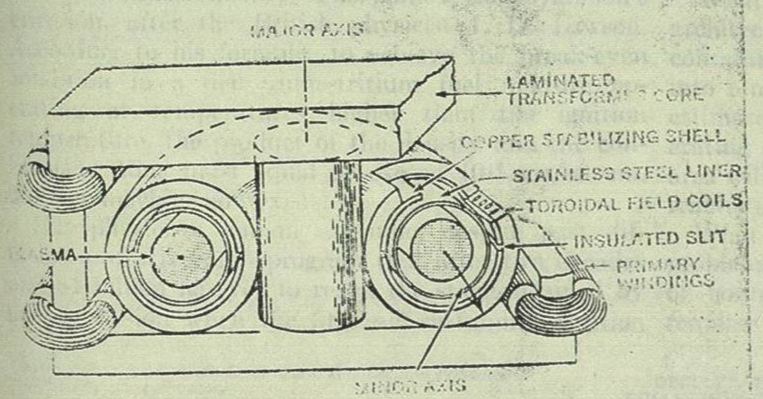
by compression. Containment has been achieved, but there are some enhanced losses, which would be a little too large for a reactor. In the second method, careful slow injections, utilizing plasma accumulated over many seconds, can control both direction of particle motion and energy spread. By such means, it is hoped that the causes of enhanced losses can be identified and perhaps eliminated.

Tokamak. This is a medium-density plasma container of the toroidal type. It represents a qualitative jump in our knowledge and skill in containing the maddeningly complex plasma long enough to achieve a fusion reaction. This machine, developed by the Russians a couple of years ago, has heated plasma to 10 million K while maintaining densities of 30,000 billion particles per cubic centimeter for 1/50th of a second, the closest approach yet to a fusion reaction. The Soviet claim met with some skepticism, since plasma measurements are notoriously difficult to make and interpret. A British team, however, from Culham Laboratory, confirmed that the temperature was indeed at the level claimed by the Soviets [11].

Tokamak also differs from earlier U. S.–built toroids called Stellerators in that it is axially symmetric, closer to the ideal doughnut shape of a torus. Raising the temperature of Tokamak plasmas to thermonuclear values appears to be a problem, however, which the Russians believe can be overcome solely by larger versions. U. S. physicists, while not agreeing that scaling-up the size of the Tokamak device will in itself achieve the desired fusion reactions, believe the Tokamak configuration is promising. One Tokamak has been built at the Princeton Plasma Laboratory and has been in operation since May, 1970. Another will go into operation at Oak Ridge by the end of this year and two more will shortly come into operation at the University of Texas and at M. I. T. New Princeton results indicate that superiority of Tokamak over U. S. configurations may simply be that Tokamaks are larger [5].

Tokamak, U. S. style. This is a toroidal plasma confinement device and has been in operation at the Plasma Physics Laboratory at Princeton, N. J., since May, 1970. A cutaway cross section of the Tokamak configuration is shown above.



Courtesy of Princeton's Plasma Physics Laboratory

A Light Approach

Another great leap forward in fusion technology within the last few years has involved the introduction of lasers for generating and heating plasma. In addition to being easier to analyze than cyclotron- or neon-tube-generated plasmas, laser-generated plasmas are hotter, denser, and purer; laser beams cross magnetic fields, without disturbing them, so that plasma production is achieved quickly and completely without leftover neutral debris. A frozen pellet of hydrogen or one of its isotopes is instantly vaporized and completely ionized by a powerful laser pulse lasting less than a billionth of a second; the pulse must be that fast to deposit energy in freely expanding plasma before it becomes transparent to the laser beam. Dr. Moshe Lubin of the University of Rochester suggests that extremely rapid lasers could confine plasmas as well as generate and heat them, obviating entirely the need for magnetic fields with their instabilities and losses [12]. He proposes an inertial confinement device in which a pellet of deuterium and tritium, dropped near a blanket of lithium, would be vaporized in picoseconds by an ultra-short, ultra-strong laser pulse. The resulting fusion would produce neutrons that bombard the lithium blanket, generating tritium atoms which could be cycled back into the reactor to sustain a closed-loop reaction. Although present-generation lasers are neither fast enough nor powerful enough to initiate such a reaction, they have already generated very small amounts of fusion reactions [12].

The Fusion-Power Balance

What are the fundamental requirements for a meaningful release of fusion energy in a reactor? Eastlund and Gough, AEC scientists and proponents of the "fusion torch," a device for converting any substance, including garbage, back to its constituent elemental atoms, state them as follows:

First, the plasma must be hot enough for the production of fusion energy to exceed the energy loss due to radiation resulting from near-collisions between electrons and nuclei in the plasma. This is called bremsstrahlung radiation. The temperature at which this transition occurs is the ignition temperature, previously referred to. A fuel cycle based on fusion reactions between deuterium and tritium nuclei is the easiest to ignite because it has the lowest ignition temperature (about 40 million C); hence it has the lowest rate of energy loss by radiation of any possible fusion fuel.

Second, the plasma must be confined long enough to release a significant net output of energy.

Third, the energy must be recovered in a useful form.

Today, they report, a large number of different devices have either achieved the deuterium tritium ignition temperature or come close to it. The main difficulties—energy-loss processes involving impurity atoms entering the plasma from the walls of the container—have been solved by a large research effort in vacuum and surface technology [13].

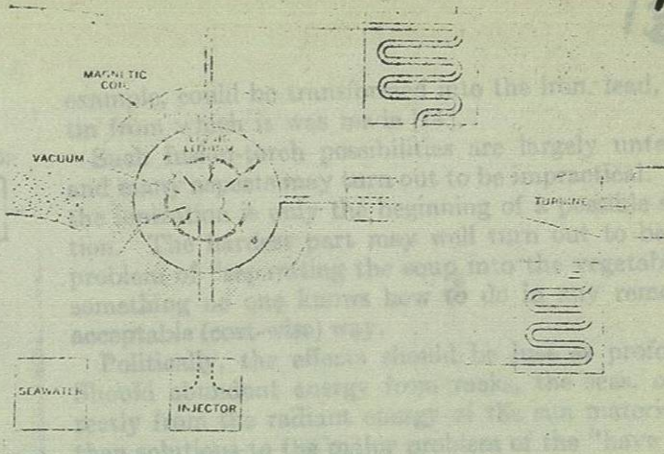
As for confining the plasma long enough to release a significant net amount of energy, Eastlund and Gough report that large containment devices have reduced the plasma instabilities responsible for large-scale plasma leakages to such low amplitude that other, more subtle effects, such as convective plasma losses and magnetic-field imperfections, can now be studied. Such studies have convinced physicists that there exists no basic law of physics that prevents plasma confinement for times long enough to release significant net fusion energy. In fact, "classical" or ideal plasma confinement has been achieved in several machines at low temperatures, a condition which, if extrapolated to fusion temperatures, would yield a plasma loss rate much lower than that required for a fusion reactor.

Lawson's Criterion

The twin achievements of ignition temperature and adequate confinement time have not, however, produced a sustained fusion reaction. Reason: Each of these achievements was produced in machines designed specifically to achieve one goal or the other, but not both.

To surpass the "break-even" point or power balance, a point beyond which the reactor is capable of producing more energy than it consumes, a machine must combine both achievements. This point is called Lawson's criterion, after the British physicist J. D. Lawson. According to his formula, to achieve the break-even condition in a deuterium–tritium fuel mixture operating at temperatures higher than the ignition temperature, the product of the density and the confinement time must equal or exceed 10^{14} sec/cu cm. No such machine now exists.

But physicists remain sanguine, despite past difficulties of a research program that after two decades and $1 billion has yet to reach the stage attained by nuclear fission when the first self-sustaining reaction went critical under a University of Chicago squash court. The main reason for such optimism is the extraordinary progress that has been made recently by various groups in learning how to raise the combination of density, temperature, and confinement time to the break-even point. Some key scientists, such as Dr. Robert Hirsch, AEC's former acting director of the controlled-fusion program, are reported exultant about eventual success. Says Hirsch: "Nature is not against us in this work. All we have to do is be careful and do the right things" [9].



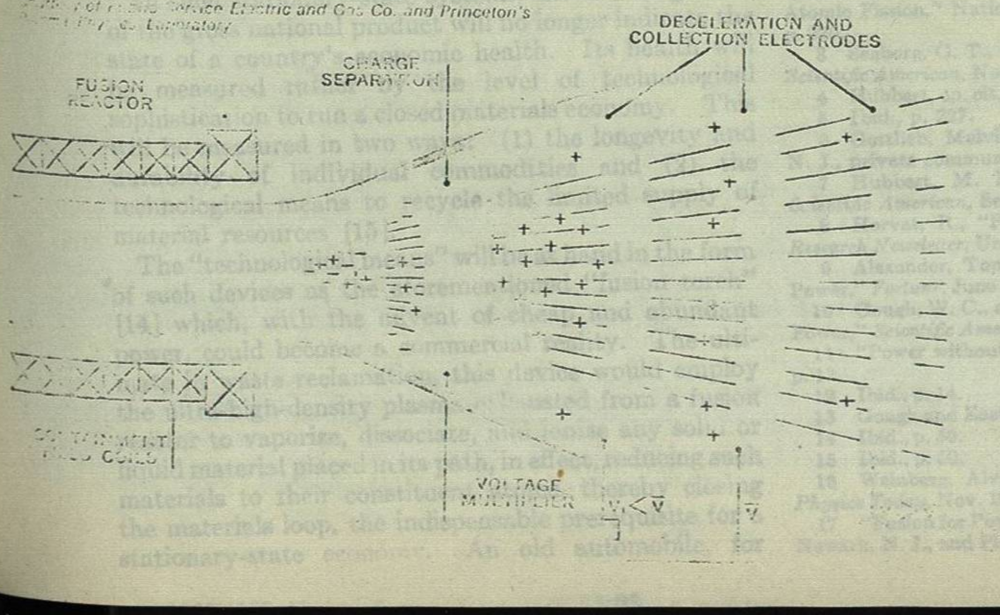
Fusion reactor based on a deuterium–tritium fuel cycle. Such a fuel would release approximately 80 percent of its energy as highly energetic neutrons. This neutron energy would be absorbed in a liquid-lithium shield, circulating the liquid lithium to a heat exchanger where water would be heated to produce steam to drive a conventional turbogenerator. Reactor core could be either linear or toroidal.

The Fusion Plant

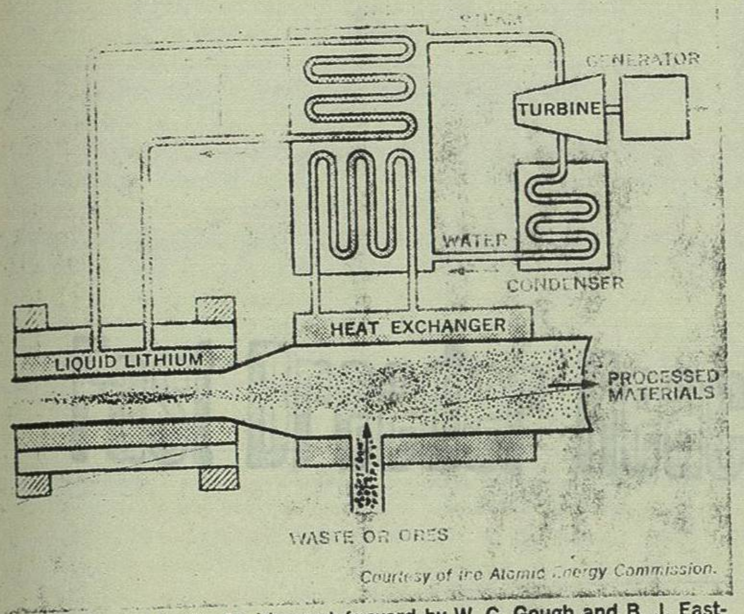
What will a fusion plant look like? There will be no architectural constraints, no need for stacks or reactor-containment buildings. Thus the plant could blend into almost any setting. The physical size has been estimated to be similar to that of a large-reactor generating station, except that extensive additional land area will not be needed for fossil-fuel storage or fission-reactor exclusion area.

What are the principal scientific and engineering problems still to be resolved? First, scientific feasibility of controlled fusion must be demonstrated. This requires scaling-up today's research devices to reactor

Courtesy of Public Service Electric and Gas Co. and Princeton's Plasma Physics Laboratory



Direct energy conversion. This type of conversion would be more suitable to those fusion fuel cycles that release most of their energy in the form of charged particles. Conversion could be accomplished by [illegible] electrons, pro- [illegible] to [illegible], and [illegible] them to upon [illegible] [illegible] charges. collected [illegible] would [illegible] [illegible] to do at [illegible]



Courtesy of the Atomic Energy Commission.

Fusion torch. An idea put forward by W. C. Gough and B. J. Eastlund of the AEC to exploit the ultra-high-temperature plasmas produced by fusion reactors. Some of the energy from these plasmas is here used to vaporize, dissociate, and ionize any solid or liquid material. In its ultimate form the fusion torch can reduce any kind of waste to its constituent atoms for separation.

size to confirm predictions based on current theory and experience. After this, difficult engineering problems will remain, such as: selection of materials resistant to energetic neutron bombardment, thermal stress, and magnetic forces; design of fuel-injection systems; design of a system for removing spent gas [17].

Conclusion

An energy-abundant world will be ushered in against the background of a profound change in life style of both advanced and underdeveloped countries. Because of finite limits to the world's reserves of material resources and to the ability of the earth's ecological system to absorb pollutants safely, the basic economic framework of all countries will be a stationary-state system in which the material economies will be "looped" or circular in place of the present inherently wasteful "linear" materials economies.

In such stationary-state systems, the rate of growth of the gross national product will no longer indicate the state of a country's economic health. Its health will be measured rather by the level of technological sophistication to run a closed materials economy. This will be measured in two ways: (1) the longevity and durability of individual commodities and (2) the technological means to recycle the limited supply of material resources [15].

The "technological means" will be at hand in the form of such devices as the aforementioned "fusion torch" [14] which, with the advent of cheap and abundant power, could become a commercial reality. The ultimate in waste reclamation, this device would employ the ultra-high-density plasma exhausted from a fusion reactor to vaporize, dissociate, and ionize any solid or liquid material placed in its path, in effect, reducing such materials to their constituent atoms, thereby closing the materials loop, the indispensable prerequisite for a stationary-state economy. An old automobile, for example, could be transformed into the iron, lead, and tin from which it was made [14].

Such fusion-torch possibilities are largely untested and many aspects may turn out to be impractical. For the ionization is only the beginning of a possible solution. The hardest part may well turn out to be the problem of "separating the soup into the vegetables," something no one knows how to do in any remotely acceptable (cost-wise) way.

Politically, the effects should be just as profound. Should abundant energy from rocks, the seas, or directly from the radiant energy of the sun materialize, then solutions to the major problem of the "have not" nations—how to improve the living conditions of their peoples above a bare existence level—would finally be at hand. This would greatly enhance the chances for world peace. After all, as has been pointed out with more than a grain of truth, much of what countries do internationally nowadays is intended to forestall future action of neighbors beset with population and raw materials problems [16]. But everyone has "granite, and air, sun, and water." The capability of using these basic elements to achieve abundant energy should be a self-serving contribution of the wealthier nations to their less-fortunate brethren.

Of course, as has been noted elsewhere [15], any effort to rationally utilize an energy-abundant economy will confront the massive economic, social, and political inertia that sustains the present system. Such questions as how to distribute the stock of wealth, including leisure, within a stationary-state economy will face severe scrutiny and arouse intense partisanship.

But this writer, for one, remains hopeful that the world's requirements for energy, intimately tied as they are to such factors as population expansion, economic development, materials depletion, pollution, war, and the organization of human societies, will ultimately be met and the scourge of war and pestilence irrevocably extirpated. Mankind will then enter on the path of its true history, one in which its energies will finally focus on those peaceful pursuits which are the true expression of the human spirit.

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