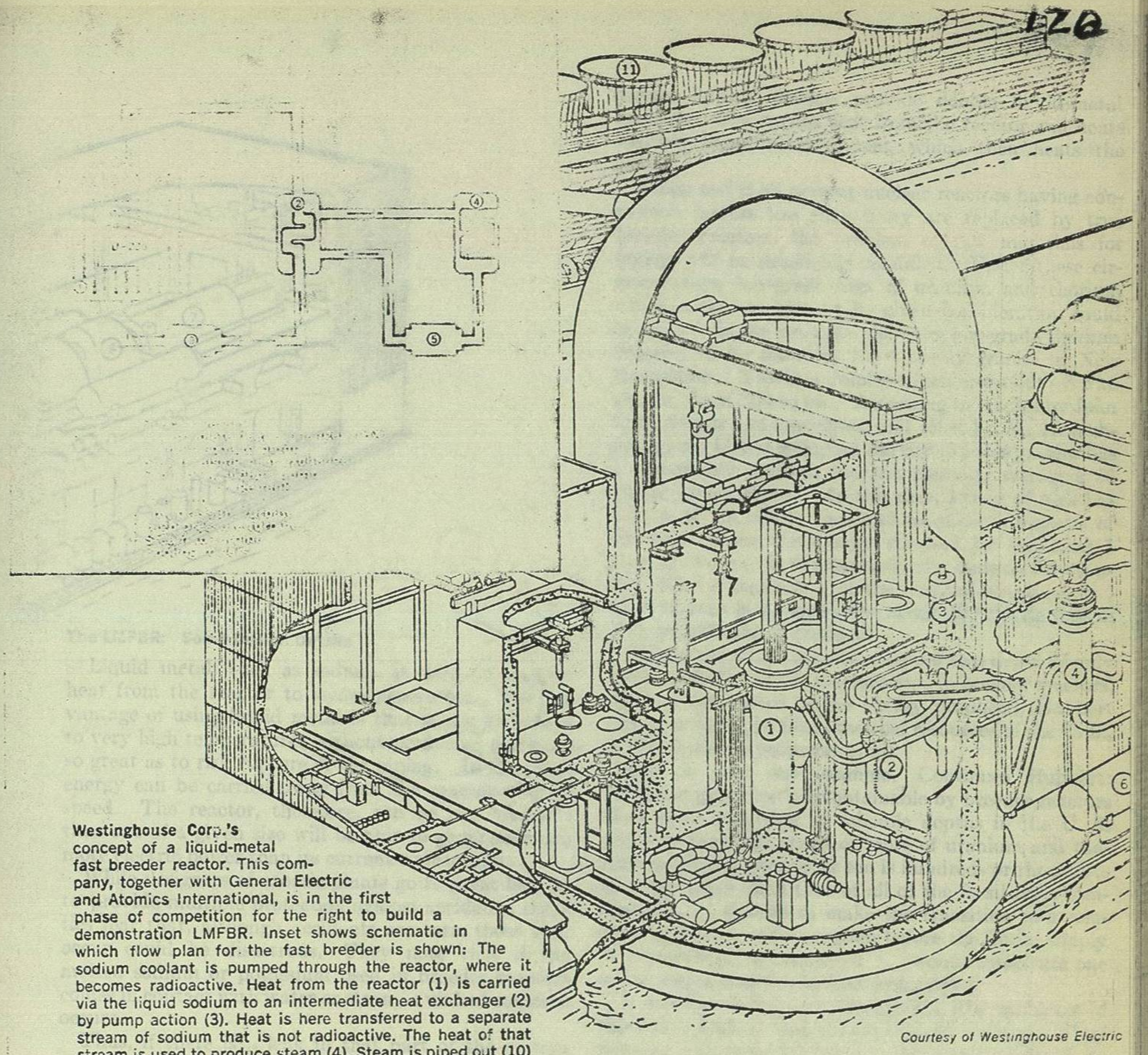


Westinghouse Corp.'s concept of a liquid-metal fast breeder reactor. This company, together with General Electric and Atomics International, is in the first phase of competition for the right to build a demonstration LMFBR. Inset shows schematic in which flow plan for the fast breeder is shown: The sodium coolant is pumped through the reactor, where it becomes radioactive. Heat from the reactor (1) is carried via the liquid sodium to an intermediate heat exchanger (2) by pump action (3). Heat is here transferred to a separate stream of sodium that is not radioactive. The heat of that stream is used to produce steam (4). Steam is piped out (10) to drive the turbogenerators.

Courtesy of Westinghouse Electric

reactor will have a doubling time in the range of 7 to 10 years [3].

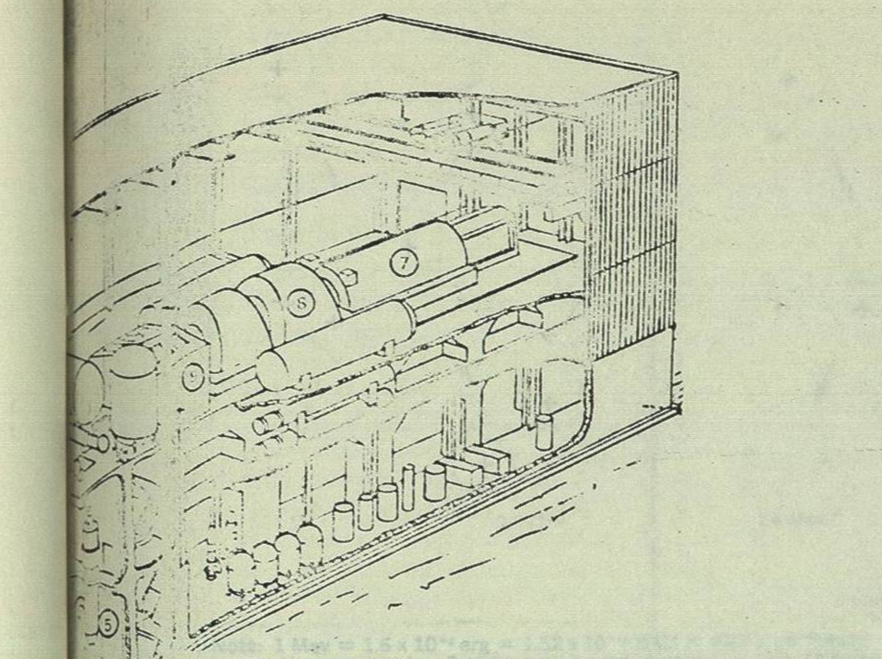
As far as energy production is concerned, the thermal energy produced per gram by either plutonium-239 or uranium-233 is approximately the same as that produced by uranium-235: about 8.2×10^{10} joule per gram. This is the equivalent to the heat of combustion of approximately 2.8 metric tons of coal or 14 bbl of crude oil [4].

Breeder Systems

The breeding concept is almost as old as the nuclear chain reaction, and the technology itself is now largely at hand. Two different breeder systems are involved, depending on which raw material is being transmuted: the thermal breeder and the fast breeder. The thermal breeder uses slow neutrons and operates best on the thorium-232–uranium-233 cycle (usually called the thorium cycle). The fast breeder uses more-energetic [illegible] operates best on the uranium-238–plutonium-239 cycle (the uranium cycle) [3].

In the United States and several other countrie fast breeder reactor cooled with liquid metal—th called LMFBR (liquid-metal-cooled fast breede actor)—has been given priority. Under AEC pices, something like a "crash program" is unde to develop a commercial LMFBR power plant by

We are not, however, putting all our atomic n in one basket. The utilities companies have pool sources to develop a gas-cooled fast breeder that uses pressurized helium as the coolant addition, other types of breeders are under d ment. The Oak Ridge National Laboratory is w on a molten-salt breeder reactor based on the th 232–uranium-233 cycle. Because it uses thorium raw material, this reactor would complemen LMFBR, which uses uranium-238. Another pr is attempting to modify the present type of light- reactors by adding blankets of fertile materia greatly increase the conversion ratio [4].



The LMFBR: Some Design Details

Liquid metal, such as sodium, is used to transfer heat from the reactor to steam generators. The advantage of using liquid metal is that it can be heated to very high temperatures without producing pressures so great as to risk rupture of the piping. In this way, energy can be carried away from the reactor at high speed. The reactor, therefore, can be run "faster"; thus one of a given size will be able to generate much more electric power than its current counterpart.

While designers of atomic plants go to great lengths to provide multiple protection against accidents, skeptics fear that, although accidents are rare, those that occur could be disastrous. They note that if the molten sodium or potassium used in breeder reactors comes in contact with water or steam, a violent reaction occurs.

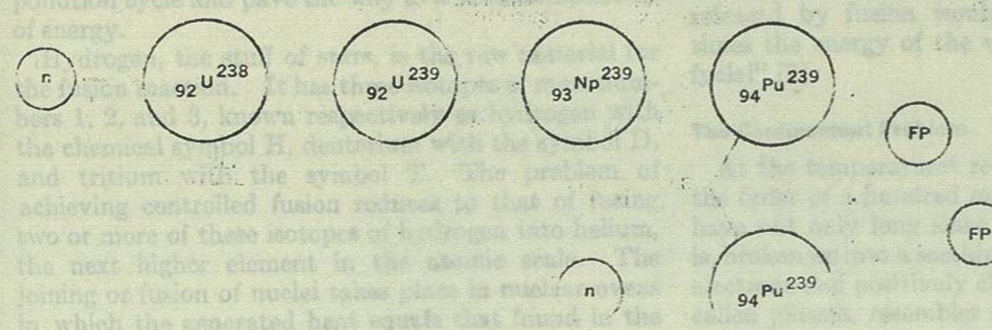
Thus, if there is a leak in that part of the system where the liquid metal is used to heat steam, it could be catastrophic. To isolate the reactor from such a danger, typical designs provide double liquid-metal systems. One carries heat from the reactor and heats another liquid-metal system, which then heats the steam.

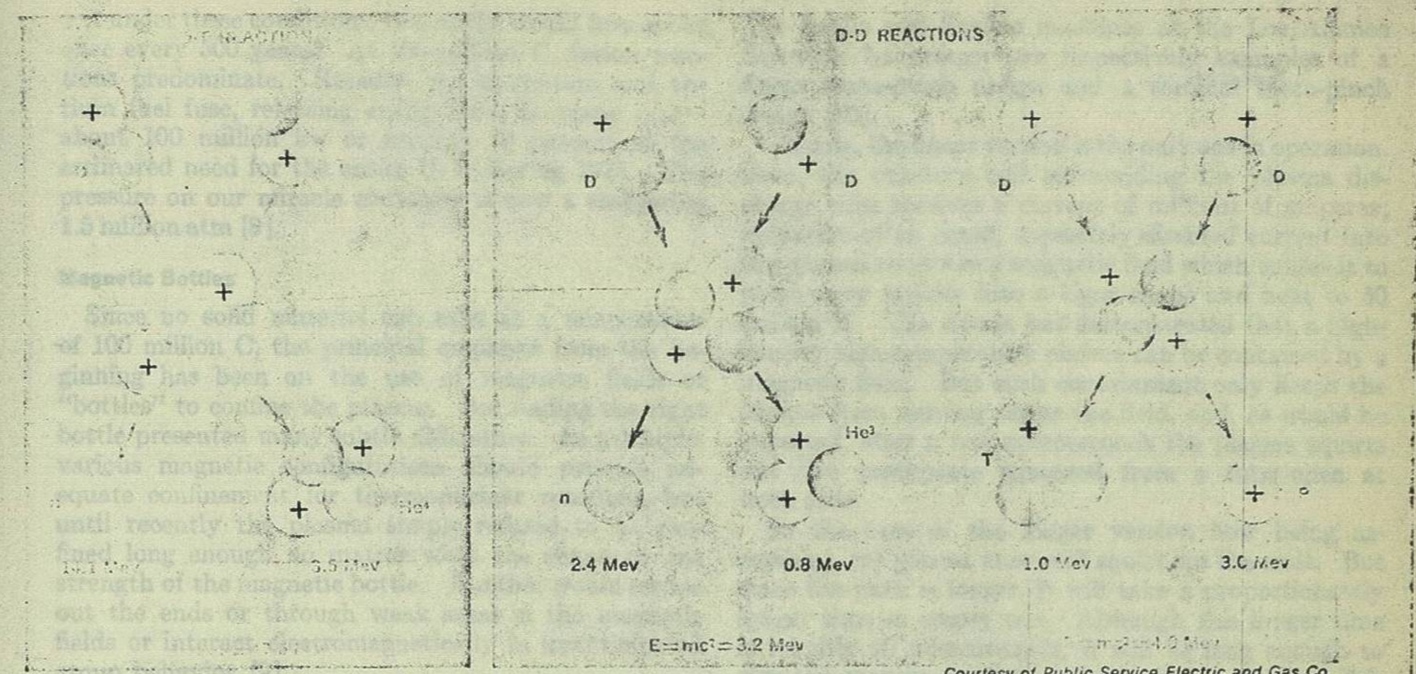
When and if all present nuclear reactors having conversion factors less than unity are replaced by true breeder reactors, the problem of raw materials for energy will be drastically modified. Under these circumstances, low-grade ores of uranium and thorium which cannot at present be given consideration could be used. As one example, there are low-grade thorium deposits to be found in the Conway granite in New Hampshire. This is a granite which crops out over an area of about 300 sq mi. According to studies by John A. S. Adams and associates, and cited by M. K. Hubbert of the U. S. Geological Survey [5], this granite has a remarkably uniform thorium content, averaging 56 grams per metric ton. In this case, 1 cu m of rock has a mass of 2.7 metric tons and contains 150 grams of thorium. Since the energy released by fissioning 1 gram of thorium is substantially the same as for uranium, the fuel equivalent of the thorium contained in 1 cu m of rock is equivalent to about 400 metric tons of coal, or 2000 bbl of crude oil.

Should the whole area be quarried to a depth of only 100 m (330 ft) and the thorium used in breeder reactors, the fuel equivalent of the energy produced, Hubbert notes, would be 20 times the coal resources of the U. S., or 750 times the resources of oil.

This is only one example. Continues Hubbert: "The energy potentially obtainable by breeder reactors from rocks occurring at minable depths in the U. S. and containing 50 grams or more of uranium and thorium combined per metric ton is hundreds or thousands of times larger than that of all of the fossil fuels combined. . . . Failure to make the transition to a complete breeder reactor program before the initial supply of uranium-235 is exhausted . . . would constitute one of the major disasters in human history."

It remains to be seen, however, if the problems of thermal pollution and public fear of "excursions" of venting radioactivity can be sufficiently allayed to permit the proliferation of atomic power to the required need.





Note: 1 Mev = 1.6×10^{-6} erg = 1.52×10^{-16} BTU = 4.45×10^{-20} kwhr
Also possible is a D-He³ reaction producing $He^4 + H + 18.3$ Mev.

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

Fusion reactions. A deuterium nucleus can fuse with a tritium nucleus (left) to form helium-4 and a neutron. It can also fuse in two other ways with another deuterium nucleus (right) to form helium-3 and a neutron or tritium and a proton (ordinary hydrogen nucleus).

These fears, if not all the "facts" on which they are founded, are very real. Against the background of these fears, siting problems become acute dilemmas. As TVA's manager of power, G. O. Wessenauer, put it to an Atomic Industrial Forum workshop last year: "An ideal site is one for which there is no evidence of any seismic activity over the past millennia; is not subject to hurricanes, tornadoes, or floods. It should be in an endless expanse of unpopulated desert with an abundant supply of very cold water flowing nowhere and containing no aquatic life. Most important, it should be adjacent to a major load center."

Sea Burning

To many scientists, the breeder reactor described above is only an interim technology, a holding action until they can master the difficult art of controlling thermonuclear fusion. Success will break the energy–pollution cycle and pave the way to a limitless reservoir of energy.

Hydrogen, the stuff of stars, is the raw material for the fusion reaction. It has three isotopes of mass numbers 1, 2, and 3, known respectively as hydrogen with the chemical symbol H, deuterium with the symbol D, and tritium with the symbol T. The problem of achieving controlled fusion reduces to that of fusing two or more of these isotopes of hydrogen into helium, the next higher element in the atomic scale. The joining or fusion of nuclei takes place in nuclear ovens in which the generated heat equals that found in the interiors of stars.

According to the AEC, the deuterium–tritium (D-T) reaction appears to be the most promising. Considering the amount of hydrogen in the oceans, deuterium can be considered as superabundant (one atom to each 6700 atoms of hydrogen). It can also be extracted easily. There is sufficient lithium in the United States alone to insure, via the D-T reaction, an energy content more than fivefold that inhering in the world's fossil fuels [6].

But if fusion were accomplished in a D-D reactor, one-fourth of the energy output could be taken out directly as electricity, an important advantage, plus the fact that deuterium is far more bountiful than tritium. One cu m of water contains about 10^{25} atoms of deuterium having a mass of 34.4 grams and a potential fusion energy of 7.94×10^{12} joule. According to Hubbert, this is equivalent to the heat of combustion of 300 metric tons of coal or 1500 bbl of crude oil. Since a cubic kilometer contains 10^9 cu m, the fuel equivalent of one cubic kilometer of seawater is 300 billion tons of coal or 1500 billion bbl of crude oil. Hubbert sums up fusion's potential: "The total volume of the oceans is about 1.5 billion cubic kilometers. If enough deuterium were withdrawn to reduce the initial concentration by 1 percent, the energy released by fusion would amount to about 500,000 times the energy of the world's initial supply of fossil fuels!" [7].

The Confinement Problem

At the temperatures required for fusion ignition, on the order of a hundred million degrees C, all materials have not only long since vaporized, but ionized, that is, broken up into a seething cloud of negatively charged electrons and positively charged nuclei. This mixture, called plasma, resembles a gas in some respects, but it is often regarded as a fourth state of matter because it has some properties unlike gases, liquids, or solids.

The confinement problem has been particularly vexing. Imagine an indestructible 1-liter container filled with a mixture of deuterium and tritium at room temperature and 1 atm pressure. Heating this mixture to 100,000 C will pull atoms apart producing a plasma

But under these conditions, two nuclei would fuse about once every 500 years! At 100 million C, fusion reactions predominate. Rapidly, the deuterium and tritium fuel fuse, releasing energy at a fantastic rate—about 100 million kw or roughly 10 percent of the estimated need for the entire U. S. during 1975. The pressure on our miracle container is now a staggering 1.5 million atm [8].

Magnetic Bottles

Since no solid material can exist at a temperature of 100 million C, the principal emphasis from the beginning has been on the use of magnetic fields or "bottles" to confine the plasma. But finding the right bottle presented many subtle difficulties. In principle, various magnetic configurations should provide adequate confinement for thermonuclear reactions, but until recently the plasma simply refused to be confined long enough no matter what the shape or the strength of the magnetic bottle. It either would escape out the ends or through weak areas in the magnetic fields or interact electromagnetically in unanticipated group behavior [9].

In general, magnetic bottles fall into two types: linear (open) or toroidal (closed). In the open type, squeezing fields of magnetism form a partial or leaky "stopper" preventing plasma from escaping out the ends of the tube. In the closed type, the tube is bent into a doughnut shape, or toroid, and here the purpose of the magnetic fields is to confine the plasma to the middle of the tube, away from material walls.

A number of existing systems are based on these types, and are classified on the basis of increasing plasma density. Three general systems are described: the theta pinch, the magnetic mirror, and the torus.

Theta Pinch. This is a high-density plasma container, which is defined as one in which the plasma pressure is comparable to the magnetic field pressure. This device has been built in both the linear and toroidal forms. Here the electric current is in the theta, or azimuthal, direction (around the axis) and the resulting magnetic field is in the zeta, or axial, direction (along the axis). The Scylla and Scyllac machines at the Los Alamos Scientific Laboratory are respectively examples of a linear theta-pinch design and a toroidal theta-pinch design [10].

To date, the linear version is the only one in operation. Here, the one-turn coil surrounding the plasma discharge tube receives a current of millions of amperes; induction of an equal, oppositely directed current into the plasma results in a magnetic field which causes it to pinch very rapidly into a cigar shape and heat to 50 million K. The device has demonstrated that a high-density high-temperature plasma can be contained by a magnetic field. But such containment only keeps the plasma from moving across the field, and, as would be expected, after a few microseconds the plasma squirts out like toothpaste squeezed from a tube open at both ends.

In the case of the longer version now being assembled, the plasma must still squirt out the ends. But since the path is longer, it will take a proportionately longer time to empty out. Although this longer time is roughly 10 microseconds, it will be long enough to give the experimentalists a chance to see whether this cigar-shaped plasma is widening out, i.e., spreading *across* the field. To make a reactor out of this approach, the device would have to be tens of miles long—too long and too expensive to be of practical interest. The interest, therefore, is in bending it around into a doughnut or torus. This has not yet been done, but is the main objective of the Scyllac experiment for the next several years [5].

Magnetic Mirror. This is a medium-density plasma container. In this device a linear magnetic bottle is partially "stoppered" at the ends by magnetic "mirrors" (regions of somewhat greater magnetic-field strength that reflect escaping particles back into the bottle). In addition, since mirror devices are necessarily very leaky, extra current-carrying structures are often used to improve the stability of the plasma. experiments being conducted are of two kinds. a warm plasma is "hypodermically" injected into a magnetic mirror, then heated and made more dense

There have been many configurations devised in the past two decades to confine plasmas for fusion research. All fall into two general types: linear (open) or toroidal (closed). In the open type, squeezing fields of magnetism form the sole "stopper" preventing plasma from escaping out the ends of the tube. In the closed type, the tube is bent into a doughnut shape, or torus and here the purpose of the magnetic fields is to confine the plasma to the middle of the tube, away from material walls.