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AN ECONOMIC ANALYSIS OF FUSION BREEDERS*

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ABSTRACT

This paper presents a study of the economic performance of Fission/Fusion Hybrid devices. This work takes fusion breeder cost estimates and applies methodology and cost factors used in the fission reactor programs to compare fusion breeders with Liquid Metal Fast Breeder Reactors (LMFBR). The results of the analysis indicate that the Hybrid will be in the same competitive range as proposed LMFBRs and have the potential to provide economically competitive power in a future of rising uranium prices. The sensitivity of the results to variations in key parameters is included.

INTRODUCTION

The purpose of this paper is to present the results of a study on the economic performance of Fission/Fusion Hybrid devices. The principal objective of the study was to obtain a perspective on the factors which drive the economic viability of Fission/Fusion Hybrid devices. The Hybrid concepts analyzed here are based on work done at Lawrence Livermore National Laboratory (LLNL) (Ref. 1). Physics and technical information for the Hybrid were obtained from the LLNL work. Economic Methodology, financial, and cost factors used in the analyses were obtained from sources other than LLNL.

The fuel cycle considered is one where ^{233}U is produced in Hybrid devices by neutron capture in thorium. This ^{233}U is sold to ^{233}U burning fission reactors. Three Hybrid designs and three ^{233}U burners were considered. The Hybrids differ only in the blanket design. The reference pebble bed design consists of thorium metal attached (clips) to beryllium balls in lithium coolant (OPT-Li). Two alternate designs, the MS(1.6) and MS(2.5), use a molten salt blanket. The two systems differ in the blanket energy multiplication with the MS(2.5) Hybrid having a higher electric power output than the MS(1.6) Hybrid.

The three ^{233}U burning fission reactors were all on a denatured fuel cycle. The reference reactor was a light water reactor (LWR) but a High Temperature Gas Cooled Reactor (HTGR) and Molten Salt Reactor (MSR) were also considered.

In order to provide some perspective on the results of the economic analysis of the Hybrid concepts, the economics of Liquid Metal Fast Breeder Reactors (LMFBR) were also examined using a consistent methodology and economic parameters.

METHODOLOGY AND PROCEDURES

The basic economic methodology used in the analysis is that presented in the Nuclear Energy Cost Data Base[2] (NECDB). With the NECDB methodology, the present worth of the income received from power and net fissile sales must equal the present worth of the costs, including fuel expenses. The levelized power cost and/or fissile material value are determined in reference years (1983) dollars. The basic figure of merit used to evaluate the Hybrid (and LMFBR) is the price to which uranium ore must rise in order for the Hybrid to be economically competitive with LWRs. This breakeven uranium price is a constant dollar levelized price over the project life.

The Hybrid is essentially a fuel factory. In its fuel cycle, ^{233}U is produced as the primary product, with some electric power also produced. This ^{233}U is assumed to be sold to a fission reactor which is on a denatured ^{233}U in thorium fuel cycle [DU3(Th)]. ^{233}U recovered from the fission reactor is recycled back to the reactor. A small amount of fissile plutonium is also recovered. This is recycled to a plutonium burning LWR [Pu(U)].

A competitive purchase price for ^{233}U and fissile plutonium may be obtained, independent of the Hybrid, using the indifference value technique. This method was used in the Nonproliferation Alternative Systems Assessment

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Program[3] (NASAP) and is described in Ref. 4. The power cost for the LWR plutonium recycle system is assumed to be the market price for power and therefore the price at which the Hybrid can sell the power it produces. A production cost for ^{233}U from the Hybrid can then be determined. The Hybrid is economic when this production cost is equal to the purchase price determined from fission reactor economics alone. The Hybrid breakeven uranium ore (U_3O_8) price is the value of U_3O_8 where this ^{233}U equality occurs. The LMFBR uranium breakeven price is determined in a similar way to that for the Hybrid except that no ^{233}U is involved.

DATA BASE

Reference technical and financial parameters are summarized in Table 1. The source of this information is the NECDB with the exception that the decommissioning cost for all systems, including the Hybrid and LMFBR was taken to be 10% of the total overnight costs. This is consistent with the NECDB estimate of $130 million for an 1100 MWe LWR.

Table 1. Technical and financial parameters

Plant economic life, years	30
Reference year	1983
Plant capacity factor, %	65
Total plant lead time, years	8
Inflation rate, %/year	6
Effective cost of money[a]	9.0
Government bond rate,[a] %/year	8.5
Decommissioning cost, % of total overnight costs	10
Fixed charge rate,[c] %/year	
Utility	16.7
Industrial	25.5

[a]Current dollar rates.

Estimated total capital investment costs are given in Table 2. The two LMFBR cost estimates shown represent a range of current estimates for future plants from an 11% cost premium to a 37% cost premium over the cost of a similar size LWR. The basic Hybrid capital investment costs are based on pre-conceptual design cost estimates furnished by LLNL. Other studies[5] indicate that improved versions of fusion reactors may lead to lower investment costs for fusion plants. The sensitivity analysis later in this paper contains factors for evaluating the effect of alternate investment costs. The HTGR capital investment costs have the same ratio to LWR capital investment costs as estimated in the NASAP studies.[3] The molten salt reactor (MSR) capital investment costs were estimated assuming that the ratio of the MSR direct costs and indirect costs to those for LWRs are the same as in Ref. 6. A 10% contingency was assumed for the LWR, HTGR and LMFBR. A 15% contingency was assumed for the more preliminary Hybrid and MSR designs. The construction time and cash flow profile for the Hybrid, LMFBR, HTGR and MSR were assumed to be the same as for the LWR.

Table 2. Capital investment cost
(1983 dollars)

Plant type	Power level (MWe)	Capital investment cost[a] ($/KWe)
LWR	1100	1390
LMFBR-High	1100	1900
LMFBR-Low	1100	1540
HTGR	1100	1455
MSR	1100	1570
Fission/Fusion Hybrid		
OPT-Li	1720	3810
MS(1.6)	1290	4110
MS(2.5)	2005	3270

[a]Includes direct, indirect, contingency and interest costs.

Operation and maintenance (O&M) cost estimates are shown in Table 3. The O&M costs for the fission reactors are based on recent estimations made with the OMCOST[7] computer program or using ratios of O&M costs (for HTGRs & MSRs) calculated using older versions of OMCOST. The Hybrid O&M cost was calculated using the LLNL[1] estimate of 2% of the total overnight costs plus $15 million per year.

Table 3. O&M costs
(1983 dollars)

	10^6 $/year
Fission Reactors	
LWR	43[a]
HTGR	40[a]
MSR	54[a]
LMFBR	46[a]
Fission/Fusion Hybrid[b]	
OPT-Li	124
MS(1.6)	104
MS(2.5)	124

[a]Excludes fuel cost.

[b]Includes all fuel costs except reprocessing.

Estimates of nuclear fuel cycle cost parameters are given in Table 4. The parameters for the LWRs and the LMFBRs are based on

Table 4. Nuclear fuel cost parameters (1983 dollars)

U_3O_8, \$/lb	Variable
Thorium, \$/kg	35
Enrichment, \$/SWU	100
U_3O_8-UF_6 conversion, \$/kgU	8
Fuel fabrication, \$/kg HM	
LWR-LEU	200
LWR-Pu,U	640
LWR-^{233}U,Th	1000
HTGR	1050 (11,700)[a]
LMFBR-Pu,U core	1650
LMFBR-U blanket (radial)	300
Hybrid fuel	*b*
Spent fuel shipping, \$/kg HM	
LWR	30
HTGR	270 (3,000)[a]
LMFBR	85
Reprocessing, \$/kg HM	
LWR - U, Pu	390
LWR - ^{233}U, Th	620
HTGR	660 (7,400)[a]
MSR	10
LMFBR	620
Hybrid-Aqueous	620
Hybrid Pyro	300
Hybrid-molten salt	10
Waste disposal,[c] mills/kWh(e)	1

[a] \$/fuel block.

[b] Included in reprocessing costs.

[c] Not included in Hybrid costs.

the NECDB and NASAP information. The enrichment cost assumes some advanced technology. The HTGR process costs were estimated based on HTGR program information. The Hybrid aqueous and pyro reprocessing costs are based on preliminary estimates as are the molten salt reprocessing cost estimates. All of the reference fuel fabrication and fuel reprocessing cost estimates assume industrial (private) financing of the facility.

Fission/Fusion Hybrid and LMFBR support ratios are shown in Table 5. The support ratio is defined here as the number of 1 GWe converter reactors supported by the reference size Hybrid (or a 1 GWe LMFBR). It is calculated by using total 30 year fissile material mass flow quantities (including recovery of final core discharge). Since the MSR has an effective conversion ratio of 1.0, it has no net ^{233}U use and therefore has an infinite support ratio. However over its lifetime, a Hybrid will produce enough ^{233}U to start 65 MSRs, compared to starting and sustaining about 15 LWRs or 19 HTGRs on the DU3(Th) cycle.

Table 5. Support ratios

System	Support ratio[a,b]
Hybrid - LWR	22.0
Hybrid - HTGR	26.4
Hybrid - MSR	Infinite
LMFBR - LWR	0.5

[a] Ratio of GWe of converter reactors supported by each of the reference size hybrid systems or by a 1 GWe LMFBR.

[b] Includes LWR-Pu(U) reactors supported by plutonium produced in DU3(Th) fuel cycles.

REFERENCE RESULTS

The estimated power generation costs for LWR recycle, LMFBRs, and the OPT-Li Hybrid with both an LWR and HTGR DU3(Th) cycle are shown in Fig. 1 as a function of levelized Uranium Ore (U_3O_8) price. The LWR recycle system [LWR-LEU + LWR-Pu(U)] shows a strongly rising cost with uranium price. The LMFBR's power costs increase slightly with uranium price since the levelized effect of the initial plutonium purchase is slightly greater than the levelized effect of the sales during operation and plutonium price rises as uranium price increases. The power generation cost for the Hybrid systems is insensitive to uranium price except for the small amount of plutonium sold.

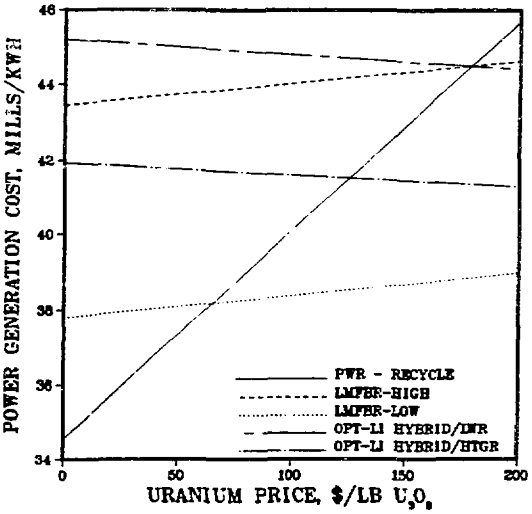

Fig. 1. Power generation cost for selected systems.

The uranium price at which the power costs for the LMFBRs or Hybrids are equal to the power cost from the LWR recycle system is the uranium breakeven price. At reference parameters, the LMFBR-High and the OPT-Li Hybrid/LWR-DU3(Th) have virtually the same breakeven uranium price. The use of the HTGR-DU3(Th) reactor reduces the uranium breakeven price for the OPT-Li Hybrid by about $50/lb. The breakeven uranium price for the LMFBR-Low is about $115/lb lower than that for the LMFBR-High design.

Figure 2 shows the power generation cost for various Hybrid/converter reactor combinations. In all cases the Molten Salt Hybrids show a smaller power cost than the OPT-Li Hybrid with the higher power production MS(2.5) showing slightly less cost than the MS(1.6) version. The combination of a Molten Salt Hybrid with either an MSR or an HTGR results in a close grouping of power costs with the HTGR systems having slightly less cost at reference conditions.

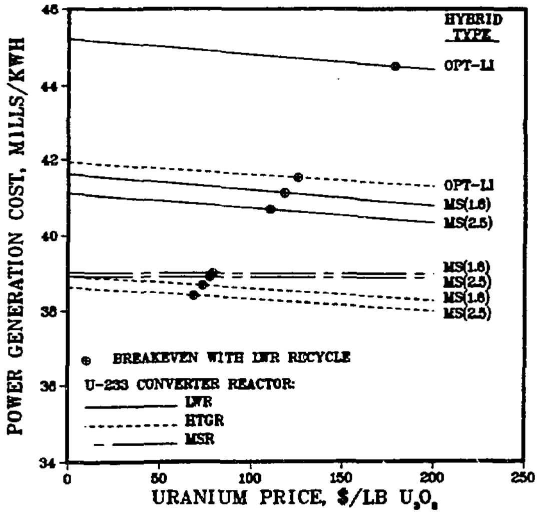

Fig. 2. Power generation cost for hybrid systems.

A tabulation of reference uranium breakeven prices for various Hybrid/ converter reactor system combinations and for the LMFBRs are shown in Table 6. The values in parentheses are estimated uranium breakeven prices at the reference pyro reprocessing unit cost. Pyro reprocessing appears to be cheaper than aqueous reprocessing but has a greater uncertainty. The results show the Hybrid in the same competitive range as the LMFBR. Sophisticated financing arrangements or government ownership of the Hybrid fuel factory could reduce its uranium breakeven price to near current uranium price levels. These arrangements, however, are inconsistent with the current political climate and regulatory rules.

Table 6. Breakeven uranium price for fission/fusion hybrid systems and for LMFBRs

(1983 $/lb·$U_3O_8$)

	Fission reactor[a]		
	LWR	HTGR	MSR
Hybrid			
Opt-Li	179 (146)[b]	125 (98)[b]	[c]
MS(1.6)	118	74	79
MS(2.5)	110	69	77
LMFBR			
High	179		
Low	65		

[a] DU3(TH) for Hybrids, Pu(u) for LMFBR.

[b] Breakeven price with pyro reprocessing.

[c] Not estimated.

SENSITIVITY ANALYSIS

Since there is great uncertainty in many of the technical and cost parameters, a sensitivity analysis was made on key parameters. The breakeven uranium price is linear with variations in many of the parameters. The sensitivities of the breakeven uranium price to parameter variations for the Hybrid/LWR-DU3(Th) combination are shown in Table 7. Similar information is shown in Tables 8 and 9 where the DU3(Th) reactor is an HTGR or MSR respectively. Sensitivities for the LMFBR are shown in Table 10. The values in Tables 7-10 are the change in the breakeven uranium price

Table 7. Sensitivity of breakeven uranium price for fission/fusion hybrids in combination with LWRs on a denatured ^{233}U fuel cycle

($/lb change in uranium price/1% parameter change)

1% change in reference parameter[a] for	Hybrid system	
	Li-Be	MS(1.6)
Hybrid capital investment	1.246	1.043
LWR capital investment cost (cost ratios unchanged)	0.793	0.692
Hybrid O&M cost	0.269	0.234
Hybrid fuel reprocessing cost	0.628	0.105
DU3(Th) fuel fabrication cost	0.746	0.769
DU3(Th) fuel recovery cost	0.367	0.378
Enrichment price	−0.316	−0.316
LWR-Pu(U) fuel fabrication cost	−0.098	−0.097
LWR-Pu(U) fuel recovery cost	−0.290	−0.289

[a] Reference parameters given in Tables 2-4.

Table 8. Sensitivity of breakeven uranium price for fission/fusion hybrids in combination with HTGRs on a denatured ^{233}U fuel cycle

($/lb change in uranium price/1% parameter change)

1% change in reference parameter[a] for	Hybrid system	
	Li-Be	MS(1.6)
Hybrid capital investment	1.043	0.869
LWR capital investment cost (cost ratios unchanged)	0.818	0.734
HTGR capital investment cost	3.409	3.494
Hybrid O&M cost	0.225	0.195
HTGR O&M cost	0.972	0.997
Hybrid fuel reprocessing cost	0.526	0.0874
HTGR fuel fabrication cost	0.465	0.477
HTGR fuel recovery cost	0.309	0.316
Enrichment price	-0.315	-0.315
LWR-Pu(U) fuel fabrication cost	-0.109	-0.108
LWR-Pu(U) fuel recovery cost	-0.294	-0.294

[a] Reference parameters given in Tables 2-4.

Table 9. Sensitivity of breakeven uranium price for MS(1.6) fission/fusion hybrids in combination with MSRs on a denatured ^{233}U fuel cycle

1% change in reference parameter[a] for	$/lb change in uranium price
Hybrid capital investment	0.293
LWR capital investment cost (cost ratios unchanged)	0.678
MSR capital investment cost	4.210
Hybrid O&M cost	0.066
MSR O&M cost	1.502
Hybrid reprocessing cost	0.020
MSR fuel reprocessing cost	0.687
Enrichment price	-0.309
LWR-Pu(U) fuel fabrication cost	-0.150
LWR-Pu(U) fuel recovery cost	-0.310

[a] Reference parameters given in Table 2-4.

for a 1% change in a parameter from its reference value. *Only one parameter was changed at a time*; all other parameters remained at their reference values.

Any increase in cost parameter values which raise the LWR-plutonium recycle power costs without impacting the ^{233}U system costs will produce a decrease in the uranium breakeven price. Such factors are the price of enrichment and the plutonium fuel fabrication or reprocessing costs. Changes in parameter values which increase the Hybrid, DU3(Th) reactor, or LMFBR power generation costs will cause the uranium breakeven price to increase.

Table 10. Sensitivity of breakeven uranium price to a 1% change in reference parameters for LMFBRs

1% change in reference parameter[a] of	$/lb change in uranium price
LMFBR capital investment cost	5.91
LWR capital investment cost (cost ratio unchanged)	
LMFBR-HIGH	1.60
LMFBR-LOW	0.461
LMFBR O&M cost	1.48
LMFBR core fuel fabrication cost	0.449
LMFBR blanket fuel fabrication cost	0.169
LMFBR fuel recovery cost	0.550
Enrichment price	-0.295
LWR-Pu(U) fuel fabrication cost	-0.254
LWR-Pu(U) fuel recovery cost	-0.351

[a] Reference parameters given in Tables 2-4.

Systems with lower support ratios are more sensitive to changes affecting the breeder costs, whether the breeder is a Fission/Fusion Hybrid or an LMFBR. This is because the system cost of the Hybrid or LMFBR is averaged in with its client reactor. In the same sense, systems with a high support ratio show a greater sensitivity to changes affecting the client reactors. This effect is sometimes clouded by fuel cycle differences such as fuel burnup for LWRs and HTGRs.

The breakeven uranium price is nonlinear with variations in several parameters. One of the more important of these is the system capacity factor. The uranium breakeven price as a function of the plant capacity factor is shown in Fig. 3 for selected systems. For the LMFBR/LWR Plutonium recycle system, the capacity factors of all the fission reactors, including the LMFBR were varied together. For the Hybrid systems, the capacity factor for the Hybrid was varied by itself (solid line) and also the capacity factor of the Hybrid and the fission reactors were varied together (dash line). Since the Hybrid is essentually a ^{233}U fuel factory whose operation is driven by ^{233}U demand whereas the fission reactor's operation is driven by electric demand, the capacity factors for Hybrids and fission reactors will not necessarily be the same.

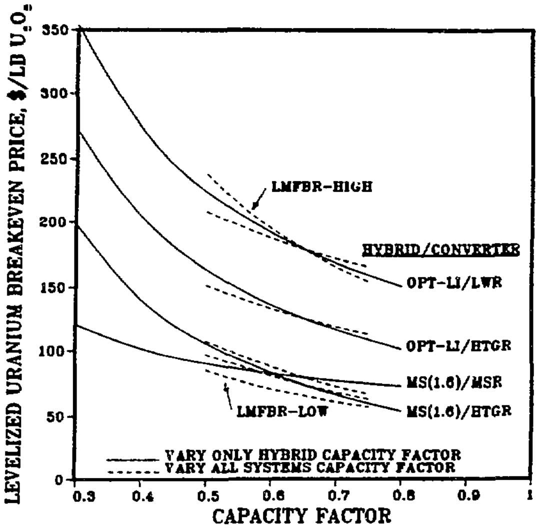

Fig. 3. The effect of system capacity factor on uranium breakeven price.

The uranium breakeven price for Hybrid systems using MSRs as the client reactor is less sensitive to changes in the Hybrid capacity factor than if LWRs or HTGRs are the client reactor. If all capacity factors are varied together, the uranium breakeven price for the Hybrid/LWR and Hybrid/HTGR systems are less sensitive to capacity factor changes than if only the Hybrid Capacity factor was varied. The opposite is true for the Hybrid/MSR because the power generation cost of Hybrid systems with MSR client reactors is virtually independent of Hybrid system costs.

SUMMARY AND CONCLUSIONS

The analysis of the economics of the Fission/Fusion Hybrid has shown that these systems will probably be in the same competitive range as proposed LMFBR designs. The reference OPT-Li Hybrid with an LWR-DU3(Th) client reactor is estimated to have the same uranium breakeven price as the LMFBR-HIGH design. The Hybrid systems are less dependent on Hybrid cost uncertainities than the LMFBR is to LMFBR cost uncertainties. This is because the Hybrid can support more of it's client reactors than the LMFBR can support plutonium consuming LWRs. However, the Hybrid systems economics are strongly dependent on the costs of the client DU3(Th) reactors.

The LMFBR-LOW design is at the low end of the reference LMFBR uranium breakeven price range of $65 to $179/lb. The LMFBR capital costs may be conservative. Innovative conceptual designs for the LMFBR are now being developed which have as their design goal capital costs similar to those for LWRs. The economics of the Fission/Fusion Hybrid can also be improved. Optimization with reduced capital investment costs are also a possibility here. A 25% reduction in the Hybrid capital investment cost would reduce the uranium breakeven price by as much as $30/lb. A Molten Salt blanket or the use of an HTGR as the client reactor will reduce the breakeven uranium cost by $50-60/lb. The use of the Molten Salt blanket and either an HTGR or MSR as the client DU3(Th) reactor will reduce the estimated uranium breakeven price to the $70-80/lb range. Government financed Fission/ Fusion Hybrid fuel factories, serving a function similar to today's enrichment plants, could drop the breakeven price into the same range as the "innovative" LMFBR designs.

The analyses given in this paper are based on calculations of static systems of reactors where all systems are assumed to start operation at the same time. Further work would involve analysis of the implementation of the system and its economics.

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