Fusion Research (III): New Interest in Fusion-Assisted Breeders

Compared with other energy technologies, perhaps the only undisputed advantage of fusion is that it could eliminate fissionable materials from a civilian power economy. A fusion reactor does not require any of the special nuclear materials that could possibly be diverted for the production of weapons or cause runaway reactions in fission reactors. It would seem crucial to the interests of the fusion program to keep it that way because other potential advantages of fusion are less certain. It will not necessarily be as clean, cheap, or safe as many have come to expect and fusion reactors certainly will not be simple devices (*Science*, 25 June and 2 July).

Now, although it may seem incomprehensible to the substantial body of people who regard weapons proliferation as the greatest danger of nuclear power, the federal programs for both laser and magnetic fusion are entertaining the possibility that their first reactors will be half fusion and half fission. What that means is a fusion reactor nested inside a hollow fission reactor, something like a box within a box, so that the plentiful neutrons produced in the inner part can be used to breed fissile material such as plutonium and produce power by fission in the outer part. The idea is already firmly enough rooted in the lexicon of fusion research to have changed reactor nomenclature. What used to be fusion is now called pure fusion, and the centaur-like concept of fission-fusion is called a hybrid.

Not a few people are distressed by the idea that a hybrid reactor could become the goal of the American fusion program. A large endeavor to develop a hybrid reactor would be a "great loss . . . if this occurred at the expense of the really basic research necessary to determine whether controlled fusion reactors are indeed feasible," according to Louis Rosen, director of the Los Alamos Meson Physics Facility and one of the first researchers to measure the basic reaction of fusion. According to Clinton Ashworth, senior technical adviser for the Pacific Gas and Electric Company, the hybrid reactor "could be a very costly diversion of time and money" and its development should perhaps be "left largely in the hands of other nations."

The assessment of many observers is that the hybrid would be subject to all the complexities of fusion along with all the problems of fission—some in a more virulent form. There may be some clever ways to approach the design, but if the two halves of a hybrid were grafted together in the most straightforward manner, the result would—in the opinion of many researchers—be a reactor with the worst aspects of both technologies.

Hybrid reactor development is not an official goal of either the laser or the magnetic fusion program of the Energy Research and Development Administration (ERDA), but it is an idea that has received increasing support. In 1975, ERDA published a 382-page report* assessing hybrid fusion schemes for the first time, and approximately 20 to 30 researchers are working on the subject at least part time. The magnetic fusion division of ERDA is spending $700,000 for engineering studies of hybrid reactor designs this year, and classifies the hybrid as an optional goal that must be studied further to determine whether it is a desirable goal or not.

The role of hybrid concepts in the laser fusion program is harder to judge because the primary goal of that program is not the production of power in any form, but the study of "nuclear explosive effects in the laboratory." Nevertheless, the proponents of laser fusion strongly emphasize the advantages of hybrid reactors, and the Lawrence Livermore Laboratory of ERDA, together with the Bechtel Corporation, has undertaken a major study to conceptually design a laser fusion hybrid and compare it to various proposals for a hybrid based on a magnetic confinement device. Finally, the importance of hybrid concepts may be measured by the fact that the first international conference on the subject, the Joint U.S.-U.S.S.R. Symposium on Fusion-Fission Hybrid Reactors, was held at Livermore 13 to 16 July.

A Fallback Program?

If hybrid reactors run the risk of contaminating fusion with the dangers of special nuclear materials and hobbling fission with technical uncertainties of fusion, why are they being considered at all? One inescapable conclusion is that various hybrid concepts are being readied to serve as a fallback in case the task of pure fusion proves to be too formidable.

What the hybrid concept buys in technical terms is a considerable relaxation of the plasma conditions needed for a pure fusion reactor. In magnetic systems, this means that the plasma temperature may be halved and the requirement for plasma confinement reduced. In laser systems, it means that the power needed in the laser beam may be greatly reduced. In other words, a fusion concept which would be only marginally successful by itself might be salvaged by making it the fusion core of a hybrid reactor. In terms of energy consumption, present studies show that it would not even be necessary for a fusion concept to reach the break-even point—at which the energy produced by a fusion reactor would equal the energy required to drive it—to be viable as a hybrid. If a device produced only half as much energy in the form of fusion neutrons as it consumed, it could function as the core of a hybrid reactor. Each 14-Mev fusion neutron could initiate a 200-Mev fission event in the outer blanket of the reactor, and studies show that this would effectively multiply the energy of the fusion device by a factor between 5 and 40.

There appear to be a number of fusion concepts that, with further intensive development, could approach the point of energy break-even in the 1980's, but which for various reasons may not be able to achieve the additional improvement needed for a fusion power station. For technical reasons the mirror machine may not achieve an energy balance much better than break-even because a great deal of plasma leaks out of the ends of the magnetic confinement region. Tokamaks seem capable of improved energy gain, but tokamak reactors appear likely to be very large and costly, so it may not be desirable to build a tokamak that performs much better than energy break-even. The lasers suitable for laser fusion are so gravely inefficient that the laser method presently needs every energy-boosting idea that might be applicable. Thus the hybrid concept can be applied to all the major projects in the U.S. fusion program without major changes in the present research strategy. For any concept that falters, the addition of a fission blanket could be a lifesaver.

If none of the presently favored concepts reach or exceed break-even by an appreciable margin, the hybrid concept

*DCTR *Fusion-Fission Energy Systems Review Meeting* (ERDA-4), edited by S. Locke Bogart. The volume is the proceedings of a 2-day meeting held at ERDA headquarters, Germantown, Maryland, 3 and 4 December 1974.

could keep the entire fusion program afloat. A number of observers of the Soviet fusion program conclude that a decision has been made to forgo pure fusion reactor development at this time. The biggest planned Soviet fusion experiment, the T-20 tokamak expected to cost over $1 billion, is being designed as a hybrid reactor according to reports received during the last year. There are apparently no environmental objections to such a move in the Soviet Union.

Alternatively, if fusion develops more slowly than other advanced energy technologies, it can be argued that the hybrid concept will offer an opportunity for fusion to make an energy contribution at an early date. If results from experiments now being constructed turned out to be favorable and detailed hybrid engineering designs were completed, the fusion community could perhaps argue 5 years from now that it had the scientific and technical underpinnings to go ahead with a hybrid reactor. This time frame is particularly relevant for the ERDA fusion program because the program may have only a rather narrow time window in which hybrid proposals are viable. The first fast breeder demonstration reactor—which a hybrid reactor would resemble in many respects—is due to begin operation about 1985. If it proves technically successful and reasonably safe, there might appear to be very little point to the expensive development of a fusion hybrid. Of course, if the breeder is only partly successful or fails, energy planners might opt for the hybrid as a backup or a replacement.

The hybrid seems to offer two potential technical advantages over the operating characteristics of a fast breeder reactor. The initial studies have shown that the capacity of a hybrid to produce fissile fuel from either uranium or thorium would be approximately an order of magnitude greater than that of a fast breeder reactor. In one of the most detailed hybrid studies to date, employing the mirror machine as the fusion device, it was found that a hybrid reactor could produce 3000 kg of plutonium per year and also produce 1000 Mw of electricity. The plutonium would be enough to fuel about five light water reactors, according to Ralph Moir and his associates at Lawrence Livermore Laboratory. It would represent a fuel doubling time as short as several years, which would be a considerable improvement over the doubling times of 12 to 50 years estimated for fast breeders. The cost of plutonium from the mirror hybrid design was estimated to be about $30 per gram.

The reason that fusion machines can be such powerful breeders is that they produce a very intense flux of neutrons, and the very fast 14-Mev neutrons are quite effective for breeding. When the fission process is initiated by the 1-Mev neutrons produced in a fast reactor, each fission event produces about two neutrons. But when initiated by 14-Mev neutrons, each fission event will produce about four neutrons and thus many more neutrons are available in the reactor for breeding. As an indication of how submarginal the fusion part of a hybrid may be, the mirror in the Livermore design produces only six-tenths as much power as it consumes. But it produces 10^{14} fusion neutrons per square centimeter per second and they increase their number severalfold before they slow down for breeding.

The second potential technical advantage of a hybrid reactor is that the fission blanket could be operated in a mode that was subcritical. If the blanket were designed in such a fashion, the possibility of a nuclear reactivity accident (runaway) would be precluded. Much more detailed engineering designs than those prepared so far will be needed to determine whether a subcritical fission blanket is feasible.

The balance between power production and fuel production in a fission-fusion reactor can be continuously varied by controlling the reactions that occur in the blanket. Designs that produce fuel but do not produce electricity or allow an appreciable amount of fission to occur are called symbionts, or sometimes electric breeders. They may offer certain advantages over other designs, but preliminary studies show that the cost of electricity alone for a symbiont would be so great as to render the price of fissile material exorbitant.

Fusion hybrids could be very attractive to the utility industry in case uranium supplies ran short before fast breeders were available, or in case the breeding rate was insufficient to keep up with demand. The utility industry needs to be sure it can write off its nonbreeder reactors over the next 30 years or more, and also tends to want well-proved technology. The idea of a complex, expensive, and possibly very unreliable fusion reactor as a base load plant for generating electricity is not an appealing one for many utility executives. They would much prefer that the first fusion plants be off-line, producing fuel for use in well-tested reactors. At best, according to Michael Lotker at Northeast Utilities in Hartford, Connecticut, if hybrids were implemented the electricity companies would like to see the complex hybrid technology operated by a separate industry that would produce fissile fuel and then sell it to the utilities. Thus the hybrid technology could be a bridge from a fission electric economy to a fusion electric economy at a much later time, in Lotker's view.

The Electric Power Research Institute (EPRI), which is now the centralized research arm for the utilities, is already funding studies to determine what the advantages and disadvantages of hybrids might be and how soon the country is likely to need them. More concretely, the EPRI fusion program is planning to build several fission modules to test on the Soviet T-20 hybrid experiment. The modules, about 1 m thick and several meters in area, would be designed by EPRI so that they would fit into the structure of the T-20 and be tested. Some modules would test neutron absorption characteristics, and at least one would be designed to breed plutonium and tritium (which any fusion reactor must produce from lithium to refuel itself). The power distribution in the module would be measured, and fission energy extracted with a coolant, as in a reactor. Details of the proposed joint program between EPRI and the Kurchatov Institute in Moscow are not complete, but it would allow the Soviets to benefit from American nuclear expertise, since the detailed design and construction of the modules would be contracted to a major U.S. nuclear supplier, and would give American researchers some firsthand experience in evaluating hybrids at an early date.

An Awkward Fission Reactor

If a hybrid reactor generates the bulk of its power by fission reactions, then it will look to the outside world to be a fission reactor. A hybrid that strongly multiplies the energy of the fusion core will be a "big, ungainly, expensive fission reactor," according to Lawrence Lidsky at MIT, so "it is unlikely that the advantages of 14 Mev neutron drive will make up for all the disadvantages."

The geometry of a fusion machine is hardly one that a fission reactor designer would choose. The blanket for a mirror or laser fusion machine is spherical, and for the tokamak it must be a torus. Fuel handling in such a complex geometry would be extremely difficult, because fuel pins (as many as 10^5 in one design) would have to be extracted from many different points, and there would be little or no space for fuel-handling machinery, especially in magnetic fusion schemes where the blanket is fitted close inside the magnets. Many researchers also think that the hybrid would be more susceptible to loss-of-coolant accidents than standard fission reactors, because the fission blanket would be much more complex, with a hollow void in the center and many holes necessary for access to the inner fusion reactor. Furthermore, a fusion device necessarily includes a great deal of delicate instrumentation that may not be compatible with the strong pressure vessels needed for fission.

"Although it is very difficult to prove an engineering impossibility, the additional constraints put on a fission reactor by posing the requirement that it contain a fusion machine are likely to be insurmountable," says Lidsky, who proposed one of the early fission-fusion designs in 1969. He thinks that there may be a few fission-fusion combinations that make sense—notably those that minimize the number of fission reactions in the breeding blanket—but the problem is far from solved.

The costs of several variations of a mirror hybrid plant studied at Livermore were estimated to be in the range of $2000 to $3000 per kilowatt of electrical capacity, but it is not clear what these numbers should be compared to. Most researchers conclude that because of its complexity a pure fusion reactor would cost more than a fast breeder, and a hybrid—because its core alone would closely resemble a fusion reactor—would cost more than pure fusion. If it could be made to work, the hybrid would surely be an expensive device, and one must ask, according to John Holdren at the University of California at Berkeley, whether the advantages of relaxing the plasma confinement requirements will not be offset by the added difficulties of cramming fission technology into the awkward geometry dictated by the requirements of the fusion core. Laser fusion concepts may offer some relief in this regard, because the most fragile part of the fusion technology—the laser itself—could plausibly be separated from the fission system.

If the goal is simply to build a fuel factor which is an alternative to the fast breeder reactor, one must ask whether it is desirable to employ fusion at all.

The Canadian government has turned to a process that uses known accelerator technology and relatively simple physics to produce neutrons for breeding—something called a spallation source. The process takes advantage of the fact that when high energy protons collide with heavy elements very many neutrons are produced—as many as 50 from each collision. Just like the neutrons from fusion, these neutrons could breed fissile material. An intense beam from a 1-billion-electron-volt (Gev) accelerator would strike a large target assembly composed of fuel rods and coolant, much like a fast reactor. Each impact would produce considerably more energy in the target than the energy of the particle, so much of the energy needed by the accelerator could be recovered and recycled. The rest would be drawn from the power grid or from nearby fission reactors if the "electric breeding accelerator station," as the Canadians call it, were located in a nuclear park.

In any of the hybrid schemes the characteristics of the reactor that consumes the fuel will have an impact on the desirability of the system, and the use of a spallation source as a breeder seems particularly suited for the Canadian reactor system. If the Canadian heavy water reactor, the Candu, were operated on a thorium-uranium cycle rather than the uranium-plutonium cycle now used, it would come close to being a breeder reactor. Specifically, during the time one fuel rod stays in the reactor, 92 atoms of uranium-233 would be bred while 100 atoms were burned. Thus, if Canada had a large fuel reprocessing system working in the 1980's or 1990's, it could recover most of the new fuel it needed from the spent fuel rods of the Candu reactors, and a spallation electric breeder could make up the rest.

An Alternative Electric Breeder

If a spallation accelerator were developed that could produce a 300-milliampere proton beam, it could breed enough fuel to supply a dozen 1000-Mw reactors, according to P. R. Tunnicliffe at the Chalk River Nuclear Laboratories of the Atomic Energy of Canada Limited. The fissile production of the system would be about 1000 kg per year. Tunnicliffe estimates that a 300-milliampere accelerator would be the economic size and it would be large. The accelerator beam power would be 300 Mw and the thermal power deposited in the target would be 1200 Mw. Thus the target would be about as large as a medium-sized reactor. If the spallation breeder and its associated reactors are considered as one system, about 2 percent of the electrical power would be needed to run the accelerator.

The Canadian researchers are hesitant to quote costs for the spallation breeder system. "We believe we are in a region where a feasible technology offers plausibly acceptable costs in the long term (25 to 30 years)," says Tunnicliffe. The cost of the accelerator alone was estimated in the mid-1960's to be about $70 million and would probably be more than $250 million now. The cost of the target might be $400 million at present prices. More relevant is the price to which uranium ore will have to rise before the Canadian breeding alternative is economically competitive, and "at the way uranium costs are going it won't be too long before we're in business," says Tunnicliffe. Others estimate the process might be viable when uranium reaches $150 per pound.

The spallation breeding concept faces a number of technical obstacles. The existing accelerator beams must be boosted from currents of 1 milliampere to 300 milliamperes. The spallation target will have to be operated at high power densities and the neutrons produced by spallation would cause almost as much radiation damage as those from fusion. But the problems of spallation seem to be more those requiring the extrapolation of existing technology than do the problems of fusion. The spallation effort at Chalk River is a relatively small project, supported at about $500,000 per year, and other research supported by the National Research Council in Ottawa is studying laser fusion for breeding. More study is needed to ascertain whether spallation will prove feasible as an alternative breeding method.

On the other hand, if breeding alone is the goal of a fusion program, different plasma criteria must be emphasized and perhaps different types of fusion machines could prove to be the best choices for breeders. The most important parameter for a power reactor is energy gain, but the crucial parameter for a fusion breeder tends to be the power density (and hence the neutron density). Tokamaks, which receive 65 percent of the support in the ERDA magnetic fusion program, tend to have very low power densities, might be the least attractive choice for a hybrid core, according to a number of fusion engineers.

The Canadian spallation program is one alternative technology that may prove successful for breeding and there may be others. If energy planners abandon pure fusion and adopt the goal of producing fissile materials, they should assess all the possibilities. There may be cheaper and simpler ways to develop an alternative breeding capability than pursuing the long and arduous program aimed at controlling thermonuclear fusion.—WILLIAM D. METZ