Fusion for the Future

by Francis F. Chen

On the road to clean nuclear fusion

How will we survive the energy crisis? Not the one we face now because of the price of Arabian oil, but the one we will face 50 or 100 years from now, when there simply won't be enough fossil fuel to support the world's population. Only three "inexhaustible" energy sources seem capable of supplying a large part of our grandchildren's energy needs—nuclear fission with breeder reactors, solar power, and controlled nuclear fusion.

The plutonium breeder has run afoul of public sentiment; regardless of its technical merits, it is frightful to the layman. And even fission cycles not involving plutonium will need radioactive waste disposal schemes that many will find unacceptable. Solar energy will surely provide much of our needed heat. It could also supply electricity, but is not ideal for that purpose because of the need to store electricity and transport it from solar farms. The best bet for a compact, deployable source of electricity would seem to be nuclear fusion. In addition to the promise of limitless energy, fusion is relatively clean, compared to fission. And there is the possibility that advanced fusion reactors would pose no radiation hazards at all.

The fusion reaction, the ultimate source of solar energy, occurs when two atomic nuclei fuse to form one new nucleus, releasing energy in the process. The sun is a fusion reactor slowly converting hydrogen (with one proton in the nucleus) into helium (two protons in the nucleus) and releasing vast amounts of nuclear energy, a small fraction of which hits the Earth as radiation.

It is not easy to produce the same reaction on Earth. Hydrogen nuclei are positively charged and have a strong electrical distaste for one another. To overcome their mutual repulsion and fuse, the nuclei must be moving at high speeds. In other words, the hydrogen gas must be at a high temperature. The sun's core is at 20 million degrees (all temperatures mentioned are on the Kelvin scale), and the hot gas is held together by tremendous gravitational forces. At this temperature, a hydrogen nucleus will live for billions of years before it reacts.

To produce the reaction on Earth, we have first of all to hold the gas together—either with a magnetic field or by its own inertia. In inertial containment, the fuel is contained in pellets heated to the point of exploding by a laser or a beam of energetic particles. The back reaction from the outward explosion holds the fuel together for the short time necessary to accomplish a fusion reaction. In magnetic confinement, a strong magnetic field is used to keep the hot gas from touching any material walls.

If we are to reproduce the fusion reaction on Earth, we must also worry about time. We can't wait a billion years for hydrogen atoms to react, so we must speed the process up. This is done by increasing the temperature to 100 million degrees and by using heavy isotopes of hydrogen (isotopes are varieties of an element which have different numbers of neutrons in the nucleus; the number of protons remains constant). With these hydrogen isotopes—deuterium and tritium— the reaction proceeds rapidly. The confinement time needs to be only one second for densities used in magnetic fusion and one picosecond (10^{-12} seconds) at densities used in inertial fusion.

Holding the Plasma

Matter, at temperatures much above 10,000 degrees, becomes an electrified fluid in which all electrons have come loose from the atoms—a plasma. The electrical properties of a plasma are so baffling that it has taken 25 years to understand them. Plasmas will find very subtle ways to leak out of magnetic containers. Critics used to scoff at plasma physicists for their inability to control plasma. Politicians and utility executives would classify fusion with other pipedreams that could never become real. This is no longer so. The progress in understanding and controlling plasma has been steady for the last decade

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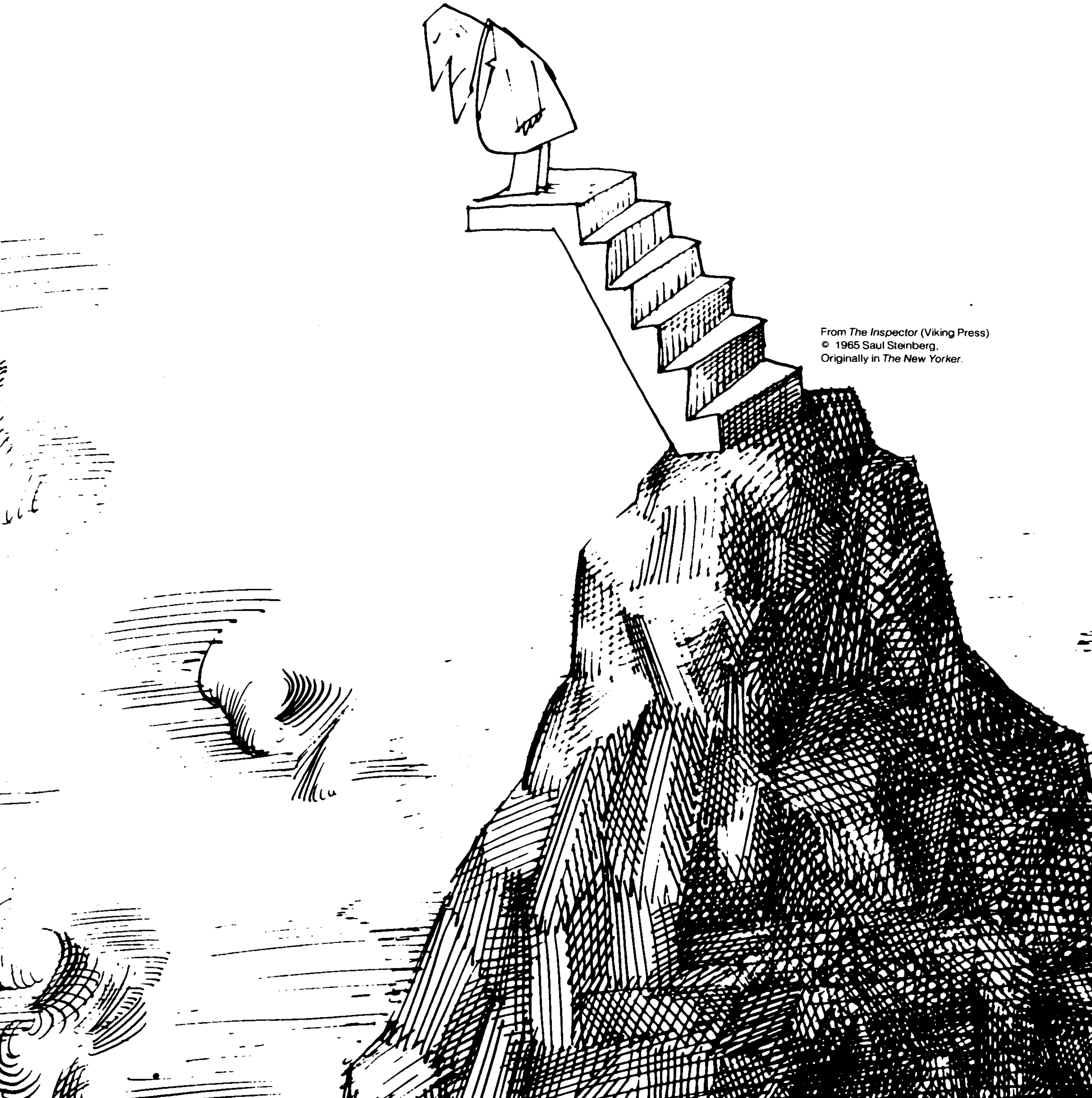
or two, and spectacular results have been reported within the last three years.

The most promising approach at present is the tokamak, and the world fusion effort is heavily weighted toward this single concept. In the tokamak, the plasma is contained in a metal vacuum chamber shaped like a fat doughnut. The magnetic field is produced by large, D-shaped, superconducting coils that pass through the hole in the doughnut. Other coils threading through the D-coils are needed to provide auxiliary fields in other directions and also to induce a current in the plasma, which adds yet another field. The complicated, twisting magnetic field shape that results is needed to hold the plasma in one place. The plasma is heated by the current produced by the magnetic field and by energetic beams of neutral atoms injected through ports in the vacuum chamber. Between this chamber and the coils lies a meter-thick "blanket" through which a coolant such as liquid lithium circulates.

The blanket serves several purposes: it absorbs the neutrons produced in the fusion reaction and



From *The Inspector* (Viking Press) © 1965 Saul Steinberg. Originally in *The New Yorker*.

converts their energy to heat; it provides a mechanism for carrying this heat away to where it can be used, eventually, in a conventional turbine; it shields the superconductors from the neutron flux. In addition, the neutrons react with lithium to breed the tritium used as fuel (deuterium occurs naturally in seawater). There are many engineering difficulties with the tokamak, but they are not insuperable. Nonetheless, fusion would be a lot cleaner if it were not for the tritium and the neutrons.

Radioactive Hazards

In the deuterium-tritium reaction, deuterium and tritium fuse to form helium and an excess neutron. Tritium is radioactive, and its presence is inescapable in this fuel cycle. To breed it requires large facilities for separating it from the lithium in the blanket and from the unburned plasma. Elaborate procedures are needed to prevent accidental or routine escape of tritium into the environment. The neutrons are also unavoidable, for they carry 80 percent of the energy produced in the reaction. An intense flux of energetic neutrons bombards the walls of the plasma chamber and the supporting structure of the blanket. Materials weaken under this bombardment and must be replaced periodically. At the end of their useful life, the structural materials are highly radioactive and must be properly disposed of. The neutrons, therefore, not only limit the life of any component close to the reacting plasma but also create the problem of radioactive waste disposal.

One should not misunderstand: fusion is still much safer than fission from the standpoints of radioactive waste disposal and possible accidental release hazard. This is partly because the fusion reaction itself does not create radioactive waste products; what waste there is comes only from the neutron activation of the solid structure of the reactor vessel. And it is partly because tritium does not accumulate in the human body, as do elements like strontium; rather, it passes rapidly through the body in the form of tritiated water.

All told, the radiological problems of fusion are roughly ten to a thousand times less severe than those of fission, though an exact figure cannot be given because different substances are being compared. Nonetheless, it would be desirable to eliminate radioactivity altogether. What would it take to do this?

Getting Rid of the Neutrons

Astrophysicists have long known reactions among the light elements that do not involve neutrons or tritium, but a number of these reactions are not feasible for fusion reactors for one reason or another. There is, however, a chain reaction that could work in which the plasma is a mixture of plain hydrogen and lithium-6 (an ~~heavy~~ isotope of lithium). There are several steps in the reaction, but the intermediate products are safe and non-radioactive. Of these, helium-3 can react with the lithium to produce more hydrogen, thus sustaining the reaction. Not recycled are helium-4 nuclei, or alpha particles, which are very stable. Robert W. Conn of the University of Wisconsin has recently calculated that this chain could be self-sustaining if the plasma confinement were only slightly better than that contemplated for deuterium-tritium burning tokamaks.

Is this, then, the nirvana that energy researchers have long sought? Not quite. This advanced fuel cycle requires (as would others like it) temperatures in the billions of degrees, as contrasted with the mere 100 million degrees needed for deuterium and tritium. We must not only produce a plasma about 30 times hotter, but also confine it equally well or better. Second, there is the problem of synchrotron radiation. Electrons gyrating in a magnetic field emit increasing amounts of radiation as the temperature is raised; this energy loss cools the plasma. The only possible remedy is to eliminate—or greatly reduce—the magnetic field upon which synchrotron radiation depends. To confine plasma, a magnetic field must be applied to its edges, but it need not pervade the interior as it does in the tokamak. This is the essence of the SURMAC (SURface MAgnetic Confinement) idea proposed by Alfred Y. Wong of the University of California, Los Angeles. As the size of a reacting plasma is made bigger, the energy production increases with the volume, while the synchrotron losses increase only with the surface area.

A practical way to realize an advanced-fuel reactor has been suggested by John M. Dawson, also of UCLA, using a *toroidal octopole.* A toroidal octopole can be envisioned by imagining a doughnut-shaped vacuum tank, similar to the tokamak. The interior of the doughnut—not the hole, but the interior of the tube itself—holds four rings, in effect very thin doughnuts enclosed in the tube of the larger doughnut. Each ring contains superconducting wires carrying several million amperes of current.

Levitating Rings

These currents, which are in the same direction in each ring, serve two purposes: they produce the plasma-confining magnetic field, and levitate the rings so that they float in the air, so to speak. In this system, the plasma is within a magnetic field that contains it as a material tank would.

Levitation of large superconducting rings is not a feat of black magic; it has been done in at least three laboratories. The force of the ring current acting on an externally applied magnetic field easily supports the ring against gravity, and the position of the ring can be stabilized by feedback controls. As long as they are kept at liquid helium temperature, about four degrees above absolute zero, superconductors will maintain their current almost indefinitely after the power source has been removed. Indeed, rings have been floated for days or weeks at a time in fusion laboratories.

The problem with using an octopole for a conventional deuterium-tritium reactor is that the neutrons cannot be stopped from striking the superconductor and heating it above the point at which normal conductivity takes over and causes the current to decay. In an advanced-fuel reactor, however, almost no neutrons would be produced which could heat the superconductor. At the same time, floating-ring machines may provide the good confinement properties required to burn advanced fuels. Behind this statement lie many years' experimentation on octopoles at the University of Wisconsin and at General Atomics of La Jolla, California, under the supervision of the octopole's inventors, Donald W. Kerst and Tihiro Ohkawa. There is thus a fortunate symbiosis between floating-ring devices and neutronless fuels—one cannot work without the other.

A neutronless fusion reactor with floating rings at four degrees above absolute zero in close proximity to a plasma at three billion degrees sounds like a wild idea, but there is no known technical reason for rejecting it. Such a reactor would almost surely be a second- or third-generation device. There is much to be learned before we can attempt a serious design. The behavior of burning plasmas would have to be studied in near-term test reactors—probably tokamaks—using conventional fuel. The confinement properties of octopoles or surmacs would have to be tested under conditions of high temperature and density. Methods have to be developed to heat plasmas to 20 or 30 times the temperatures achieved to date. The properties of materials exposed to this environment need to be studied. And so on. The list is long, but the allure of a perfectly safe reactor with no fuel problems warrants undertaking this latest technical challenge.

The Rings

Consider the construction of floating rings designed for intermittent operation. Starting at the center of their cross section, they will have superconducting windings of niobium-titanium or niobium-tin, twisted with copper and immersed in liquid helium; then a layer of crinkled foil superinsulation; then a heat-absorbing material, such as lithium, which would melt during operation; then a layer of high-temperature insulation; then a refractory vacuum jacket made of something like tungsten or molybdenum, which would glow from bombardment by plasma particles and radiation; and finally a "first wall" of a low-atomic-number material such as carbon to minimize the impurities sputtered into the plasma. Such a ring could be made to float in a plasma for about two days before the liquid helium needed to be recooled. If liquid helium could be piped in and out through small tubes passing through but magnetically shielded from the plasma, the rings could be made to float indefinitely. The rings being 50 to 100 centimeters in cross-sectional diameter, it is even conceivable that a refrigerator could be built into each ring to keep the liquid helium cool. The refrigerator would be driven by the thermal gradient between the plasma-facing side and the wall-facing side, and the excess heat would be radiated away by the hot surface.

At present the most successful means of heating the plasma is to inject beams of energetic neutral atoms, which are able to penetrate through the magnetic field. To reach three billion degree temperatures, one would have to use one-megavolt (one million volt) beams of neutral atoms, something which would be extremely hard to develop. In a surmac, however, one could conceive of using beams of *charged ions*, which are relatively easy to produce, and to inject them through a magnetic gate that would close after each pulse.

A neutronless reactor would be quite a novel concept, for almost all the energy would be produced in the form of x-rays. (The x-rays would be of low energy and not pose a safety problem.) In both fossil fuel plants and fission reactors, the energy is delivered in the form of heat. Because the operating temperature is limited by materials, the efficiency with which this heat can be converted to electricity is held to about 40 percent. If energy is delivered in x-rays, however, one could conceive of absorbing them in a high-atomic-number gas like xenon, or in a high-atomic-number metal suspended in a gas, in such a way that the flowing gas is at a higher temperature than the walls could stand.

A scheme proposed by Abraham Hertzberg of the University of Washington would convert this heat to rotary motion with an efficiency much higher than achievable in a conventional thermal cycle. This would lessen the environmental impact of the power plant in the area of waste heat.

Is all this an idle pipedream that will never come true? Perhaps so, but no one has proved it yet. Until this happens, it is important to recognize that nuclear fusion not only could provide us with relatively safe, inexhaustible energy in the form of deuterium-tritium reactors around the year 2030, but also holds the promise for completely safe advanced fuel reactors in the more distant future. At UCLA, physicists cannot easily forget the words of Michael Faraday, which greet them on the way to classes: "Nothing is too wonderful to be true." □