

ENERGY

as an ultimate raw material

or—problems of burning the sea and burning the rocks

By Alvin M. Weinberg

MY purpose in these remarks is to speculate on the role of energy in the "Asymptotic State of Humanity"—that is, the state toward which we are moving, inexorably, because man's urge to multiply is limitless whereas his resources are finite. In my talk I draw very heavily from many authors, in particular, Palmer Putnam,¹ Hans Thirring,² and, above all, Harrison Brown,³ who has given much ingenious thought to the matters which I discuss. I choose to dwell on energy, first, because as physicists our basic subject of study is energy; and, second, because the character of the asymptotic state of mankind—whether it will be a bare existence or a passably abundant life—will depend centrally on our capturing an inexhaustible energy supply, either by learning how to burn the seas (fusion) or to burn the rocks (fission) or to trap the sun's energy in a practical way.

That the asymptotic state of humanity depends, for its shape, on energy has been stated perhaps most strikingly by Sir Charles Darwin in his book, *The Next Million Years*.⁴ Darwin points out that if the human doubling time of about 100 years persists, then in the year 2959 there will be about 2.7×10^{12} persons on earth, in 3959, 2.7×10^{15} . In fact, at this rate the mass of humanity would equal the mass of the earth by about 6500 A. D., which is of course absurd. Evidently, one way or another, the population of the earth will stabilize. For my purpose I shall assume a stabilized human population of 7×10^9 —the figure suggested by Brown, Bonner, and Weir in their much less ambitious, but more factual, *The Next Hundred Years*.⁵ But no matter what asymptotic population one chooses, the demand for energy will continually increase. For, as our natural resources dwindle, as we are forced to extract metals from lower grade ores, or water from the sea, or liquid fuel from carbonates and



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water, we shall have to pay more and more in energy simply to do what we have been doing, let alone to improve our lot. Eventually, as Harrison Brown has stressed, mankind will have to make do with only four basic raw materials: the sea, the rocks (of average composition since true ores will have been exhausted), the air, and the sun. (If we equate the sun to fire, these are essentially Aristotle's four elements!) The question really is not whether we shall reach this state—it is merely when we shall reach it.

Professor Brown and his associates have drawn up an energy balance sheet for such an asymptotic society of seven billion people who must eventually subsist on the sea, the rocks, the air, and the sun (Table 1).

Table 1. Asymptotic Yearly Energy Input Pattern*
(World Population 7×10^9)

Source	Equivalent Metric Tons of Coal (Billions)	Equivalent Heat Energy	
		10^{18} Btu	Mwyr Heat
Solar energy (for $\frac{2}{3}$ of space heating)	15.6	.42	140×10^5
Hydroelectricity	4.2	.10	38×10^5
Wood for lumber and paper	2.7	.07	24×10^5
Wood for conversion to liquid fuels and chemicals	2.3	.06	21×10^5
Liquid fuels and "petro" chemicals produced via nuclear energy	10.0	.27	90×10^5
Nuclear electricity	35.2	.96	320×10^5
	70.0	1.88	633×10^5

* From Brown, Bonner, and Weir, Reference 5, p. 113.

The total projected yearly energy consumption is 1.9×10^{18} Btu or 6.3×10^7 Mw years heat; i.e., the equivalent of 70×10^9 tons of coal per year, or 10 tons per person per year. This is about 18 times the present equivalent energy input of 0.35×10^7 Mw heat; i.e., four billion tons of coal equivalent. At this ultimate rate, the present fossil fuel reserves of perhaps 2400×10^9 tons would hardly last 35 years. The nuclear component of the yearly energy input, according to Brown's estimate, amounts to about 45×10^9 tons of coal equivalent or 4×10^7 Mw heat.

In this asymptotic state one can visualize the energy economy being divided into three major sectors: sunlight, primary nuclear sources, and energy converters. It is certain that sunlight will be used to produce food and, according to Brown, for much of our space heating. I shall consider later whether it will also become a primary source. The primary nuclear sources (fission and fusion) probably will be centered in great power plants—possibly, on the average, 20 times larger than the largest present-day coal-fired steam plants, since nuclear plants are so much less expensive in large size than in small. These plants would supply energy for direct use. They would also be used to supply energy for conversion to more convenient form, or for chemical reduction. For example, the reduction of iron oxide to metallic iron, which now uses about $\frac{1}{4}$ of our coal,⁶ can also be done either directly by electrolysis or a little less directly by electrolysis of water and reduction of FeO with the hydrogen which is produced. If the energy cost is $\frac{1}{2}$ ¢/electric kilowatt hour (kwh), the additional energy charge would amount to only $\frac{1}{2}$ ¢/pound of iron. Similar considerations apply to all other metals: they appear in nature in oxidized form, and electricity can be used to reduce the ores to metals.

Energy from the primary source can be used to convert sea water into fresh water at an ultimate energy cost of only 9.6 Btu/gallon if the conversion is 100 percent efficient—this would amount to a theoretical minimum cost of only a few cents/1000 gallons. This theoretical cost may be compared with a recently reported cost of \$1.00/1000 gallons of water from a new long tube multiple-effect still.⁷ As for converting energy from the primary source into food, sunlight is far cheaper than energy from other sources. However, in the production of nitrates from the air, energy other than sunlight is required and, with the intensive agriculture which would be needed to feed 7×10^9 people, one can expect a much increased production of nitrates. Thus, indirectly, our increased food requirements will also increase our energy demand.

The primary energy source can be used to provide small-scale mobile energy—in principle, either by electrical storage systems or by chemical storage systems. An example of a simple chemical storage system would be electrolytically produced hydrogen; this could be used in the production of liquid fuel hydrocarbons from carbonate rocks even after our coal per se is gone.

The energy cost is rather high, but not outside the realm of ultimate feasibility.

We thus see that an asymptotic state of civilization, stabilized at, say, 7×10^9 population, can be based upon the rocks, the seas, the air, and the sun—provided only that we have available a primary energy source and that we have worked out good methods for converting energy into convenient packages. This search for new primary energy sources (and for new energy converters) has become an enormous scientific frontier in which physicists naturally are taking the leading role.

Energy Converters

THE new energy converters (among which I classify devices which convert energy, other than mass energy, from one form into a more convenient form) include, among others, the silicon batteries, the thermionic converters, the thermoelectric power producers, and the fuel cells. The first of these, the silicon battery, converts solar energy into electrical energy. It is expensive and bulky, and one can hardly visualize full-scale power plants based on this device. The thermionic converter⁸ and the closely related thermoelectric power producer convert heat, obtained from a primary source, directly into electricity. Their advantage in an ultimate power economy is that they would possibly produce electricity more simply than do the conventional power stations; since the efficiencies attainable with them are rather less than are now achieved conventionally, these devices would not extend our energy supply. The fuel cell converts chemical energy directly into electricity—hopefully in small packages. Since chemical energy, in the form, for example, of hydrogen and oxygen, can be obtained directly from the primary energy source, one can see fuel cells as one way of ultimately using primary energy for mobile power. However, other less exotic schemes, such as greatly improved storage batteries or production of liquid fuel from energy, carbonate rocks, and water, are possibly a more direct and attractive route toward conveniently using the primary energy source.

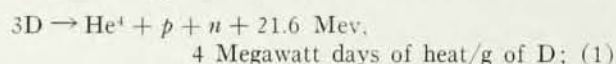
I have no doubt that considerable success will be achieved over the years in improving secondary energy converters. But unless we have substantial success with our primary energy sources, the asymptotic state of mankind cannot be nearly as comfortable as is the present world. I shall therefore examine the status of the art of providing an asymptotic primary energy source.

There is, of course, the possibility that the sun's energy can be used as the primary source. In the projected energy economy it represents 22 percent of the total input, in addition to its use for production of food and wood. But the diluteness of the sun's energy, and its unpredictability, militates against its use as a primary source in large power stations. The solar energy striking the earth is 1.7×10^{14} kw and to produce *all* of the energy required in our energy

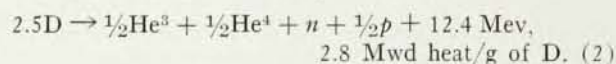
balance would require collectors occupying about 35 000 square miles, assuming an efficiency of collection of 100 percent and of conversion to electricity of 25 percent. Actually the efficiency of collection and conversion to electricity, according to Palmer Putnam,⁹ is only about 7 percent, so that the total required area may be as high as 10^5 square miles.¹⁰ This is perhaps not entirely out of the question, though it does seem extremely unwieldy. Thus to quote Putnam,¹¹ "The direct collection of solar energy on a vast scale by myriads of tracking mirrors, thermocouples, or other devices, its overnight storage, its conversion to transportable electricity, and its delivery at low cost from Arizona to Pittsburgh or from the Sahara to the Midlands appear remote in the light of what we know today." At the presently estimated capital cost of \$1000/kw,¹² the ultimate electrical energy input would cost about four trillion dollars—a large sum, but in the ultimate span of human history not impossible (World War II was estimated to have cost 1.5 trillion dollars). A more concentrated, long-term energy source based on either the rocks or the seas thus seems to be extremely worthwhile, if not absolutely essential.

Sea Burning and Rock Burning

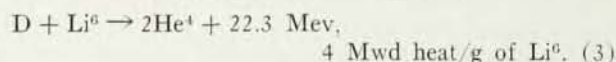
WHERE, then, do we stand in our efforts to burn the sea and to burn the rocks? First, I consider the availability of the raw materials. In the case of fusion based on D-D, the raw material is found almost entirely in the sea. Assuming that if the D-D reaction goes, then so will the D-T and D-He³, we have the over-all energy and material balance:



if D-D and D-T can be made to go, but, because of the higher Coulomb barrier, the temperatures required for D-He³ are not achieved, the balance is

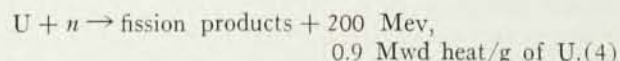


If only the D-T can be made to go, Li⁶ is also a basic raw material, and the over-all balance is:



In these reactions, the neutrons, He³, and tritium produced in the intervening reactions are used up again; they act as catalysts much as the carbon acts as a catalyst in the carbon cycle.

By comparison, the fission reaction is:



The surprising result is that per gram of raw material, fission gives as much as $\frac{1}{3}$ to $\frac{1}{5}$ the energy of the deuterium-tritium-He³ cycle (Equations 1 and 2).

The amounts of deuterium, Li⁶, and U + Th contained in the seas and in the earth's crust, together

Table 2. Amounts of Deuterium, Li⁶, U, and Th on Earth*

Raw Material	Source	ppm	Total Mass (Tons)	Energy Content (Megawatt Days of Heat)	Will Last at 4×10^7 Mw (Heat) Rate
Deuterium	Sea	33	6×10^{13}	2.4×10^{20}	1.7×10^{10} yrs.
Li ⁶	Crust	5	21×10^{13}	8×10^{20}	5.4×10^{10}
U	Crust	4	16×10^{13}	1.5×10^{20}	1.0×10^{10}
Th	Crust	12	50×10^{13}	4.5×10^{20}	3×10^{10}
Total U + Th	Crust	16	66×10^{13}	6×10^{20}	4×10^{10}

* The basic data in this table are from B. Mason, *Principles of Geochemistry*, page 41, John Wiley, New York (1952).

with their energy content, and the length of time they will last at the asymptotic rate of 4×10^7 Mw heat, are shown in Table 2. In making this table, I assumed reaction (1) for the deuterium, and reaction (3) for the lithium.

Before assuming, from Table 2, that either sea burning or rock burning would forever fulfill our energy requirements (the solar system is hardly expected to last longer than 10^{10} years), we must ascertain that less energy is required to extract the raw materials D, Li⁶, and U + Th from their asymptotic natural environments than is returned by burning these fuels. In the case of deuterium, the balance is clearly very favorable. Perhaps it is easiest to see in terms of monetary cost of extracting deuterium from water. The present cost of deuterium is about \$28/lb of D₂O or 30¢/gram of deuterium. If one gram of deuterium is burned, by reaction (2), say, 3 Mwd of heat or about 22 500 kwh of electricity, worth about \$100, are produced. The fuel cost of the deuterium on this basis is less than 0.013 mill/kwhe which is almost, but not quite, negligible.

With respect to U + Th, the situation is also favorable, provided we burn all the U and Th, not just U²³⁵. About $\frac{1}{5}$ of the U + Th or 3 grams/ton is contained in rather easily leachable portions of the granites, according to Brown and Silver.¹³ The energy content of this "easily" recoverable U + Th is equivalent to about 10 tons of coal or 3 Mwd heat/ton of granite. The energy required to recover this 3 grams/ton of U + Th is estimated by Brown and Silver to be equivalent to from 25–50 lbs of coal as seen in Table 3.

Table 3. Energy Required to Process Granite*

Quarrying, crushing, hauling	7–9 kwh/ton
Acids	10–25 kwh/ton
Other direct charges (water pumping, etc.)	1 kwh/ton
Hidden costs	0.7–2.3 kwh/ton
	19–37 kwh/ton ~ 25–48 lbs coal

* Brown and Silver, Reference 13

Brown estimates the asymptotic cost of treating one ton of granite to be from \$1.00–\$2.25—this amounts to about 30¢–80¢/gram of U + Th or 0.05–0.12 mill/kwhe fuel burnup cost, assuming that all of the extractable U + Th can be burned by the process of breeding. The *burnup* cost is relatively small even if, as suggested by Keith Brown,¹⁴ the asymptotic cost per gram of U + Th is as high as \$1.00–\$3.00/gram; in that case (assuming the extreme of \$3.00/gram) the fuel burnup cost would be 0.5 mill/kwhe, which is still very low. The situation is unfavorable if only the U²³⁵ is burned; in that case the energy recovery is only 1/300th as much and this would hardly pay for extracting the U + Th.

The total amount of energy "practically" available from U + Th in the rocks is of course a good deal less than that given in Table 2. We ought not to count the parts of the crust under the seas, nor the material more than, say, 3 km below the surface, nor the granites which carry a very great overburden of sediment. On the other hand, since the energy balance is so favorable, one could mine rocks with even 0.3 gram/ton U + Th and still get some 20 times more energy than is required to extract the fissionable material. One therefore cannot escape the impression that the extractable reserve of fissionable material is large enough to sustain humanity for the indefinite future.

Just how large a mining operation would be required to maintain an energy output of 4×10^7 Mw heat? Since one gram of fissionable material burned each day would maintain a heat rate of one megawatt, the total U + Th burned per day would be about 40 tons. To obtain this amount of fissionable material would require the mining of about 10^7 tons of rock per day. This may be compared with the world's daily production of coal and lignite which in 1953 was 0.6×10^7 tons.¹⁵ Thus the whole mining operation required to sustain the asymptotic energy economy would be on about the same scale as the mining operation which now sustains our much smaller, fossil-fuel-based, energy economy.

I know of no studies relating to recovery of low-grade Li ores. I should suppose that, if anything, Li

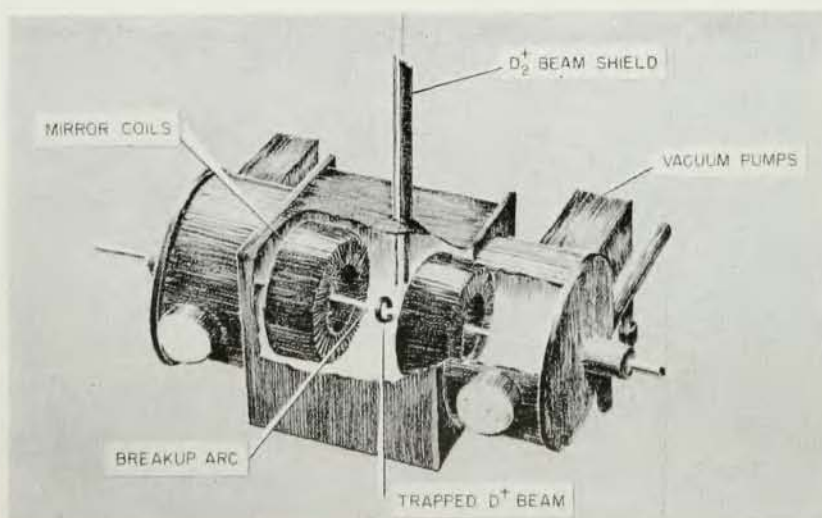
would be easier to extract than U or Th, and that the asymptotic fuel cost of Li, just as the asymptotic fuel cost of U + Th, will always be negligible. However, the total amount of Li recoverable would probably be of the same order as the total amount of U + Th which is recoverable; if we must rely on the D + Li⁶ cycle, then the amount of Li would probably limit the total energy recoverable from deuterium. In this case the extraction of lithium from the rocks would involve a mining operation of the same order as the extraction of the residual fissionable materials.

Problems of Sea Burning

THE essential point of the foregoing remarks is that *either* sea burning or rock burning could *in principle* be made the primary asymptotic energy source for the rest of mankind's history, and the cost of the energy produced could be at least within striking distance of the range of today's energy costs for a time which is very long compared to the present span of human history. The advantage of sea burning therefore is not, as is often assumed, that deuterium is the only essentially inexhaustible fuel. The advantages are seen to be rather less fundamental—perhaps most important is that fusion is a relatively cleaner process than fission. The radioactive wastes associated with deuterium reactors ought to be much less troublesome than those associated with uranium reactors. Whether this is a crucial advantage is certainly very difficult to say at present.

Granted that achievement of sea burning would represent a major advance, comparable to the discovery of fission, there remains the question of where we now stand in this quest for a successful deuterium reactor. One approach to sea burning (high-energy molecular injection into a mirror field using the Luce arc for molecular break up and trapping) at the moment¹⁶ seems to have many adherents, possibly because it is the newest, and the full nature of the difficulties is not entirely clear. Suffice to say that a very large DCX-type machine of the general type developed at Oak Ridge (Figures 1 and 2) has been built in the

Fig. 1. Direct current experiment (DCX): In the schematic drawing, the injected beam of 600 kev D₂⁺ molecular ions is dissociated into D⁺ ions as it strikes the Luce carbon arc (which runs parallel to the axis of the magnetic mirror). The Larmor radius of the D⁺ ions is half the Larmor radius of the molecular ions; hence the D⁺ ions circulate in a trapped ring which gradually randomizes into a very hot plasma.



USSR. It is called OGRA. In OGRA, break up of the molecular ions is by collision with the residual gas, rather than with the Luce arc as in DCX. Smaller devices embodying the DCX principle are being studied at Aldermaston in England and at Saclay in France.

The older approaches—the pinch and the stellarator—both have encountered very serious plasma instabilities which are really not well understood. The hydrodynamic phenomena which have been encountered in these plasmas are suggestive of turbulence. It is known that in passing from the stable laminar to the unstable turbulent regime in ordinary hydrodynamics all transfers (of heat, mass, momentum) increase; conceivably the same could hold true in magnetohydrodynamics. Some things like turbulent instabilities have been observed in all the pinch and stellarator experiments; the plasma becomes violently unstable whenever one begins to approach plasma densities and temperatures near the interesting range, and, as in ordinary turbulence, the transfer of energy and matter to the walls increases catastrophically. Whether these instabilities are inherent, or are simply the result of the particular way in which the plasmas are produced, is a matter of argument at present.

The extraordinary difficulty of confining the plasma

may be judged by considering the pressure in the plasma. At a density of $10^{15}/\text{cm}^3$ and a temperature of 40 000 ev (4×10^8 °K), which are the ignition conditions for D-D, the plasma pressure $P_p = nkT$ is 60 atmospheres. This is a pressure which is usually held by stout steel walls—what must be done in Sherwood is to hold this pressure by magnetic lines of force! This latter difficulty could perhaps be reduced, as has been suggested by R. F. Post, if it were possible to show a net gain of energy at lower plasma densities. This could be the case if cryogenic cooling of the magnet coils were feasible.

It would be terribly premature to say that Sherwood—i.e., sea burning—is impossible, especially since the mirror geometry (on which DCX is based) has thus far shown no instability. On the other hand, it would be equally incorrect to assume that mankind's future energy supply is assured on the basis of what we now know about the problem of sea burning. The fair-sized experimental program being pursued in the US (amounting to about $\$38 \times 10^6$ in the next fiscal year), and the apparently comparable program in the USSR are in my view well justified; yet it would be a gross error if our effort at sea burning were to divert us from a full-fledged effort aimed at the much more imminent rock burning.

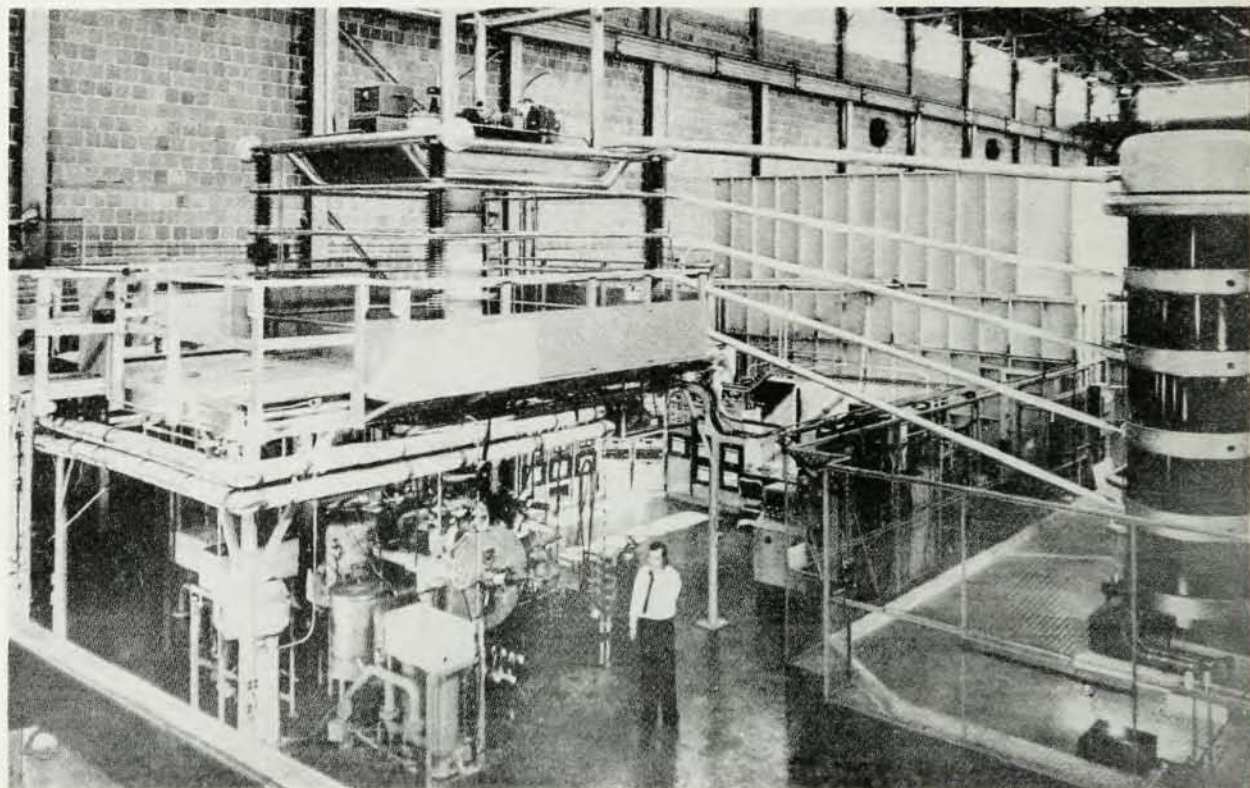


Fig. 2. A general view of the DCX experiment at Oak Ridge National Laboratory. The high voltage supply and the accelerating tube which feeds 600 kev D_2^+ molecular ions into the magnetic mirror may be seen in this photograph.

Problems of Rock Burning

THE problems of rock burning are of an entirely different order than are the problems of sea burning. We certainly have not shown that we can ever burn any fraction of the deuterium; burning U^{235} , on the other hand, is rather a routine process. But, in the asymptotic state, burning U^{235} is not sufficient. In order to make the extraction of $U + Th$ from granites energetically feasible, we must burn considerably more than the U^{235} . Beyond this, in order to make the ultimate fuel burnup costs even reasonably low, say less than 1 mill/kwh, we must burn not less than about 1/10 of the $U + Th$ which we assume to be available at the previously quoted asymptotic figure of 30¢–80¢/gram—that is, we must burn about 60 times as much U^{238} and Th^{232} as there is initial U^{235} .

In order to burn more than the initial reservoir of U^{235} it is necessary to breed: i.e., to use the neutrons in excess of those needed to maintain the chain reaction, to convert the fertile U^{238} into fissionable Pu^{239} , or the fertile Th^{232} into fissionable U^{233} . Fundamental to the analysis of such breeder reactor cycles is the breeding ratio and the doubling time: the breeding ratio, BR , is the ratio of new fissionable atoms created per fissionable atom destroyed; the doubling time is the time required to double the inventory of fissionable atoms. If the breeding ratio is less than unity, then the fraction of total fertile material which can be burned is $1/(1-BR)$. The doubling time is the product

$$\text{Doubling time} = [\text{specific power} \times (BR-1)]^{-1},$$

and is positive only if the breeding ratio exceeds unity.

From the very long-term point of view which we are adopting here, all that is necessary to burn all the uranium and thorium is to achieve a breeding ratio of unity. However, the breeding ratio must refer to all the fissionable material burned in the whole energy system. Since there will undoubtedly always be some nuclear plants which, for compactness, must forego any breeding, it will be necessary to make up for these plants with plants which produce more fissionable material than they burn. Thus it seems inescapable that the solution to the ultimate energy problem by way of rock burning depends on reducing to practice the nuclear breeding process: i.e., making practical breeder reactors with reasonably short doubling times—of the order of 10 years.

Fast Breeding and Thermal Breeding

BREEDING cycles can in principle be based on either uranium as the raw material or on thorium as the raw material. From the asymptotic standpoint, thorium is preferable since it is three times as abundant, and therefore should be three times as cheap as uranium. On the other hand, because of its more favorable geochemistry, uranium in readily workable deposits seems to be three or four times as abundant as thorium and so, in the short run, uranium breeding may be

preferable. Serious work on both breeding cycles is now being pursued, and I shall briefly summarize the current status of this work.

In the uranium cycle, the determining nuclear constant $\eta(Pu^{239})$, i.e., the number of neutrons produced per neutron absorbed in a plutonium nucleus, is high enough ($\eta \sim 2.9$) to give a substantial breeding gain only if the chain reaction is maintained with fast neutrons. The problem in fast neutron breeding is not, "Can a breeding ratio greater than one be achieved?" It is, first, "Can enough power be extracted from the necessarily very compact fast reactor core to allow the holdup of expensive fertile material to be kept within reasonable bounds?" and, second, "Can the fuel be burned sufficiently, before requiring reprocessing, to allow the whole cycle to be economical?" Of the two problems, probably the former is ultimately the more difficult. At present the fast breeder EBR-II being built by Argonne National Laboratory is rated at about 300 kwe/ton of natural uranium; this includes both the U^{238} in the blanket and the natural uranium needed to supply an initial charge of U^{235} for the core. At the asymptotic price of 30¢–80¢/gram, this amounts to \$900–\$2500/kwe for the installed fuel. At this price fast neutron breeding would begin to be as expensive as solar energy, and evidently great improvements would be needed. The situation is of course much more acute if the higher asymptotic price of \$3.00/gram is assumed. At such high inventory costs, solar energy indeed becomes a very serious competitor.¹⁷

Two factors make the situation much more hopeful, however. First, the rating of 300 kwe/ton is surely much lower than will be ultimately achieved, especially since the fueling of the core will eventually be done with bred Pu^{239} , not with U^{235} extracted from natural uranium. Second, and possibly more important, there is probably enough low-cost uranium and thorium available to start the asymptotic energy system at reasonable cost; the very expensive material from the granite would be needed only as make-up for fissionable material which has been burned. As make-up \$3.00/gram uranium would add only 0.5 mill/kwe to the cost of electricity. Even at the very low rating of 300 kwe/ton, the amount of uranium and thorium required as initial inventory for Brown's asymptotic nuclear energy system (4×10^{10} kwh) is only about 30×10^6 tons. This may be compared with recent estimated potential reserves of uranium and thorium available at \$30–\$50/lb— 20×10^6 tons for uranium, and 5×10^6 tons for thorium. The inventory cost, even at \$50/lb (10¢/gram), thus amounts to about \$300/kwe, which is a serious cost but certainly not impossible from the very long-term standpoint. Rather, I consider it remarkable that we see at hand a way of starting our asymptotic energy system with materials that are even now practically available, and that we can keep the system supplied with fuel for essentially all time by means of a mining operation only somewhat larger than the present coal mining operation of the world!

As for the second problem—high burnup—this is a

problem common to all solid fuel reactors, not simply to fast reactors. At present, fuel for fast reactors has to be reprocessed five to ten times before the original load of plutonium is completely burned. Each reprocessing probably would cost \$5.00/gram of fissionable material; this would add \$25–\$50 to the cost of burning a gram of Pu. However, from the very long-term standpoint this may not be as serious as the high inventory charge.

At present the major effort in the fast breeder development is aimed at reducing fuel cycle costs either by increasing fuel burnup (through the use of better alloys or fluid fuels or oxide fuels), or by simplifying the chemical processing using pyrometallurgical methods, for example. The problem of reducing inventory is at present relatively less urgent since uranium costs about 2¢/gram, not 30¢–80¢/gram; yet we see that, unless we can start our system with relatively cheap (10¢/gram) uranium, the problem of high inventory will be a formidable one.

The other breeding cycle is based on Th- U^{233} . Here the value of η at high energy ($\eta \sim 2.5$) is not sufficiently greater than its value at thermal energy ($\eta \sim 2.25$) to make it advantageous to try to breed at high energy. Moreover, because thermal reactors can tolerate such coolants as D_2O very well, and because in principle the fuel can be a liquid, the major problems of the fast reactor (small burnup and relatively low heat rating) are much less severe in the thermal reactor. In spite of their inherently lower breeding ratio, the theoretical doubling times in the U-Th thermal systems are, because of their very high output per kg of fissionable material, about equal to those in the fast (U-Pu) systems. Moreover, if an output of 1500 kwe/ton of Th can be achieved, then Brown's entire asymptotic nuclear system could be initially fueled with only about 7×10^6 tons of thorium, an amount which is very likely available at 10¢/gram of Th. At this price the inventory charge is only \$70/kw. Thus, if thermal breeding in the Th cycle in systems with low holdup (~ 1500 kwe/ton) and liquid fuel could be achieved, this system could serve as the asymptotic energy source for mankind.

But, as usual, there are problems. Perhaps the most fundamental is the value of $\eta(U^{233})$ at thermal energy. Recent British measurements have placed this all-important number as low as 2.18; since the neutron losses in a homogeneous thorium breeder amount to about 16 percent, such a low value of η would essentially make breeding in the thorium cycle impossible. Because of this alarming turn of events, the Oak Ridge National Laboratory and other AEC Laboratories have embarked on a major effort to redetermine $\eta(U^{233})$ with one percent precision. The experiments to date—mainly manganese bath experiments and large critical experiments in ordinary H_2O^{18} —suggest strongly that $\eta(U^{233})$ at thermal energy exceeds 2.25, and that thermal breeding should therefore be feasible in the U^{233} -Th cycle.

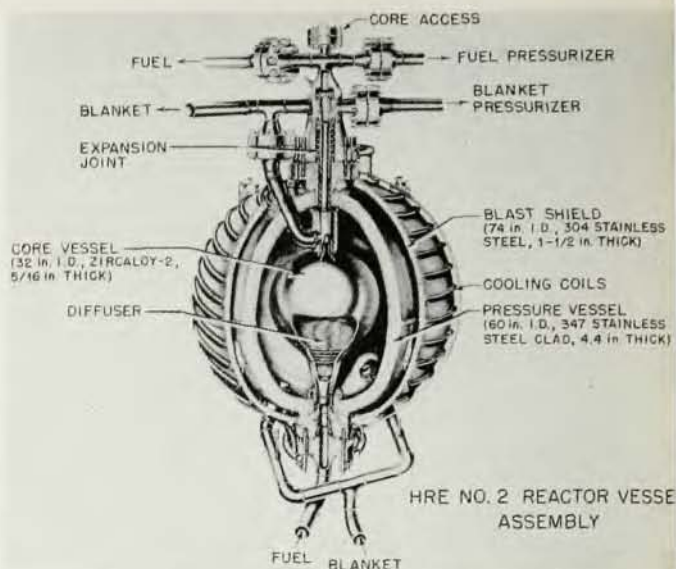


Fig. 3. Homogeneous reactor experiment No. 2 (HRE No. 2). Core tank, made of zirconium, is pear-shaped. Region between core tank and pressure vessel is, in a fully developed breeder, occupied by a slurry of ThO_2 suspended in D_2O .

Most of the engineering efforts to achieve breeding in the U-Th system center around the aqueous homogeneous reactor development at ORNL, although smaller efforts based on fused salts or U-bismuth fuels are also under way. In the aqueous homogeneous reactor a solution of UO_2SO_4 in D_2O is circulated through a zirconium core tank so shaped that the solution chain reacts inside the tank but not outside. The tank is surrounded by a blanket which ultimately is to be a slurry of ThO_2 in D_2O ; neutrons leaking out of the zirconium core tank are absorbed in the ThO_2 slurry to produce additional U^{233} (Figure 3). The great advantage of such a system is that because the fuel is in liquid form, the fission products which would poison the reactor and therefore reduce the breeding possibilities can be continuously drawn off; also, there is almost no limit to the extent to which the fuel can be burned, unlike fuel in solid fuel elements which is subject to radiation damage and other deleterious effects. The disadvantage of the system is that UO_2SO_4 in D_2O at $300^\circ C$ and 2000 psi is intensely corrosive and difficult to handle; and, since the fluid must be circulated to extract heat from it, the entire system (piping, pumps, etc.) becomes extremely radioactive.

Nevertheless, two small reactors embodying this principle have been operated at Oak Ridge: the HRE No. 1 which produced 1 Mw of heat for a short period in 1953, and the HRE No. 2 which has been operating as an experimental device since late in 1957 at powers up to 6 Mw. The HRE No. 2 was originally a two-region system with fuel separated from the blanket by the Zr tank. However, in the course of power runs local overheating resulted in a hole in the Zr tank, and

the system now operates as a one-region reactor with fuel in core and blanket. The cause of the overheating is still rather obscure, although it seems to be connected with the hydrodynamic design which allowed accumulation of solids, or of a second, uranium-rich liquid phase on the core wall. Experiments at HRE No. 2 are now proceeding in an attempt to identify the cause of the local heating and to learn how to raise the power densities to the 1500 kwe/ton desired for the long-run systems.

In spite of these difficulties the aqueous thermal breeder seems to be basically feasible and to satisfy all the requirements of an asymptotic fission energy source—high power rating, low inventory, simple fuel cycle, and the ability to breed. But it will be a long and difficult job to iron out the engineering bugs; perhaps a generation will be required to reduce aqueous homogeneous breeders to reliable full-scale practice.

Have We a Responsibility to Future Generations?

IT is fair to ask why this generation should have any particular responsibility to generations many many years hence—why should we bother to develop an asymptotic energy source? I think there are several reasons, some practical, others moral, why we should pursue aggressively the ultimate energy source.

First, the practical reason: it is merely that asymptotic breeder reactors could be as economical as any other reactor once they are fully developed. Thus the motivation for pursuing the breeding systems, as compared to other reactor systems, at present has an economic base, even in the current economic framework.

As for the moral reasons, I see at least two. The March 1959 issue of *Population Bulletin* puts it aptly: the next twenty-five years may see the world's population rise from 2.5×10^9 to 4×10^9 . "... we should

do well to ponder the significance of this development in terms of the destiny of our species.

"These next twenty-five years form part of a process which began some 200 000 years ago and which is about to culminate in man's full possession of the earth.

"The growth of world population during the next twenty-five years, therefore, has an importance which transcends economic and social considerations. It is at the very heart of the problem of our existence."¹⁹

It is the lot of our generation to see clearly that the threshold into the asymptotic population state will surely be crossed—in this sense it is our generation or the next which probably will first witness the culmination of man's history on earth. I suppose each person has his own personal reaction to this knowledge; mine is that I would somehow feel more comfortable if, as a member of the generation which first sees the asymptotic population state approached, I could also leave to future generations the means to live relatively abundantly in this asymptotic state.

Finally, there is the broad political implication of this vision of an asymptotic, energy-abundant world. Should we succeed in supplying energy really cheaply from the rocks, or, with good luck, from the seas, on as vast a scale as I contemplate, then the problem of have-not nations ought to become much less acute than it now is. Much of what countries do internationally nowadays is intended to forestall future actions of neighbors beset with population and raw materials problems. But everyone has granite and air and sea and sun. One would hope that solving the problem of living relatively abundantly with only these raw materials would help to dispel these historic causes for strife among men and that, in the wake of such development, mankind could turn its energies to those peaceful pursuits which are the true expression of the human spirit.

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