ENERGY

Fusion Power: Will It Ever Come?

Prospects for practical applications of fusion power to solve our energy problems appear dubious on engineering grounds.

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In the early 1950s, the hydrogen bomb wakened public awareness to the explosive power of nuclear fusion and launched hope in the physics community to use fusion as a power source. Fission made the trip to utility reasonably quickly, and now, 14% of the world's electricity is produced in that way. But although practical, controlled energy release from fission followed the discovery of that process by only 3 years, fusion power is still a dream-in-waiting. The explaination has more to do with engineering than with physics.

Two achievements are essential to produce electricity from a primary fuel: attaining the temperature needed to convert the source into heat and extracting the heat from the reacting region. In a nuclear fission reactor, uranium-235 can undergo the chain reaction with neutrons of ordinary temperature, and heat can be extracted directly by coolant circulated through the reactor. The scheme is compact, and it is cheap enough to compete with combustion plants.

There is no shortage of pairs of isotopes of light elements that can be made to fuse, but a potential energy barrier must be exceeded by the energy of collision. The combination requiring the least energy is D-T (deuterium-tritium). It requires a stable, long-lived plasma of reasonably high density with a temperature of about 100,000,000 K, but many efforts have failed to reach these conditions for a net power-producing plasma. The other plausible candidate (D-D) requires a temperature five times as high with no feasible means of heat removal.

Heat removal is troublesome even with the D-T reaction. A large amount of energy (17.4 MeV) is released from each fusion. Although 14 MeV is carried away by a neutron—to be slowed and absorbed in a blanket containing lithium and thus "breed" more tritium—the energy released will make everything radioactive out to the radiation shield beyond the blanket. Worse, the material of the reactor vessel will undergo radiation damage, which alters its physical properties. Any material used for the reactor vacuum vessel will become increasingly brittle. Back in the 1970s, design studies indicated that the vessel would need periodic replacement (*1–3*).

Another operational problem entails maintenance of vacuum integrity. The reactor vessel will have to approach much as 20 m in its major dimension and would need many connections to heat transfer and auxiliary systems. It must operate at very high temperatures and undergo stresses from thermal cycling. Vacuum leaks would be inevitable and problem-solving would require remotely controlled equipment (*4*).

During the 1970s, projects in the United States, the United Kingdom, and Japan worked on conceptual full-scale fusion plant designs. Cost for the UWMAK-III design from the University of Wisconsin was estimated by the Bechtel Corporation to be between four and six times those of coal-fueled and nuclear plants of the period (*5*, *6*).

Although the importance of reducing reactor dimensions was well recognized, recent work has focused on trying to achieve the necessary conditions in the plasma. In 1991, a team in California designed a plant with an output of 1000 megawatt-electric (MWe), comparable to modern nuclear power stations. The result, ARIES-I, was based partly on technologies yet to be developed (*7*). The reactor vessel was 17 m in its major dimension, fabricated from a silicon carbide composite. It operated at 650°C and benefited from an imagined average heat transfer rate of 1.2 MW/m^2—six times the design rate for reactors that use helium coolants and twice that of pressurized water reactors.

Finally, the construction cost for any future fusion plant can be estimated by examining the blanket-shield component. Its area equals that of the vessel, so that its thickness is determined simply by choosing an average heat transfer rate. A 1000 MWe plant requires a thermal power of about 3000 MW, 20% of which must be absorbed by the vessel wall. If we assume an average heat transfer rate of 0.3 MW/m^2, the vessel wall and blanket-shield each must have an area of 2000 m^2. To absorb the 14 MeV neutrons and to shield against the radiation produced requires a blanket-shield thickness of ~1.7 m of expensive materials. This is a volume of 3400 m^3, which, at an average density of about 3 g/cm^3, would weigh 10,000 metric tons. A conservative cost would be ~$180/kg, for a total blanket-shield cost of $1.8 billion. This amounts to $1800/kWe of rated capacity—more than nuclear fission reactor plants cost today (*8*). This does not include the vacuum vessel, magnetic field windings with their associated cryogenic system, and other systems for vacuum pumping, plasma heating, fueling, "ash" removal, and hydrogen isotope separation. Helium compressors, primary heat exchangers, and power conversion components would have to be housed outside of the steel containment building—required to prevent escape of radioactive tritium in the event of an accident. It will be at least twice the diameter of those common in nuclear plants because of the size of the fusion reactor.

Scaling of the construction costs from the Bechtel estimates suggests a total plant cost on the order of $15 billion, or $15,000/kWe of plant rating. At a plant factor of 0.8 and total annual charges of 17% against the capital investment, these capital charges alone would contribute 36 cents to the cost of generating each kilowatt hour. This is far outside the competitive price range.

The history of this dream is as expensive as it is discouraging. Over the past half-century, fusion appropriations in the U.S. federal budget alone have run at about a quarter-billion dollars a year. Lobbying by some members of the physics community has resulted in a concentration of work at a few major projects—the Tokamak Fusion Test Reactor at Princeton, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, and the International Thermonuclear Experimental Reactor (ITER), the multinational facility now scheduled to be constructed in France after prolonged negotiation. NIF is years behind schedule and greatly over budget; it has poor political prospects, and the requirement for waiting between laser shots makes it a doubtful source for reliable power. ITER was born in 1987, but no dirt has been dug, and U.S. membership is temporarily in moratorium.

New physics knowledge will emerge from this work. But its appeal to the U.S. Congress and the public has been based largely on its potential as a carbon-sparing technology. Even if a practical means of generating a sustained, net power-producing fusion reaction were found, prospects of excessive plant cost per unit of electric output, requirement for reactor vessel replacement, and need for remote maintenance for ensuring vessel vacuum integrity lie ahead. What executive would invest in a fusion power plant if faced with any one of these obstacles? It's time to sell fusion for physics, not power.

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References and Notes

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10.1126/science.1125657