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The Case for Epithermal Breeders

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The primary criteria for the selection of 1000-MW(e) base-load power plants will undoubtedly be reliability, operability, and cost - in that order but with the understanding that costs must be competitive with all comers. Present day light-water low-conversion reactors meet all of these criteria. There is concern, however, that in the future a rising power demand will not be matched with the required supply of low cost uranium and hence breeders are needed.

A type of breeder can be conceived that meets the criteria of reliability and operability equally as well as a light-water low-conversion reactor. It is in fact a light-water breeder using all of the conventional components of light-water low-conversion reactors. Of course, such a concept is based on the Th-U²³³ cycle.

Data for the following concept were taken from Levine.⁽¹⁾ Cross section and physical constant data used in that paper are in conservative conformance with the best data available today.

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Consider first the effect of moderating power on the breeding ratio for a light-water-moderated Th-U²³³ breeder. Results of Chernick and Moore⁽²⁾ for a system unperturbed by any other neutron absorber than the moderator are shown in Table 1.

Table 1. Breeding Ratio vs Moderating Power

$\xi\Sigma_s/N_{23}$	B.R. (H ₂ O)
1,000	1.199
2,000	1.200
5,000	1.139
10,000	1.007

Note that the breeding ratio is sensitive to the resonance factor and exhibits a maximum at a moderating power of 2000.

Let us now examine the effect of other neutron absorbers on the breeding ratio at that same moderating power of 2000.

Assuming that the higher isotopes of uranium are at saturation concentrations, the absorption of higher isotopes lowers the breeding ratio at $\xi\Sigma_s/N_{23} = 2000$ to 1.162. However, at saturation there is a bonus from fast fissions in U²³⁴ and U²³⁶. For light-water moderation with the moderating power = 2000, the extra contribution to the breeding ratio is 0.020. Prior to saturation, the absorption in the higher isotopes

will be less while at saturation the bonus from fast fission will be fully effective so that a reasonable breeding ratio taking into account the higher isotopes appears to be 1.182.

Next let us take into account captures in Pa^{233} . Because of its high resonance integral, Pa^{233} will capture a large number of neutrons at fast spectrums. Assuming a resonance integral of 1200 barns, a specific power of 0.5 MW/kg, and equilibrium Pa^{233} concentrations, the $\Delta\text{B.R.}$ at $\xi\Sigma_s/N_{23} = 2000$ is 0.040. The breeding ratio taking into account Pa^{233} is now 1.142.

Fission products are divided into two groups according to whether or not they saturate. Levine assumed that only those having cross sections $>10^4$ barns saturate (Xe^{135} , Sm^{149} , and Sm^{151}), and that all others have concentrations proportional to the fuel burnup. At a resonance parameter of 2000 and a specific power of 0.5 MW/kg, $\Delta\text{B.R.} = 0.040$. As in standard light-water low-conversion reactors, we will permit the saturating fission products to be locked up with the fuel until burnup makes necessary fuel removal. The breeding ratio is now 1.102.

The nonsaturating fission products at 10% burnup (100,000 MWd/T) and at a resonance parameter of 2000 absorb neutrons such that $\Delta\text{B.R.} = 0.024$. The fuel in this system is assumed to be mixed oxides of U^{233} and

thorium. In order that subsequent fuel dissolution rates in the reprocessing plant be high, 2% MgO is also admixed with the fuel. It is estimated that mixed oxide fuel of this sort will in the near thermal fluxes assumed be able to withstand burnups of 100,000 MWd/T. Although $\Delta B.R.$ at 10% burnup = 0.024, the average $\Delta B.R.$ for the time the fuel is in the reactor is 0.012. The breeding ratio is now 1.090.

The internal supporting structure and the fuel cladding are to be of Zircaloy. With the exception of a few small resonances, zirconium exhibits a $1/v$ behavior. At a moderating power of 2000 and at a zirconium-to-water atom ratio of 0.07 (estimated from the cladding and structure of a light-water reactor), I have estimated the $\Delta B.R.$ to be 0.07 times the light-water $\Delta B.R.$ (0.06 from ref. 1). The $\Delta B.R.$ due to zirconium is thus 0.004. The breeding ratio is now 1.086.

Thorium oxide-uranium dioxide fuels of the type described can be reprocessed by known aqueous processes with U^{233} process losses no greater than 0.1% per core reprocessed. (Incidentally, the losses for Pu^{239} reprocessing will be considerably greater because of the more complex chemistry of Pu.) At 10% burnup, there will be 10 core reprocessings for complete burnup with a $\Delta B.R.$ of 0.01. Taking processing losses into account, the breeding ratio is now 1.076.

In this concept, control will be accomplished by thorium control rods, and leakage will be a small fraction of one percent. Thus with all of the losses taken into account, a breeding gain of 1.07 appears achievable.

An alternative case has been taken for a higher specific power, namely, 1 MW(t)/kg₂₃. In this case, the Pa²³³ and Xe¹³⁵ will have a much greater absorption at the same moderating power than that in the previous case, so that a larger moderating power of 3500 was assumed. The pertinent data for the breeding ratio calculations are given in Table 2.

Table 2. Breeding Ratio at Moderating Power of 3500

<u>Contributor</u>	<u>ΔB.R.</u>	<u>Net B.R.</u>
Higher isotopes		1.138
Fast fission	(0.009)	1.147
Pa ²³³ *	0.028	1.119
Saturating F.P.'s	0.048	1.071
N.S.F.P.'s (av)	0.010	1.061
Zr clad and structure	0.007	1.044
Reprocessing loss	0.010	1.034
Leakage	0.004	1.03

* Pa²³³ loss averaged by fuel shift.

The Pa²³³ contribution given above is an average on the assumption that the fuel can be shifted out of high flux regions at monthly intervals.

An illustration of this concept is given in Figure 1.

For both reactors, the core is surrounded by about a 15-ton close-packed thorium blanket. The blanket thorium in the upper and lower sections is located in the fuel type holes and serves also as control rods. At reactor start-up, in order to hold down the considerable excess reactivity, sufficient thorium control rods are lowered into the core to counteract the poisons subsequently to be generated by Pa^{233} , saturating fission products, and nonsaturating fission products. After about one day, Xe^{135} has come to equilibrium. The thorium control rods equivalent to Xe absorption are withdrawn at the rate Xe^{135} accumulates. Similarly, the thorium control rods equivalent to the other poisons are withdrawn at the rate that these accumulate. For the reactor concept in Figure 1, recall that the fuel rods are shifted from top to bottom at monthly intervals to average out the Pa^{233} poison. Thorium control rods equivalent to the Pa^{233} are withdrawn as Pa^{233} accumulated in the central portion of the core and are installed again when a fuel shift returns bred U^{233} to the central portion of the core. Thus it appears that a breeding ratio of 1.07 can be obtained at a moderating power of 2000 and a specific power of 0.5 MW(t)/kg₂₃ (to be termed reactor design EB1) and a breeding gain of 1.03 can be obtained at a moderating power of 3500 and a specific power of 1 MW(t)/kg₂₃ (to be termed reactor design EB2).

It can be shown that at these moderating powers the water-to-thoria volume ratios are simple functions of the enrichment as follows:

$$\text{At } \frac{\xi \Sigma_s}{N_{23}} = 2000,$$

$$\frac{W}{\text{ThO}_2} = 32.3 E, \text{ where } E = \text{weight fraction of } ^{233} \text{ in thoria}$$

$$\text{At } \frac{\xi \Sigma_s}{N_{23}} = 3500,$$

$$\frac{W}{\text{ThO}_2} = 56.7 E$$

The remainder of the design, then, consists of picking an enrichment that will (1) satisfy criticality considerations, and (2) satisfy the thermal and hydraulic parameters of a realistic reactor.

I have assumed that any enrichment over 1% will satisfy criticality considerations for the large $\text{ThO}_2\text{-U}^{233}$ water-moderated reactor involved.

In order to come up with a realistic thermal and hydraulic system, I have used the Westinghouse design of 1000-MW(e) closed cycle water reactor as a model for comparison. (3)

The Westinghouse water reactor (which I shall term WWR) has the following characteristics important to this design.

Core thermal power	3220 MW
System pressure	2050 psia
Av fuel temperature in core	1535°F
Fuel pellet diameter	0.354 in.
Clad thickness (Zr)	0.015 in.
Fuel length	132 in.
Total number of fuel rods	51,216
Core power density	80.7 kW/liter
Core specific power	1.83 MW(t)/kg U ²³⁵
Core volume UO ₂	12,000 liters
Core volume H ₂ O	28,000 liters

After a series of trial and error calculations, I chose enrichments consistent with the design moderating powers that resulted in power densities similar or less than WWR assuming that the thermal efficiency of the new systems would be the same as the WWR. The results are as follows:
(for comparison, WWR figures are also given)

	$\frac{\xi \Sigma_s}{N_{23}}$	Specific power, MW(t)/kg ₂₃	E, %	Thermal power, MW	ThO ₂ , tonnes	ThO ₂ , liters	H ₂ O, liters	Power density, kW/liter	Core volume, liters
EB1	2000	0.5	4	3200	185	19,100	24,800	73	43,900
EB2	3500	1	2	3200	186	19,500	22,000	77	41,500
WWR	3500	1.83	3	3200	131 (UO ₂)	12,000	28,000	80.7	40,000

Note that the enrichments are such that the reactor should be critical.

Note also that the core volumes are about the same as those of the WWR but that even if they were normalized to the same volume there would be less water in both EB1 and EB2 than in the WWR. Essentially, because of the lower density of ThO₂ as compared with UO₂ and because of the harder spectrum in EB1, water must be squeezed out of the epithermal designs to be consistent with the specific powers and enrichments chosen.

If we assume that the EB1 and EB2 fuel rods are kept at the same spacing (pitch) as those in the WWR and have the same length as in the WWR, the appropriate water-to-ThO₂ ratios can be obtained by increasing the pellet diameters. This results in a pellet diameter of 0.42 in. for EB1 and 0.43 in. for EB2. This change actually improves the thermal characteristics of these reactors as compared with the WWR and remains within the capabilities of the materials covered.

The power level of the reactor is fixed by the heat transfer across the surface of the fuel elements.

$$P = UA(T_{\text{fuel}} - T_{\text{coolant}})$$

The maximum temperature at the center line of the thoria fuel rod will bear the following ratio to the maximum temperature of the urania rod (assuming the same power level in both reactors).

$$\frac{\Delta T_{\text{thoria}}}{\Delta T_{\text{urania}}} = \frac{\frac{P r_{\text{thoria}}^2}{\text{liters thoria} \times k_{\text{thoria}}}}{\frac{P r_{\text{urania}}^2}{\text{liters uranium} \times k_{\text{urania}}}} = \frac{\frac{P(0.42)^2}{19,100 \times 0.008}}{\frac{P(0.354)^2}{12,000 \times 0.008}} = 0.9$$

Thus the fuel temperature will remain about the same under these assumptions although, if desired, because of the higher melting points of thoria, we could permit the maximum thoria temperature to exceed that of urania by a factor of 1.3. Let us retain the temperature of the coolant the same as that of the WWR so that the pressure in the vessel remains the same, and operate at about the same fuel temperature so that the over-all temperature gradient is the same as that of the WWR. Even so, we have increased the surface area by a factor of 20% and increased the velocity in the channels so that the heat transfer coefficient should be greater. We will have to pay by way of a greater pressure drop but the increased pumping power will certainly be less than the 20% increase in thermal power extracted.

Rather than going through a detailed thermal-hydraulic analysis, however, I believe the following conclusions have now been established.

1. That light-water-moderated epithermal reactors can breed at specific powers in the region of 0.5 to 1 MW(t)/kg₂₃.
2. That they can be designed with such thermal and hydraulic characteristics that their thermal efficiencies will be as great as conventional low conversion light-water reactors.

However, if they are to be selected by utilities, epithermal breeders also must involve costs no greater than conventional light-water reactors and furthermore, no greater than the costs of the fast breeders which are promised in the relatively near future.

I have attempted to make an analysis of the relative costs of epithermal light-water breeders to fast breeders and low-conversion light-water reactors.

EB1 is compared with the Westinghouse Fast Breeder design and EB2 with the General Electric Fast Breeder design. Design data were taken from the normalized evaluations in COO-279.⁽⁴⁾ The pertinent characteristics of these reactors are as follows:

	<u>WFB</u>	<u>EB1</u>	<u>GEFB</u>	<u>EB2</u>
Breeding ratio	1.57	1.07	1.25	1.03
Enrichment, %	15.7	4	18	2
Fissile inventory, kg	3900	6400	2400	3200
No. of fuel pins	50,000	51,000	128,000	51,000
Pellet o.d., in.	0.27	0.42	0.22	0.43

An analysis of the costs of these reactors is given in Table 3.

Table 3. Power Costs of Breeder Reactors (m/kWh)

	<u>WFB</u>	<u>PI*</u>	<u>EB1</u>	<u>PI</u>	<u>GEFB</u>	<u>PI</u>	<u>EB2</u>	<u>PI</u>	<u>EB1**</u>	<u>PI</u>
Fuel cycle cost										
Fabrication	0.40	[0.3]	0.30	[0.20]	0.42	[0.30]	0.30	[0.2]	0.30	[0.2]
Inventory	0.62		1.02		0.40		0.54		0.77	
Shipping	0.07		0.07		0.07		0.07		0.07	
Reprocessing	0.34	[0.55]	0.14	[0.10]	0.31	[0.49]	0.14	[0.1]	0.14	[0.1]
Fissile credits	(0.57)	[0.20]	(0.07)	[0.02]	(0.34)	[0.16]	(0.04)	[0.04]	(0.07)	[0.02]
Total fuel cycle cost	0.86	[1.05]	1.46	[0.32]	0.86	[0.95]	1.01	[0.24]	1.21	[0.32]
Operating costs	0.34		0.25		0.34		0.25		0.25	
Capital costs	<u>2.50</u>	[0.50]	<u>2.20</u>	[0.02]	<u>2.50</u>	[0.50]	<u>2.20</u>	[0.02]	<u>2.20</u>	[0.02]
Total costs	3.70	[1.55]	3.91	[0.34]	3.70	[1.45]	3.46	[0.34]	3.66	[0.34]
Max costs including possible increases	5.25		4.25		5.15		3.95		4.00	

Low-conversion light-water reactor costs at ~1975 = 3.66 m/kWh

*PI = Possible Increases.

**EBI assumes second core is conventional UO₂ core.

These costs were arrived at as follows. The fabrication costs for the Westinghouse Fast Breeder (WFB) and the General Electric Fast Breeder (GEFB) are the normalized values from COO-279. The remote fabrication of mixed $\text{UO}_2\text{-PuO}_2$ at 15 to 18% Pu content (involving small batches for criticality control) in pins of 0.22 to 0.27-in. diam with possible hollow cores will certainly be more expensive than the remote fabrication of $\text{ThO}_2\text{-U}^{233}\text{O}_2$ pins of 2 to 4% enrichment (permitting larger scale operations) and of 0.42 to 0.43-in. diam. I have allowed a reduction in cost by a factor of 1.3 for EB1 and EB2. Note that these costs are still higher than the cost of conventional fuel fabrication by a factor of 2. I have also estimated possible increases in fabrication costs for both fast and epithermal reactors. These are estimated as 0.3 m/kWh for fast fuels and 0.2 m/kWh for epithermal fuels, and are considered to be due to possible higher manufacturing costs. Of course, if, in addition only half the assumed burnup of 100,000 MWd/T is found to be possible, the fabrication costs will almost double.

COO-279 included a small capitalization charge the meaning of which was not clear. I am neglecting this charge and including all capitalization costs in an inventory charge. One of the ground rules of the COO-279 report was the assumption of AEC ownership of fuel and a 4.75% use charge. Let us update this to assume private ownership of fuel at a 9.5% interest charge.

Taking into account the inventories of the various reactors and assuming 1.3 cores per reactor for inventory (inventories in reprocessing and fabrication are taken into account separately), results in the inventory costs shown in Table 3. The values shown in column 5 of Table 1 are for EB1 on the assumption that the first core is the $\text{ThO}_2\text{-U}^{233}\text{O}_2$ breeder core but that it is replaced with a low-conversion UO_2 core while the first core is being reprocessed. This does not extend the uranium reserves as far, but has an appreciable effect in lowering inventory costs.

The shipping and reprocessing charges have been updated from COO-279 by taking into account the recent Argonne study on costs of processing fast breeder reactor fuels. (5)

Shipping costs are assumed to be the same for all fuels. The most optimistic value (volatility process) was taken for the fast breeder carbide and oxide fuels with the most pessimistic value taken as the possible increase in reprocessing costs for these fuels. These costs are high because the high fissile material content requires criticality control in the reprocessing plant forcing one to batch operations and relatively small scale plants. Even these estimates are probably at least 10% low because the assumption was made that the reprocessing industry would be satisfied with the same low rate of return on investment (7%) as the utilities. On the other hand, the low fissile

content in the epithermal fuels will permit all the advantages of a large scale aqueous process to be accrued and the AEC projected costs for such processes should be applicable to the epithermal fuels.

The Pu and/or U^{233} credit shown reflects the breeding ratio of the reactor. The possible credit decreases are due to poorer physics.

Operating costs as estimated by GE and Westinghouse were used for the fast breeders and operating costs as estimated by Westinghouse for light-water reactors were used for the epithermal light-water breeders.

Construction costs of \$125/kW at private ownership interest rates and 80% load factor were used to arrive at the capital costs for the fast breeders whereas construction costs of \$110/kW and the same load and interest conditions were used for the epithermal breeders. The estimated possible increases are due to reduced capacity factors (from 80 to 70%) and higher construction costs (\$10/kW).

My conclusions are that both fast breeders and epithermal light-water breeders can probably be built at costs competitive with light-water low-conversion reactors but that the uncertainties in the fast breeder system are equivalent to at least 1 m/kWh greater than the uncertainties in the epithermal light-water breeder.

Of course the epithermal light-water breeder is not the solution to the very long term resources replenishment problem. However, it should extend our resources for a very considerable period of time and in that time period provide sufficient competition to uranium to keep uranium prices down. To extend our resources even further it is possible to design a graphite moderated epithermal gas-cooled reactor breeder which can have specific powers as high as 7 MW(t)/kg_{233} . In order to operate at this high specific power the reactor will have to operate at very high temperatures and permit the fission products to escape the fuel. The high temperatures will permit the ultimate application of a Brayton cycle or an MHD system with ensuing higher efficiencies. A concept of such a reactor is shown in Figure 2.

This analysis has attempted to show that there are paths in epithermal breeding that have not yet been explored. It is my hope that reactor designers will think them sufficiently interesting to seriously exploit them.

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PRESSURIZED WATER Ep THERMAL BREEDER REACTOR

FIG. 1

NOTE:
PERIODICALLY CERTAIN
CORE FUEL ELEMENTS
ARE SHIPPED FROM
RIGHT SIDE TO LEFT
SIDE & LEFT SIDE TO
RIGHT SIDE OF CORE
THIS SHIFTERING IS DONE
BY THE FUEL ELEMENT
DRIVES WITHOUT RE-
MOVING THE HEADS

GAS COOLED E_p THERMAL BREEDER REACTOR

FIG. 2