

Breeder reactors: A renewable energy source

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Since energy sources derived from the sun are called "renewable," that adjective apparently means that they will be available in undiminished quantity at present costs for as long as the current relationship between the sun and Earth persists, about 5 billion years. It is the purpose of this note to show that breeder reactors using nuclear fission fulfill this definition of a renewable energy source, and in fact can supply all the world's energy needs at present costs for that time period.

The world's uranium resources are sufficient to fuel light-water reactors for only a few tens of years, and since uranium is used about 100 times more efficiently as an energy source in breeder reactors than in light-water reactors, it is frequently said that the amount of uranium available can support the world's energy needs for only about 1000 years. Under this definition, nuclear fission is not a very-long-term energy source.

Such arguments ignore the fact that usual estimates of the world's uranium resources refer to quantities available at the current market price of about \$40 per pound. At that price, uranium supply contributes about 0.2 cents/kW h to the cost of electricity from light-water reactors. However, if used in breeder reactors, the cost/kW h is reduced by more than a factor of 100, so one can afford to use much more expensive uranium. For example, uranium costing \$1000/lb would contribute only 0.03 cents/kW h to the cost of electricity and would thus represent less than 1% of the total cost. At that price, the fuel cost would be equivalent to that of gasoline priced at a half cent per gallon.

How much uranium is available at a price of \$1000 per pound? There are large supplies available at far below that cost in the Conway granite of New England and the Chattanooga Shales of Tennessee, but for the longer-range viewpoint we concentrate here on uranium from the oceans. It now seems quite certain that uranium can be extracted from the ocean at well below \$1000 per pound (best estimates are that current technology can produce it at \$200–400 per pound)¹ and there is even some optimism that it can become competitive at current market prices (\$40/lb). It is clear, then, that uranium from seawater must be considered as a completely acceptable fuel for breeder reactors, contributing less than 1% to the cost of electricity. In terms of fuel cost per million BTU, even at \$400/lb the uranium cost is only 1.1 cents, whereas coal costs \$1.25, OPEC oil costs \$5.70, and natural gas costs \$3–4.

Seawater contains 3.3×10^{-9} (3.3 parts per billion) of uranium,¹ whence the 1.4×10^{18} tonne² of water in the oceans contains 4.6×10^9 tonne of uranium. The energy content of uranium burned in a breeder reactor is 1 MW day/g or 1000 GW day/tonne; at 37% efficiency, readily achievable in a breeder reactor, this is 1.0 GWe yr/tonne (GWe = GW of electricity). All of the world's present electrical usage, 650 GWe, could therefore be supplied by the uranium in seawater for $(4.6 \times 10^9 / 650 =)$ 7 million years.

This calculation, however, ignores new uranium being carried into the sea by rivers. Rivers bring 3.2×10^{13} tonne/yr of water into the oceans,³ and their uranium content averages 1.0×10^{-9} (one part per billion),⁴ whence a total of 3.2×10^4 tonne/yr of uranium enter the oceans from this source. This source S is presumably in equilibrium with removal from the oceans by sedimentation at a rate λQ where Q is the quantity of uranium in the oceans. The differential equation for Q is

$$\frac{dQ}{dt} = S - \lambda Q$$

for which the solution with $Q = 0$ at $t = 0$ is

$$Q = (S/\lambda)(1 - e^{-\lambda t})$$

giving an equilibrium $Q = S/\lambda$. Assuming that equilibrium has been reached, $\lambda^{-1} = Q/S = (4.6 \times 10^9 \text{ tonne}) / (3.2 \times 10^4 \text{ tonne/yr}) = 140\,000 \text{ yr}$. Since this is such a short time geologically, it is reasonable to assume that equilibrium

has been reached, and that the value of Q at $t = 0$ is immaterial to the discussion. Moreover, the fact that λ^{-1} is so much longer than the time for dilution of material through the world's oceans, less than 1000 yr,⁵ means that nonuniformity of uranium concentration is not a long-term problem.

If we were to withdraw uranium at a rate R , the differential equation for q would become

$$\frac{dQ}{dt} = S - R - \lambda Q$$

leading to an equilibrium $Q = (S-R)/\lambda = Q_0(1-R/S)$ where Q_0 is the present value of Q . This equilibrium would be approached with a time constant of 140 000 yr. The cost of uranium extraction should be approximately inversely proportional to Q , so if we allow the cost to double, $R = S/2 = 1/6 \times 10^4$ tonne/yr. We thus can withdraw 16 000 tonne/yr of uranium from seawater continuously for hundreds of millions of years. This is enough to produce 16 000 GWe or 480 quadrillion BTU per year which is 25 times the world's present electricity usage, and twice the world's present total energy consumption.

In view of the geological cycles of erosion, subduction, and uplift, this process could continue until a large fraction of the uranium in the Earth's crust, 6.5×10^{13} tonne, is consumed. If we assume that half of that quantity, 3.2×10^{13} tonne, is to be consumed over the remaining 5×10^9 years of the existence of life on Earth, the annual usage could be 6500 tonne/yr. This is enough to produce 6500 GWe, or 200 quadrillion BTU/yr, which is approximately 10 times the world's present electricity consumption, and approximately equal to the world's present total energy consumption. Note that at this consumption rate, $R = 6500$ tonne/yr, $R/S (= 6500/3.2 \times 10^4) = 0.2$, and $Q = Q_0(1-R/S) = 0.8 Q_0$, so the concentration of uranium in the seas would decrease by only 25%. If one used the exact same extraction plant and procedures, one would end up with 80% as much product, so the price of uranium would rise by 25%. Actually one would reoptimize the plant and procedures, so the price would rise by less than 25%.

We thus conclude that all the world's energy requirements for the remaining 5×10^9 yr of existence of life on Earth could be provided by breeder reactors without the cost of electricity rising by as much as 1% due to fuel costs. This is consistent with the definition of a "renewable" energy source in the sense in which that term is generally used.

Nuclear fusion has been advertised as a method for "burning the seas." We see that nuclear fission with breeder reactors is an alternative method for "burning the seas," and it has the considerable advantage that the technology for doing it is in hand.

¹F. R. Best and M. J. Driscoll, *Trans. Am. Nuc. Soc.* 34, 380 (1980); F. R. Best and M. J. Driscoll, *Trans. Am. Nuc. Soc.* 38, 200 (1981).

²1 tonne = 1 metric tonne = 1000 kg.

³R. M. Garrels and F. T. MacKenzie, *Evolution of Sedimentary Rocks* (Norton, New York, 1971).

⁴F. F. Koczy, in *Nuclear Geology*, edited by H. Faul (Wiley, New York, 1954).

⁵B. L. Cohen, *Nuc. Technol.* 47, 163 (1980).