stalled, and physicists from other countries, most particularly from the Soviet Union, were beginning to talk about fusion at international meetings, and the secret was effectively out. So in May 1958, after considerable prodding from Congress, the AEC declassified Sherwood, and Russians and Americans, among others, began talking to one another.

By that time, American physicists had devised a remarkable collection of ingenious devices designed to confine and heat plasmas by squeezing them, pinching them, wrapping them in clouds of high-energy electrons, shooting them from ion guns, you name it. The results were uniformly abysmal, though the information was often useful and the experimental and theoretical knowledge of plasma physics that had been so lacking before was beginning to accumulate. The original breezy optimism, however, was gone. The men in the field today, wiser with the passage of years, describe controlled thermonuclear fusion as the most difficult problem of general scientific interest in the history of physics. They're not exaggerating.

While United States scientists worked with their many devices, scientists in the Soviet Union were concentrating most of their attention on one particular kind of machine. Its conception and creation are credited to two brilliant Russian physicists, Andrei Sakharov and Lev Artsimovich. The Russian machine, which Artsimovich announced to the world in 1965, was called the Tokamak. The word is generic now: Machines of the Russian type are called tokamaks, accent on the tok. Like the Princeton machine, the tokamak solves the problem of end loss by having no ends. It is shaped like a large hollow doughnut, a geometric form called a torus. In a tokamak, the magnetic lines of force spiral around the toroidal chamber in helical paths like the stripes on a barber pole and the particles ride along, finding no ends from which to escape.

An important feature of the tokamak is its technique for heating the plasma. Rather than heating by squeezing, or heating by the injection of hotter particles, as some of the American machines were attempting, the Russians decided to let the plasma heat itself. Since plasma conducts electricity, they induced a current into the doughnut-shaped ring of plasma and the current, encountering resistance just as current in the wires of a toaster encounters resistance, generated heat. The Russian tokamak made the first major breakthrough in confinement time—in holding the plasma steady for longer than the briefest fraction of a fraction of a second—and it heated the plasma to better than 10,000,000 degrees, far hotter than anyone had achieved up to that time, though not nearly hot enough for fusion.

Despite the joy radiating from the Soviet Union, not many physicists believed the Russian results. The logic of the skepticism, says one American physicist who remembers it well, was, "Hell, our toroids don't work, why the hell should theirs?" Many American scientists were skeptical of the quality of the Russian measurements, particularly their measurements of the plasma temperatures they claimed to have achieved.

Since any but the most minute solid probes stuck into a plasma disturb it, it can't be measured directly. Measurements have to be made by capturing what comes out of the plasma or by shooting various kinds of radiation in. Today, as in 1965, experimenters measure the neutrons coming out of the plasma, the X rays, the light, the magnetic field, the microwaves. The most accurate method of measuring the temperature happens to be by bouncing laser light off the plasma and seeing how it scatters. And in 1965, the Russians weren't up on lasers.

Princeton therefore proceeded to tinker with its stellarator, Oak Ridge and Livermore with their mirrors, Los Alamos with its pinches. Then, in 1968, a team of British physicists went to the Soviet Union for six months to settle the issue once and for all, taking along their own lasers and thousands of pounds of gear, since the Soviets are not famous for their ability to deliver spare parts on short notice. The British report came through: The Russians were right. Oak Ridge converted from mirrors to tokamaks. Princeton dismantled its stellarator and in nine months rebuilt it as a tokamak. From 1969 on, the tokamak has been the leading contender to become the first practical, working fusion reactor. "The Russians," says Dr. Michael Roberts of Oak Ridge, who went over to see the Russian machine in 1968, "were very pleasant, helpful, tolerant, because people from all over the world asked the same questions over and over. They wouldn't read the scientific papers, they had to ask the source—*tell me, tell me, tell me, too!* We were like flies around those guys all day long. They were very tolerant."

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Since 1969, the Russian discovery has become the American lead, and Furth of Princeton speculates why. "The Russians have a lot of sense, which is reflected in the fact that they got onto the tokamak. They stick to those fine old-fashioned things, keep it simple and push it a little further. They still hang chandeliers in their labs for light. I think our very failure to keep up with them on the stellarator was because it was too clever. We've got a far better industrial base than the Russians, and the stellarator made too much use of the fancy things we can do. This shows up in competition with the Russians a million times. It's like their rockets. Ours have all sorts of curlicues on them because our industry can provide them, so why not yield to the temptation? Nonetheless, it was the Russians who put up the first rockets and the first men. And, incidentally, who then got wiped out when we got wise and applied all our technology. The same thing is happening with reactors; they set us on the right track and now the superior industrial base we have, even though we aren't as smart as they are, can be used to get ahead. Once we had converted the stellarator to a tokamak, we were getting 20 times as many pulses from ours, because ours had water-cooled coils, as they could get from theirs, and that meant we were getting 20 times as much information."

But Roberts adds: "One does not want to muddy the fact that the Russians did the work. We don't want to say it's our idea. It's not. We picked it up and carried it with them, but without their help it wouldn't have been possible. They had made a ten- or fifteen-year commitment and carried it through a lot of discouragement, and they could very easily have not told us anything, kept it quiet, and then come out in 1980 or 1990 with a working fusion machine. They didn't do that."

Nineteen eighty and even 1990 are generally considered optimistic estimates of when anyone will produce a working fusion reactor. The problems are still formidable and many necessary achievements still exist only as extrapolations from present work. Plasmas have been successfully confined for the brief time necessary for fusion to become self-sustaining—and even longer—but not at thermonuclear temperatures. Plasma instabilities have been conquered in some existing machines—but it remains to be seen if the same techniques will work in machines large enough and hot enough to make fusion a practical source of electricity. No tritium has yet been burned in any experimental device, for the simple reason that tritium, alone among the three isotopes of hydrogen (simple hydrogen and deuterium are the two others), is radioactive and requires shielding and remote handling, requirements that aren't conducive to experimentation and have so far been avoided. Experimenters use ordinary hydrogen gas for their experiments and sometimes they use deuterium, but the first working reactor would be fueled with a mixture of deuterium and tritium, because a deuterium-tritium reaction takes place at the lowest temperature of any of the various hydrogen fusion reactions possible; and until an experiment achieves all the necessary parameters of temperature, confinement and duration with a mixture of those two gases, the game ain't over. The deuterium-tritium-burner experiment is coming on, and ought to be under way by the early Eighties, so the AEC now estimates. Until then, the work of scaling experiments up to larger and larger sizes goes on in labs scattered across the United States as well as in many other countries, each lab producing some of the results that must eventually all come together to make a fusion reactor. It's worth a quick trip around the American labs to see the magnitude—and the ingenuity—of the effort.

Plasma-physics labs, whether on Government, university or private property, all manage to look like aircraft-assembly shops run by especially sloppy supervisors. There's the same smell of hot plastic and ozone in the air, the same clutter of wires and mock-ups and aluminum sheeting, the same open-collared, trim-waisted collection of craftsmen, except that in the case of the labs the craftsmen are likely to be Ph.D. physicists who have devoted their adult lives to working with parts of the great universe too small and wily to see, parts that operate with such arcane subtlety that they can be mastered only with exotic mathematics and exotic machines.

The largest fusion-research laboratory in the United States presently is the Princeton-sponsored and AEC-funded lab at Princeton University. Until last spring, the primary research machine at Princeton was the ST-Tokamak that was converted from the stellarator in 1969, but Princeton is now completing a machine three times the ST-Tokamak's size, a machine called the PLT that will be about four feet high and ten feet across, with coils of pure copper wrapped around it larger yet. The solution to the problem of particles' diffusing outward to the walls, physicists have decided, is simply to build tokamaks with larger chambers, because then it takes longer for the particles to make their way out to the walls. A full-scale reactor will therefore be a large machine, indeed, 20 feet high and 60 feet across. So the PLT, the largest machine this side of Moscow and in many ways a more useful experiment than the new Moscow tokamak the Russians are building, isn't nearly the final step in the search. But the search must go on by steps, each scaling up by about a magnitude of three from the previous step, because that's about as far as the theoreticians can reasonably extrapolate from the previous experimental results. The problem was less grievous when the scale of experiments was smaller, but the PLT, for example, will be the last experiment at Princeton that can make use of the huge motor-generator sets originally installed to charge the magnets on the stellarator, and even without that extra cost, the PLT is costing some $13,000,000. The next experiment will cost over $100,000,000 and no one wants to design a $100,000,000 machine without reasonable certainty that it will prove what it's supposed to prove.

Oak Ridge has a tokamak—ORMAK, it is called—similar in size to the Princeton ST-Tokamak. It is currently being used to study new methods of plasma heating. The generators that run ORMAK are, ironically, the same generators that ran some of the machines that separated from ordinary uranium the uranium 235 that was used in World War Two to make the first atomic bomb.

The most physically striking of all the fusion experiments is the SCYLLAC experiment at Los Alamos, under the direction of Dr. Fred Ribe. SCYLLAC is toroidal, although the torus is shaped more like a giant bicycle tire than a doughnut, and it heats and confines its plasma simultaneously by rapidly squeezing—pinching—it with an enormous pulse of magnetism out of a bank of thousands of specially designed condensers. Since the pinch must come from every direction simultaneously, SCYLLAC looks like a giant representation of the Medusa, with hundreds of white cables running out in bundles from the coils around the torus. SCYLLAC is a device called a theta pinch, not a tokamak, one of several alternatives the AEC continues to pursue on the wise assumption that it's better to be safe than sorry. Ribe believes his theta pinch will work, and if it does, it could have the immense advantage of producing electricity directly, without the need for the usual complicated heat cycles whereby energy from a fusion reaction heats liquid metal and then, in turn, the liquid metal heats water to produce steam to turn generators. In a SCYLLAC type of reactor, the plasma would be compressed magnetically to produce fusion, and the energy released by fusion would then push back against the magnetic field, inducing current directly into the system that made the magnetic field in the first place, a sort of breathe-in-breathe-out operation that might work at far greater efficiencies than ordinary heat-exchange systems. SCYLLAC is far less stable than the tokamak systems, however, and Ribe's machine is probably not going to be a first-generation reactor design.

Another and largely classified work that is going on at Los Alamos is the study of an entirely different kind of fusion system, one that looks simple and may prove to be, remembering always that magnetic confinement looked simple, too, when it was in its infancy, as this new system is today. Imagine a reactor that consists of a pressure vessel filled with liquid lithium, swirled so that it has a vortex at the top like the vortex that sometimes forms in your bathtub when you let the water out, and into this vortex is injected a pinhead-sized drop of frozen deuterium-tritium, which is then zapped by an enormously powerful laser beam. The drop, hit by such force, begins to implode—to be squeezed to great density—and the heat and pressure of that squeezing produce fusion reactions that produce high-energy neutrons that are captured in the lithium, heating it hot enough to make steam. That is the vision of laser fusion, and the reason it is classified is that the powerful lasers being developed might well find applications in military weapons systems.

Livermore works with laser fusion, but its main effort these days is work on various configurations of mirror machines, which aren't likely to become first-generation reactors either but which offer hope, as SCYLLAC does, of a day when fusion energy can be converted directly into electricity without an intervening heat cycle.

There are smaller fusion experiments, both magnetic and laser, at universities and private laboratories around the United States, but the most interesting and in some ways the most promising experiment of all is located at General Atomic in La Jolla, California, where a brilliant Japanese scientist named Tihiro Ohkawa has been working on fusion for 14 years, wresting impressive results from a budget that can be counted in pennies compared with the dollars available to the big AEC labs. Ohkawa, who is a trim, handsome, articulate man in his mid-40s, is revered in Japan in much the same way, and for much the same reasons of extraordinary brilliance, Einstein was once revered in the United States. He has no giant motor-generator sets; he couldn't afford them. Instead he scrounged 600 submarine batteries from the United States Navy and designed a complicated set of loading switches to feed the batteries' considerable power to his machines on command. With his low budget and some extremely simple machines, Ohkawa has achieved the longest confinement time yet produced, a full second, and has designed a modified tokamak that is likelier than any other tokamak design to be the shape of the first practical fusion reactor. Ohkawa's tokamak was the only one operating in the United States when the Russian breakthrough came.

Ohkawa's Doublet series—he is presently building Doublet III, having worked his way up through I, II and IIA—is toroidal, and a Doublet still looks like a doughnut the long way around, but if you cut through the doughnut, took a bite out of it, as it were, the cut ends would look like slices the long way through a peanut. Doublets, in other words, have noncircular cross sections. The purpose of this alteration requires us to detour through the complicated subject of plasma instability.

As plasmas get hotter and hotter, the particles that make them up move faster and faster, flying around the chamber in longer and longer helical paths. Sometimes, as they do so, they begin to work together, resonating at various frequencies

"I'll say one thing for my husband, he knows what he wants in life and goes after it!"

and developing far more punch than the individual particles ever have when acting on their own. It is just such resonances that account for the tendency of plasmas to kink and buckle and flute and break through their magnetic confinement. The problem since the beginning has been to identify these instabilities, figure out what causes them and design equipment that can suppress them before they get out of hand. Each new generation of experiments, pushing temperatures higher and achieving longer confinement times, has encountered a new set of instabilities, and it is because physicists think they've seen, or can predict, most of the major kinds of instabilities that they've decided a fusion reactor will eventually be practical.

One of the most serious instabilities occurs when a particle does what Furth calls "biting its own tail." When a particle becomes energetic enough, it can zip all the way around the torus without colliding with any other particle and end up in exactly the same place it started, and when it does that, it can begin to resonate in concert with its fellows. Ohkawa's peanut cross section eliminates that effect by making the particle's path as long in cross section as it is the long way around. Now, a circular tokamak can also eliminate this effect, but only by applying far stronger magnetic fields than the Doublet, because of its special design, requires. "We are getting," says Ohkawa, "about the same kind of plasma the circular tokamak is getting, with one exception: We're using only 8000 gauss [a measure of magnetic-field strength: The earth's magnetic field equals one gauss] compared with 25,000, 30,000, 40,000 gauss for the circular tokamaks. That's one third or one fourth. And the cost of the magnetic field goes like the square of the magnetic-field strength, which in one third means about one tenth of a circular tokamak. So if Doublet III works, we can get away with magnetic energy that costs ten times less." The point is vital, because it won't be enough to make a functioning fusion reactor; we must also make a functioning fusion reactor whose costs are comparable with those of existing kinds of electrical generating systems. Ohkawa's Doublet system may well show the way.

The AEC presently expects that the path to a commercial fusion reactor will require five steps taken on four machines, each one larger and more expensive than the last. The first step—one step beyond the PLT—will be a machine large enough to prove the feasibility, in temperature, confinement and duration, of controlled fusion, but using ordinary hydrogen gas. That machine would then be converted to a deuterium-tritium burner, with all the attendant paraphernalia necessary to handle tritium's radioactivity. At that point—perhaps by the early Eighties—scientific feasibility and what physicists call break-even would be accomplished facts. Break-even, the crucial point, comes when the plasma is putting out as much energy as is needed to heat it. Attention by then will be turning toward engineering problems: toward developing superconducting coils to replace the coils that today are cooled by water or liquid nitrogen, toward developing the heat-exchange systems, toward matching costs with potential electrical output. The next step would be to build an experimental prototype that would actually generate some electricity. In the early to mid-Nineties, the AEC would build a true prototype, electrical generators and all, and industry might well begin to place a few orders. Finally, by the year 2000, engineers would complete a demonstration plant. Fusion as a practical means of generating electricity would therefore become available sometime after 1990.

The road between now and then is perilous, because what the AEC and industry are busily building today are fast-breeder nuclear reactors that produce more dangerous, highly radioactive plutonium than they consume in uranium. Plutonium is one of the most lethal substances on earth and it has a half life of 24,360 years. We are about to begin producing it in large quantities, plutonium that poisons, plutonium that large countries and small can easily fashion into bombs, plutonium that might even be used by criminal groups to fashion fizzle bombs that could threaten the hijacking of entire cities. Fusion has no such potential for destruction. Tritium is only mildly radioactive and has a half life of 12½ years, which is why it is so rare that a fusion reactor using tritium would have to breed its own in order to keep going economically. Fusion reactors can't blow up, only, as we have seen, blow out. And down the road a few more decades into the 21st Century is the likelihood of fusion reactors capable of achieving deuterium-deuterium fusion, which needs much hotter ignition temperatures than deuterium-tritium fusion but which has the virtue of releasing no radioactivity at all except the small residual irradiation of the materials in the reactor vessel itself, materials that will present nothing like the disposal problem of the poisons produced in nuclear reactors.

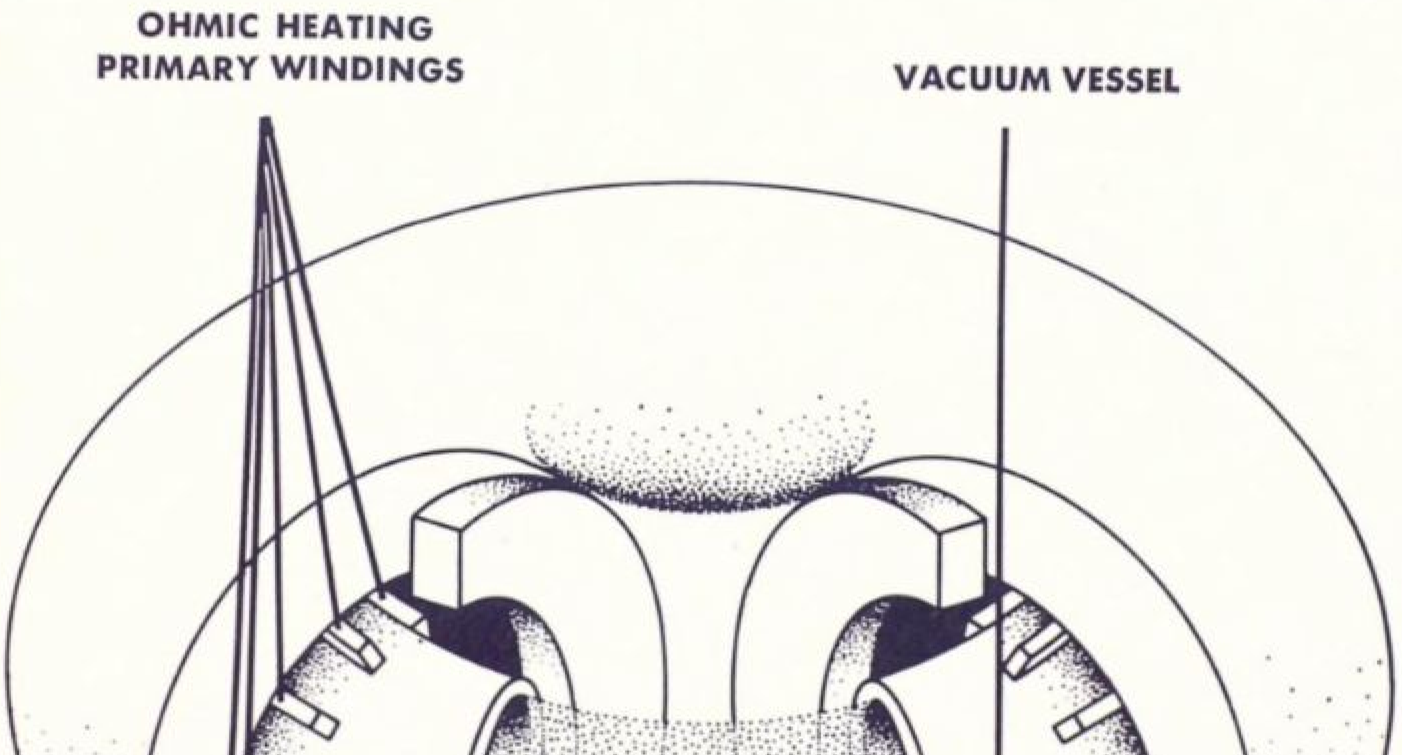
What will an operating fusion reactor look like? It will be large, as large as fossil-fuel power plants today, and it will cost as much as they do, a billion dollars or more. At its heart will be a thermonuclear plasma burning at 100,000,000 to 200,000,000 degrees centigrade. At those temperatures, plasmas radiate no visible light; the plasma will be invisible. Surrounding it, if Ohkawa's Doublet system proves as successful as it appears it will, will be a toroidal chamber shaped, in cross section, like a peanut or a kidney, and surrounding that chamber will be a cellular structure—physicists call it a blanket—through which circulates hot liquid lithium in which tritium is bred. The lithium circulates out of the blanket to a processing area where tritium is extracted for feeding back into the reactor. Surrounding the lithium blanket might be a blanket of graphite heated by the neutrons coming from the plasma fusion reactions, a blanket of graphite through which circulates helium gas. The neutrons would heat the graphite; the heat would exchange to the helium and the helium would circulate outside to run gas turbines that run generators.

Beyond the graphite blanket would be located superconducting coils of niobium-titanium alloy that would produce the confining magnetic field, and you must consider the state of modern technology that allows men to place metal cooled to within two degrees of absolute zero, the lowest temperature possible in the universe, next to plasmas burning at tens and tens of millions of degrees, among the highest temperatures in the universe.

Outside all this gear would be shielding, control systems and the electrical generating and delivery systems, the whole package operated, one imagines, by young guys with beards and long hair and no more than engineering degrees who thought it looked like a good line of work.

When fusion will become a common source of electricity—when your lights and mine are burning on the fusion of a puff of gas made from ordinary water—is anyone's guess, but fusion reactors could be going up all over the land by 2010 if energy needs and the problems we've been having with fossil fuels demand them. And at that point, whether we choose to apply the technology on a large scale or not, man will have solved the most urgent of all the technological problems that have plagued him since the discovery of fire: He will have found access to all the energy he wants. If he needs it in some form other than electricity, fusion can supply that, too, by splitting water into hydrogen and oxygen and then making methanol, a clean-burning form of alcohol, from the hydrogen. He can take fusion heat and use it directly to smelt iron or warm cities. And when the heat builds up, and thermal pollution of the earth becomes a serious problem, he can devise systems for radiating the excess heat out into space.

THE HEART OF THE MATTER



Schematic of a tokamak fusion reactor: A magnetic field generated by the field coils confines the plasma inside its vessel. A second field, generated by the primary windings, heats the plasma to 30,000,000 degrees C. Simple? So's the sun, which doesn't work as well.

Civilizations can, from one perspective that is perhaps not the most salutary, be defined by the amount of energy they use. In ancient times most of that energy came from organized muscle, in modern times from fossil fuels, but muscle or fossil, there has never been enough energy available to satisfy world-wide demand. Nor, one should note, has it ever been distributed with anything like equality among the civilizations and nations of the world, which is why Winston Churchill wept for joy when the Japanese attacked Pearl Harbor and the United States joined World War Two: because he knew what enormous resources we had, and therefore knew, on December 7, 1941, beyond any doubt, that the war was won.

We—the United States—are now the most avant-garde of civilizations, and that is not so satisfying a fact as it might seem to some, as it certainly seems to the physicists working on nuclear fusion. It might not be obvious at home, where the damned equipment is always breaking down, but it is obvious to anyone traveling abroad, and especially to anyone traveling in the Third World of Asia and Africa, that we live to a completely different set of expectations than do most of the people of the world, grown tall on our excess supplies of protein, carrying along our pocket calculators, our electric wrist watches, the mere outcroppings of a civilization that has banked everything not on the strength of its spirit but on the subtlety of its machines. Our hearts are run on batteries, we will soon have artificial kidneys sewn in and artificial eyes, and those are mere outcroppings, too. What kind of world will we face when we have no need of energy from anybody, not from the Arabs, not from the Russians, not even from the coal and oil buried under our own dark ground? When our cars run on hydrogen and produce, as waste, pure water; when we have no pollution because we've turned all our smokestacks off and dismantled our fission reactors and even, as we eventually will, make all our own raw materials by breaking up our wastes, with fusion heat, back into the elements from which they came and reconstituting them? When we carry computer terminals in our pockets or sewn into our skulls that connect us instantly to all the wisdom of all the libraries and data banks in the land? Will we be supermen then? Will we want to be? Will we look with more favor then upon the underprivileged of the world than we do today, which is hardly at all?

Will there come a time—won't there almost certainly come a time?—when the good news will blink across the continent from a smog-free L.A. to a quietly purring New York that the computers are ready to take us in, that if you want to you can program your brain into a data bank and enjoy a thousand times the sensory input your meager fleshly body provides, enjoy visions in the infrared and the ultraviolet as well as in the narrow visible spectrum of the human eye, share the vast wisdom stored in the machines, share the sensory range possible to all those exotic receptors, pleasure, like Krishna, 1000 shepherdesses simultaneously in the starlit night, not even know you aren't in a body, whichever body you want to be in that day, man or woman or child or somewhere in between, and possibly eagle and earthworm, too? But know that so long as you aren't accidentally erased you can live forever? Do you doubt that all but the most nostalgic of Americans, all but Euell Gibbons and David Brower and the Hillbilly of the Hillbilly Hills will be lining up eagerly outside the processing-room door?

And not only does the prospect seem likely but there is a real question, which the philosophers of doom—pollution doom and human-condition doom and overpopulation doom—haven't even thought about tackling yet, of whether at this late date we even have a choice left, of whether technology, like its predecessor, evolution, doesn't work to its own inexorable laws, and to have started down that road, as the world started long ago and as the United States has raced ahead like the messenger at Marathon, is to be condemned to follow it to its end. We Americans have followed it farther, curlicues awhirl, than any other nation in history, which ought to leave us wondering what the rest of the peoples of the world, the ones who still eke out a life of sorts on 1200 calories a day, are going to do about us, if indeed there's anything they can do, now that the nuclear weapons are made and counted and laid out in their long barrows scattered across the world. When Cortez rode into Tenochtitlán in his shining armor on his unbelievable horse, Montezuma already knew the show was over and gave up without a fight, though the fight came later and Cortez had to sack the beautiful city, starve its children to the ground, and perhaps the other peoples of the world know that, too, or else why are they scrambling to industrialize as fast as they can?

One of the beauties of fusion, one of the qualities that make its perfection a noble experiment, indeed, is that it can help everybody get there faster, if that is where they want to get, because it runs on the most common element on earth, mere hydrogen, mere water, the crystal liquid that flows down all the streams and rivers and oceans of the world, and will continue to flow until those waters dry up, which will not happen until the day the sun uses up the hydrogen in its core and begins to burn outward, expanding into a great colored giant of a star, enveloping the earth. And by then, one way or another, we will all be gone, pulses of energy wafting out toward the stars, like seeds or like viruses, depending on how you take us. That isn't a madman's ravings, nor even what is so condescendingly called science fiction by people who don't like to think about the destinations of the roads they so willingly travel on: That is as certain as the day long ago when the first halfman first picked up and hefted the levered bone. We are halfway there; fusion, controlled thermonuclear fusion, is about to carry us the rest of the way; the sun burns at the height of the sky; and the only question left worth asking is whether or not evolution is really over, the god having descended, as on the stage where Oedipus tore out his eyes, in the machine, a bizarre machine shaped like a doughnut, with magnets for hands and a heart so furiously heated that it gives forth no light at all.