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Economic Analysis of a Magnetic Fusion Production Reactor[1]

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The magnetic fusion reactor for the production of nuclear weapon materials, based on a tandem mirror design, is estimated to have a capital cost of $1.5 billion and to produce 10 kg of tritium/year for $22,000/g or 940 kg/year of plutonium in the plutonium mode for $250/g plus heavy metal processing. A tokamak-based design is estimated to cost $1.5 billion and to produce 10 kg of tritium/year for $29 thousand/g. For comparison, a commercially sized tandem mirror fusion breeder selling excess electricity and fissile material to commercial markets is estimated to cost $3.6 billion and to produce tritium for $2.6 thousand/g and plutonium for $34/g plus heavy metal processing.

KEY WORDS: magnetic fusion production reactor; tritium production; fusion breeder; economic analysis.

INTRODUCTION

This paper is a report on the results and methods used to estimate the cost of nuclear weapon materials produced by magnetic fusion. It is one of a series of reports[1–6] on an FY 1982 study into the use of magnetic fusion for materials production. Information used in this economic analysis is documented in the series. In some cases, preliminary information was used because of the concurrent nature of the work, but the differences are considered to be minor.

In addition to the technical uncertainty inherent in a new technology, there is the rather mundane but important aspect of how to analyze economic performance. For our analysis, we chose to approximate the method used to analyze another candidate for materials production, the electronuclear breeder (ENB) reactor.

It must be emphasized that the cost estimates calculated here are uncertain mainly because fusion is still in the research and development stage. Plasma physics and engineering will experience both improvements and setbacks relative to our present concepts. While such research and development must be done, we feel the prospects for success are good. Our optimism is based partly on results expected from the already large research and development budget of $0.5 billion/year, which is evidence of a national commitment to fusion research and development.

Our cost estimates are also uncertain because of the limited amount of work done to date on the design and costing of the particular conceptual designs. Even if the plasma physics is as advertised, significant ambiguities still exist for more conventional issues such as balance-of-plant (BOP) costs. Man-hours must be expended to address such issues. No realistic engineering development program has been worked specifically for the materials producer,

[1]This paper represents work carried out from 1980 to 1982 and was in draft form in 1982. It was received for publication with only minor editing of its 1982 version, explaining the fact that some of the material is dated.

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but program plans exist for fusion engineering research and development. To date, only 2.5 man-years of effort have been expended to study the weapon materials production role for fusion.

ECONOMIC ASSESSMENT METHOD

We predict the cost of the product—tritium and/or plutonium—for both a tandem mirror and tokamak base case, as well as for a number of tandem mirror variations. The seven parameters used to calculate predicted product cost are:

1. Annual net production.
2. Direct capital cost of reactor.
3. Indirect and other costs added to direct cost to find the total capital cost of the reactor.
4. Total capital cost of lithium–aluminum process plant.
5. Annual capital fixed-charge rate.
6. Annual operation and maintenance (O&M) costs.
7. Annual electrical power cost.

Annual net production is the product of blanket net breeding ratio (BR_{net}, as determined in Ref. 5), fusion power level (P_{fusion}), and plant capacity factor (CF). We assumed, for all cases, that the CF is 0.7 and that the plant's tritium fuel is produced in situ.

The direct capital costs for the two base-case reactors are taken from Ref. 2 and include engineering, assembly, and installation, but not contingencies. Changes in capital cost for the tandem mirror variations are described later.

The indirect cost factors used are from two sources. For the "base economic method" our intention was to approximate the method used to evaluate the ENB. The ratio of total to direct capital costs for the ENB is 1.24; therefore, the indirect cost factor used to evaluate the fusion breeder is 0.24. A second economic method, the PNL method, was used as a variation and is based on guidelines for constant dollar analysis used to evaluate commercial fusion reactor designs.[7] For the PNL method, total capital cost is 1.65 times direct capital cost. The 1.65 factor is the product of the indirect cost factor (1.35) and a factor for interest during construction (1.22).

The total capital cost of the lithium–aluminum process plant is held constant for all cases except the commercial one.

The annual capital fixed-charge rate times the total capital cost gives the annual capital cost. For the base economic method, the fixed-charge rate is 6.5% based on a 5% interest rate for 30 years. For the PNL (constant-dollar) economic method, the fixed rate is 10%.[8]

Annual operation and maintenance costs consist of general reactor O&M costs at 2% of the total capital cost[9] plus an O&M cost of $38 million for the lithium–aluminum (Li–Al) process plant, which is assumed to scale with tritium production, as well as a blanket replacement cost, assuming 20% replacement each calendar year. This means a 3.5-year blanket exposure lifetime is assumed. Blanket replacement cost is assumed to be the same as original blanket cost, which should be high because the beryllium would be recycled. The annual electricity cost is the product of energy required and a unit cost of 28 mill/kWh (or power sold at 23 mill/kWh).

RESULTS

The results of this economic analysis are given in Table I. Important effects of variations from the base case are described below. Cases 1 and 3 through 13 are tandem mirror cases; Case 2 is the tokamak base case.

Case 1 is the tandem mirror base case. It has a capital cost of $1.5 billion and produces 10.8 kg of net tritium for $22 thousand/g. At 427 MW fusion, it has a total nuclear power of 540 MW. It consumes 355 MW of electricity. A breakdown of costs for Case 1 is given in Table I.

Case 2 is the tokamak base case, which produces 9.5 kg of net tritium at an estimated cost 31% higher than that for the tandem mirror base case. The main reason for this cost difference is that the tokamak requires more electrical power (560 MW) than the tandem mirror does (355 MW).

Case 3 is like the tandem mirror base case (Case 1), except the economic evaluation was done with the PNL method already described. The main difference between the two is that the annual capital cost doubles. The total annual cost, thus product cost, increases 42%.

Case 4 is the tandem mirror base case (Case 1), except the plasma Q (fusion power/plasma heating power required) has been reduced 50%. The effects of this reduction, compared to the base case, are:

(a) Twice as much neutral beam and RF power is required. Therefore, their number, capital cost, and electrical power requirements double.

Table I. Economic Assessment Summary[a,b]

					Reactor capital cost $millions		Annual costs ($millions)					Product cost ($/g)	
Case no. and case	Fusion power (MW)	Net tritium (kg/y)	Net plutonium (kg/y)	Net electrical power (MW)	Direct	Indirect	Capital	Reactor O&M	Li–Al plant O&M	Blanket replacement	Electricity	T	Pu[c]
1 Tandem mirror base case ($Q = 4.5$)	427	10.8	0	−355	1115	268	97.6	27.7	38	17.2	61.0	22,400	—
2 Tokamak base case	450	9.46	0	−560	1095	263	96.0	27.2	38	20.6	96.1	29,400	—
Tandem mirror variations													
3 Base case with PNL economics	427	10.8	0	−355	1115	725	195.9	30.1	38	17.2	61.0	31,700	—
4 Base case with $Q/2$	427	10.8	0	−611	1838	356	127.0	37.0	38	17.0	105.0	30,000	—
5 Base case with 1/2 the neutral beam and RF efficiencies	427	10.8	0	−657	1466	284	103.0	29.0	38	17.0	113.0	27,800	—
6 Base case— Pu mode	427	0	935	−363	1130	271	99.0	28.0	24	17.0	62.0	—	246
7 Double-power tandem, tritium plus Pu mode	827	11.2	987	−336	1394	334	120.0	37.0	57	34.0	58.0	13,700	155
8 Case 7 with thermal conversion[d]	827	11.2	987	0	1548	372	133.0	41.0	57	34.0	0	11,800	134
9 Base case with $Q/4$	427	10.8	0	−1,122	2202	528	185.0	55.0	38	17.0	193.0	45,200	—
10 Base case with $Q = \infty$	427	10.8	0	−99	706	169	57.0	18.0	38	17.0	17.0	13,500	—
11 Base case with $Q/9$	427	10.8	0	−2,417	3961	951	327.0	98.0	38	17.0	403.0	81,200	—
12 Base case with 50% central-cell power and length	227	4.86	0	−342	969	233	86.0	24.0	19	9.0	57.0	40,000	—
13 Commercial breeder	3,140	85.0	or 6,600[e]	1,100	2933	704	236.0	73.0	—	70.0	−155.0[g]	2,647	33.9[f]

[a] The base economic method of analysis was used for all but Case 3.
[b] The cost for the Li–Al plant was $119 million for all cases.
[c] Less uranium–plutonium fuel-cycle costs.
[d] Breakeven electric power producer.
[e] ^{233}U/year, not ^{239}Pu.
[f] Less thorium–uranium fuel-cycle costs. Plutonium production cost should be similar.
[g] At 23 mils/kWh.

(b) Direct converter system powers (electrical and thermal output) and cost are scaled directly with input power, which increases 53%.

(c) The gross electrical power of the plant increases 73%, which, in turn, increases the BOP electrical system cost by 51% because of the 0.75 power scaling assumed.[(10)]

(d) The plant's cooling requirement increases 30% which in turn increases the cooling system cost by 22% because of the 0.75 power scaling assumed.[3] Net electrical power and its cost increase 72%.

[3] Crude BOP scaling laws recommended by Bill Allen, Bechtel.

The overall effect is a 30% increase in total plant capital cost and a 33% increase in total annual costs. Thus, product cost increases 33%.

Case 5 is Case 1, with neutral beam and RF efficiencies reduced 50% (to 0.25). The effects of this reduction, compared to the base case, are predicted to be as follows:

(a) The plant's gross electrical power increases 73% which in turn increases the BOP electrical system cost by 51%.
(b) The plant's cooling requirement increases 35% which in turn increases the cooling system cost by 25%.
(c) The net electrical power purchased increases 85%.

The overall effect is a 6% increase in total plant capital cost and a 24% increase in annual, thus product, cost.

Case 6 is like the base case, except that its excess breeding capacity is used to produce plutonium. This is done by replacing some of the lithium aluminum in the blanket with uranium, causing a 65% increase in blanket M (energy multiplication), which, in turn, increases cooling system capital cost and electrical power requirements. Cooling system cost is assumed to scale as power to the 0.75 power, and its electrical power requirement is taken as 3% of thermal. The net result is a 1% increase in annual costs. Notice that uranium fuel fabrication costs and processing costs for the uranium plus 0.5% plutonium are not included and should be added to the calculated cost for plutonium. A uranium-plutonium process system should probably not be part of this plant because heavy metal throughput would be so low (less than 200 Mt/year). An existing aqueous processing plant or low-cost method for processing small throughputs such as pyrochem should be employed.

Case 7. With twice the central-cell length and fusion power of Cases 1 and 6, Case 7 produces about the same net titanium and plutonium as the two cases combined. The objective with Case 7 is to determine the economy of scale. The estimated effects on reactor direct cost of doubling central fusion power by doubling its length are detailed in Table II. The total direct reactor cost is 25% higher than the base cost. Total cooling requirements increase to 1652 MW (compared to 866 MW), but the net input electrical power need drops to 336 MW (compared to 355 MW) because the 40-MW_e increase in direct converter power output more than offsets the added cooling system power requirement. When the annual cost of Case 7 is compared to the combined annual cost of Cases 1 and 6 ($306 million vs $481 million), a 36% drop in costs is achieved for about the same output.

Table II. Direct Costs ($Millions) for Case 7 (827-MW_{fusion} Case)

Cost items	Change from base case	Subtotal
Magnets		
End plugs and shields	none	188
Central cell	30×(2)	60
Neutral beam	none	200
Shields (central cell)	54×(2)	108
Microwaves	none	100
Electrical systems		
Direct converter	6×(125/85)	9
Copper coils	none	10
Vacuum system vessel	none	25
Cryopanels and refrigeration	none	10
Outgas cyclers and roughing pumps	none	10
Blanket	86×(2)	172
Instrumentation and control	none	40
Tritium handling and pellet injectors	none	45
Remote maintenance equipment	none	50
Breeding slug changeout machine	22×(2)	44
Cooling system	$65\times(1652/886)^{0.75}$	104
Buildings		
Containment	80×(1.4)	112
Auxiliary	50×(1.25)	63
Electrical	none	44
Total direct costs		1394

Case 8. Case 8 is Case 7 with thermal conversion added in a crude way to determine how it might affect economics. The assumption here is that all the thermal power in Case 7 (1652 MW) is sent to a saturated steam cycle giving a net efficiency of 20%, which makes the system about break even in electrical power. The cost of this thermal conversion system is scaled from a 2924-MW thermal, 34.2% efficient system costing $298 million (1979 dollars).[10] This cost is escalated to 1982 dollars by assuming 3 years

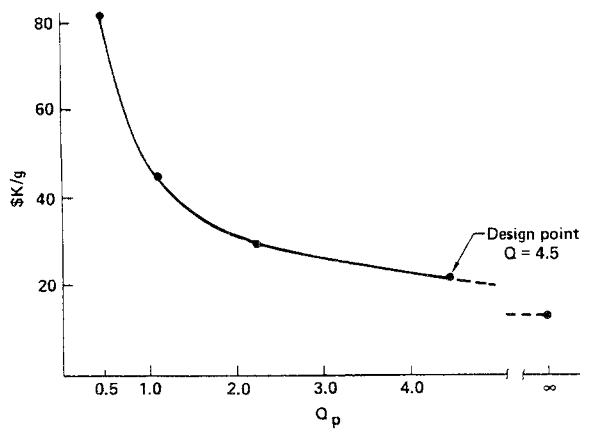

Fig. 1. Tritium production costs vs plasma Q ($P_f = 427$ MW).

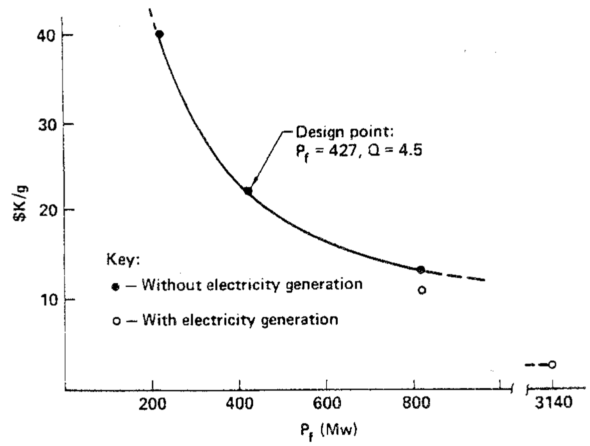

Fig. 2. Tritium production costs vs fusion power level, P_f (MW).

at 10% and is scaled by thermal power to the 0.75 power. The net effects are a 10% increase in capital cost and a 14% drop in product cost.

Cases 9 through 11. These are additional variations in Q and fusion power about the base case (Case 1). These additional cases were done to allow plots of tritium cost vs plasma Q and vs fusion power to be drawn (Figs. 1 and 2).

Case 13. This is a commercial-scale case. The base-case production reactor and its variations operate at low power (200–800 MW fusion) relative to the commercial fusion breeders being studied (~ 3000 MW fusion). A case in point is the fission-suppressed tandem mirror hybrid reactor design (beryllium blanket case) studied in 1981.[11] This reactor has the following parameters:

Fusion power (MW)	3140
Net electrical power (MW)	1100
Net fissile production, at 70% capacity factor (kilograms of ^{233}U/year)	6600
Direct cost, excluding thorium fuel cycle facilities (millions of 1980 dollars)	2562

If this cost were escalated to 1982 dollars at 7%/year and the same base-case economics were used, this commercial-scale plant would produce 6600 kg of ^{233}U at a cost of \$34/g, plus fuel-cycle costs, or 84.6 kg of tritium/year for \$2600/g assuming the same total moles of product are produced. Some combination of fissile plus tritium production would be the mode of operation, with the electricity and excess materials produced being sold on the commercial market. Plutonium could also be produced.

From this simple comparison, it is clear that the economy of scale is significant. By going from the 427-MW fusion case to a 3140-MW fusion commercial system, the total capital cost goes up by a factor of 3.3 and product cost goes down by a factor of 8.4.

CONCLUSION

The results of this economic analysis indicate that magnetic fusion might be an economically competitive technology for the production of nuclear weapon materials. Both the initial capital investment and operating costs appear competitive; the resulting product cost also appears competitive even in a small plant sized to produce 10 kg of tritium/year and using a low-temperature blanket that produces no electricity. When production is doubled by doubling central-cell length and fusion power, the capital cost increases 25% while the product cost drops 36%. When thermal conversion is added to this case, capital cost increases 10% while product cost drops 14% because it is electrically self-sufficient. The economy of scale is really apparent when a commercial-size plant producing fissile fuel and electricity for commercial markets, in addition to weapon materials, is considered. For the commercial example considered, the material cost is 86% lower than for the base case.

The plasma energy gain for a given fusion power level was also found to have a profound effect on economics. For example, a 50% decrease in Q for the tandem mirror base case leads to a 30% increase in capital cost and a 33% increase in product cost.

The tokamak, which produced the same amount of material as the tandem mirror base case, was found to give similar economics.

Future work to assess the economics of magnetic fusion for weapon material production should include:

- Better estimates of BOP costs and scaling.
- The use (as required) of better or additional economic assessment methods.
- Sensitivity analysis for the tokamak case.
- The correction of inconsistencies.
- Assessment and comparison of the latest studies for commercial fusion breeder design.
- An effort to determine if on-line refueling, actuated by the reactor cooling water, would reduce downtime and thus improve the economics.
- An estimate of capital and O&M cost uncertainties to determine their effects on product cost.
- An examination of the uncertainty effects of further tandem mirror physics on product cost.

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