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THE COST OF TRITIUM PRODUCTION IN A FUSION REACTOR

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ABSTRACT

A computational model is presented in order to assess the cost of tritium breeding in a fusion power reactor. This model compares the differential cost of the Li-bearing breeder blanket with that of a steel shield and adds the "loss of revenue" due to the lower energy multiplication of the breeder blanket compared to the steel shield. The cost of tritium production ranges from $215-$300/g for a simple breeder up to $1420/g for a high temperature breeder.

INTRODUCTION

Numerous conceptual design studies have been prepared of large-scale electrical power generating stations based upon fusion reactors using the deuterium/tritium (D/T) fuel cycle. Because of the absence of an external source of tritium, all of the designs have incorporated a scheme to produce a continuous supply of tritium by use of the nuclear reaction, ^{6}Li(n,α)T. In such studies, the cost of the tritium production has not been considered. This cost is difficult to determine because the Li-bearing tritium breeder which surrounds the plasma is used for two functions; namely, (1) to produce tritium and (2) to convert the energy from the plasma neutrons into thermal energy for the power cycle. If the tritium breeders were not provided, another neutron absorber would be needed. Consequently, the cost of tritium breeding becomes intertwined with the power cycle.

On the other hand, some cost must exist for tritium production and the determination of this cost is becoming important for at least two reasons; namely:

1. A recent study[1] has shown that in reactors specifically designed for tritium production the cost varies from $10,000 per gram of T in conceptually designed fusion reactors up to $100,000/g(T) in present-day fission, heavy-water reactors. Additionally, some emerging technologies have the potential of significantly reducing these costs. If the cost of indigenously produced tritium in a fusion power reactor exceeded these alternative supply costs, then the utility operator of the fusion electrical power plant might choose to purchase tritium from a supplier. In such an event, the cost of licensing and transporting the radioactive tritium would have to be considered; however, the supplier could be adjacent to the power plant which would reduce the transportation costs.

2. In comparison of the D/T fusion fuel cycle power cost with competitive energy systems, such as fossil fuels, nuclear fission fuels or even alternative fusion fuel cycles, using natural abundance fuel materials, all of these, except tritium, have a current commodity price which can be extrapolated into the future based upon their projected availability. For instance, the Apollo-L3 tokamak reactor study[2] utilizing the D-^{3}He fuel cycle has shown that competitively priced electricity can be achieved with fuel costs of $1000/g of ^{3}He.

Because of these reasons, it is desirable to quantify the cost of tritium production in a fusion reactor. This article presents an initial cursory study which qualitatively considers some of the cost factors involved and delineated areas in which more quantitative data are needed.

Two schemes were considered for this study to calculate specifically the cost of tritium production, namely:

(1) Comparison of the D/T fusion fuel cycle with a non-tritium fuel cycle.

Although this scheme appears reasonable, it is complicated by the fact that the nuclear fusion cross-sections are smaller for all the alternative fuels than for D/T. For instance, in the ARIES-III study[3] of a tokamak fueled with D-^{3}He, the lower nuclear fusion cross-section was overcome by modest increases in the strength of the toroidal field magnets, the plasma current and the ion temperature. In addition, most of the fusion power is carried by energetic ions which cause intense surface heating of the first wall and divertor, instead of the neutronic heating from the D/T reactions which is distributed throughout the breeder blanket. Consequently, the cost of tritium fuel as compared to ^{3}He fuel becomes obscured by these modifications in the plasma confinement hardware and thermal responses of the surrounding structure.

(2) A more straightforward approach to calculating the cost of tritium production is possible if two nearly identical D/T fusion reactors are compared in which one breeds tritium but the other does not. A continuous supply of tritium is assumed to be made available for the alternative reactor, perhaps from a nearby tritium production reactor. In this scenario, the plasma parameters and the D/T fuel cycle for the breeding and the non-breeding reactors would be identical, so that the gross configurations of the two fusion reactors would be similar. The only difference would be that one reactor utilizes a Li-bearing, tritium breeder while in the alternative design the tritium breeder system is removed and replaced with a neutron absorber. Steel was selected as the alternative absorber, because of its good shielding properties, high neutronic to thermal energy conversion and good thermal performance up to $\sim 500°C$. Except for the substitution of steel for the breeder system, the blanket remains as designed so that the effects solely due to the breeder could be determined.

Table 1: Tokamak Studies and Costs Used in Comparison Studies

Reactor	Structure	Coolant	Breeder System	Cost (1990) \$/kg	Cost of Electricity mills/kWh
ARIES-I	SiC	He			72
			Li_2ZrO_3 (isotopically modified Zr)	1490	
			Be (neutron multiplier)	580	–
ESECOM-He/Li_2O	RAF Steel*	He			57
			Li_2O (natural isotopes)	53	
ESECOM-V/Li	V	Li	Li (natural isotopes)	52	63
Breeder Replacement			RAF Steel	59	–

*Reduced activation ferritic steel.

In order to make such a study, three recent tokamak studies, for which cost information is well-documented, were analyzed in the normal tritium breeding mode and the alternative non-breeding mode. These three studies were chosen because they represent three classes of reactor breeder systems; namely, (1) a ceramic breeder requiring a neutron multiplier, (2) a ceramic breeder not requiring a neutron multiplier and (3) a liquid metal self-cooled breeder (Table 1). The reactor studies considered were: (1) the recently completed ARIES-I[4] study which utilized a high temperature SiC structure containing a useful high temperature breeder, Li_2ZrO_3, in which the Zr was isotopically tailored to reduce undesirable long-term transmutation products. Beryllium was inserted into the blanket as a neutron multiplier so that the tritium breeding ratio (TBR) would be > 1.0; (2) the helium cooled, Li_2O breeder (He/Li_2O) contained in reduced activation ferritic steel (RAF) structure as described in the ESECOM[5] report; and (3) also from the ESECOM study, the flowing liquid lithium (natural isotopic abundance) breeder and coolant in a vanadium structure (V/Li).

For the alternative blanket in each of the reactors, the breeder and neutron multiplier were removed and replaced with an equal volume of RAF steel. This is a simplifying assumption and has several limitations, namely:

1. In most cases the steel is a better neutron absorber than the breeder; consequently, the inboard and outboard blanket-shield could be smaller, decreasing the size of the toroidal field magnets and thereby reducing the cost of the reactor. Also, ARIES-I was designed to eliminate highly activated waste products at the end-of-life for the blanket components. The insertion of steel into such a blanket would not be compatible with such a philosophy; consequently, SiC would probably be inserted instead of steel and the thickness of such a neutron shield would have to be determined.
2. Coolant channels are strategically placed within the blanket to remove heat principally generated in the breeder and neutron multiplier. With the steel inserts more or less coolant channels may be required. For the ceramic breeders, which are poor thermal conductors in rather small tubes, the steel should be adequately cooled. For liquid Li, which has a higher thermal conductivity, the steel would not be adequately cooled; consequently, 30% void space was allowed in the steel for additional coolant channels.
3. For the ceramic breeders the blanket designs are complex because one set of He channels is used for coolant while another set is used to bleed tritium generated in the breeder to a tritium processing system. Without a bleed as in the blanket, the design and fabrication of these blankets would be less complex and, consequently, less expensive.

This latter option was used in this study and the cost of tritium breeding was considered in two areas, namely: (1) the construction and operation of the reactors, and (2) the effect upon the thermal performance of the reactors. Next, the cost accounting methods are described, and then the results are presented and discussed.

COST ACCOUNTING METHOD

Both the breeding and the non-breeding versions of each of the reactors considered are assumed to be identical except for the breeder blanket; therefore, only the costs of the breeder and the tritium reprocessing equipment associated with the tritium recovery from the breeder need to be considered. These costs were taken from the ARIES-I System's Code[4] and the GENEROMAK[6] study and updated by use of the USA Consumer's Price Index to the year 1990. The accounting procedures generally followed the format given in these two studies, but in an abbreviated form.

Table 2: Cost Comparison of Breeding and Non-Breeding Reactor Concepts (in $\$10^6$ per 1990)

System	ARIES-I		ESECOM-He/Li_2O		ESECOM-V/Li	
Blanket	Breeder	Non-Breeder	Breeder	Non-Breeder	Breeder	Non-Breeder
CAPITAL EQUIPMENT						
Breeder	88	0	28	0	7	0
Be	162	-	-	-	-	-
Steel Insert	-	104	-	121	-	87
Tritium Processor	43	0	58	0	112	0
DIRECT COST	543	208	114	242	126	174
Indirect	190	73	43	91	47	65
Contingency	54	21	17	36	19	26
Total Capital Cost	787	302	174	369	192	265
ANNUAL OPERATIONAL COST						
Capital Return	51	20	11	24	13	17
O&M	11	4	2	5	3	4
Blanket Replacement	42	35	9	40	2	29
Total	104	59	21	69	18	50
Tritium Production, kg/yr	81.8		111.8		104.2	
Differential Tritium Cost, $/g(T)	550		-429		-307	

The costing analysis considered the acquisition cost of the Li-breeder and its operation as compared to the cost of the steel shield. The accounting procedure determined a capital cost for each scenario. Then, an annual cost of operation was determined based upon the repayment of the borrowed capital, operation and maintenance, and cost of blanket replacement, as delineated below and summarized in Table 2.

CAPITAL COSTS DEFINITIONS

Breeder Blanket: Because the shell of the blanket was considered to be identical for the two versions of each reactor, only the cost of the material filling each blanket was considered. The volume or weight of the breeder material was given or could be determined for each reactor; consequently, the total cost of the Li-bearing material and the neutron multiplier were determined. For the alternative blanket the volume of breeder was removed and filled with RAF steel. One blanket and one spare were purchased at the time of construction of each reactor.

Tritium Processor for the Breeder Blanket: This item is not specifically delineated in the system code. An algorithm for tritium processing from the vacuum system, $\$0.5$ M $(g/d)^{0.7}$ (in 1980$), was used but considered only the tritium flow rate in the blanket reprocessing system. This assusmption is reasonable for the ceramic breeder systems because the tritium exists in a gaseous form as it does in the vacuum system. The tritium removal system or the liquid Li breeder would be much more complex than for tritium removal from helium; therefore, the cost of the liquid Li processor was doubled (2x). No tritium processor was included for the RAF steel.

Indirect Cost: As given in each of the reactor studies, the capital costs were multiplied by 35% for the ARIES-I case and 37.5% for the ESECOM study to obtain the indirect costs. Contingency costs were 10% and 15%, respectively. The total capital cost is the sum of direct, indirect and contingency costs.

Annual Cost: The total capital costs were amortized at an interest rate of 5% (excluding inflation) over a period of 30 years. The annual operation and maintenance costs were assumed to scale as 1.4% of the direct costs. For the blanket replacement cost, the blanket lifetime was assumed to be 3 years limited chiefly by the radiation damage to the first wall; therefore, 1/3 of the cost of a new blanket was held in escrow each year. For the ARIES-I blanket, 50% of the breeder and Be were recycled. No recycle was permitted for the steel or other breeder materials. The annual cost was, therefore, the sum of the capital return, the O&M and the blanket replacement costs. The differential cost between the two versions of each blanket is the annual cost of tritium production.

The annual tritium production is the daily production times the operational days/year based upon the availability of 0.76 for ARIES-I and 0.65 for ESECOM.

The unit cost of tritium production is, therefore, the annual differential cost divided by the annual production of tritium.

LOSS OF REVENUE DUE TO TRITIUM PRODUCTION

The absorption of the fusion neutrons in the surrounding blankets usually results in energy multiplication. This neutronic energy multiplication is as high as 1.70 per fusion neutron in a steel absorber. In the blankets as designed with the coolants and structures in-place, this energy multiplication with the steel would be degraded to ~ 1.50; hence, the overall energy multiplication was conservatively assumed to be 1.40 times the fusion energy reaction.[7] The energy multiplication was calculated by the designers for each of the cited reactor studies and resulted in total fusion energy multiplication factors as given in Table 3. As noted, the energy multiplication with the Li-breeder materials in-place would be significantly lower than with a steel absorber replacing the breeder in the blanket. This loss in thermal energy multiplication in turn results in lower electricity production and a loss in revenue from the sale of this electricity. This annual loss of revenue was calculated for each version of the reactors

Table 3: Loss of Revenue in the Sale of Electricity Due to Indigenous Tritium Breeding

	ARIES-I		ESECOM-He/Li_2O		ESECOM-V/Li	
	Breeder	Non-Breeder	Breeder	Non-Breeder	Breeder	Non-Breeder
LOSS OF REVENUE						
Fusion Power, MW	1925	1925	3028	3028	2862	2862
Energy Multiplication	1.22	1.40	1.18	1.40	1.22	1.40
Total Nuclear Power, MW	2349	2695	3568	4239	3484	4007
Energy Conversion Efficiency	0.426	0.426	0.336	0.336	0.344	0.344
Net Electric Power, MWe	1000	1148	1200	1424	1200	1378
COE, mills/kWh	72	72	57	57	63	63
Annual Revenue, $M/yr	479	550	390	462	431	494
Revenue Loss, $M/yr	71		72		63	
Revenue Loss, $/g(T)[a]	870		644		605	
TOTAL COST*						
Tritium Breeding, $/g(T)	1420		215		298	

*Sum of Table 2 and line (a) above.

cited and charged to the annual tritium production, based upon the annual availability and the cost of electricity (COE) cited in each of the reactor studies (Table 3).

RESULTS AND DISCUSSIONS

Review of Table 2 indicates that the differential cost of the breeder as compared to the steel insert is the highest for the ARIES-I reactor, resulting in an annual cost differential of $45 M/yr (or $550/g(T)). This is due to the high cost of the isotopically modified Li_2ZrO_3 and the Be. For the two ESECOM reactors the annual cost of the all steel version of each is higher than for the blanket with the breeder in place; i.e., $48 M ($429/g of T) and $32 M ($307/g of T) for Li_2O and Li respectively. This unusual finding is a result of the prices suggested in the systems code in which the cost of Li_2O, Li and RAF steel are $53, $52 and $59/kg respectively; consequently, because of the high density of steel, when it is substituted on a volume basis, it is much more costly than the Li-bearing materials. Whether these Li-bearing materials can be produced and fabricated into breeder blankets at these low costs is a subject requiring more study and experimentation.

The charge to tritium production attributed to "loss of revenue" (Table 3) is nearly the same for all three reactors, varying from $605 to $870/g of tritium. This result is due to the fact that the energy multiplication is nearly the same for all three breeder materials and all are lower than that of the steel absorber.

When the total cost of tritium production (operational costs plus loss of revenue) is considered the results indicate that the costs can range from $215 to $298/g of tritium in the ESECOM reactors to as high as $1420/g in ARIES-I. These costs are significantly lower than the cost of tritium determined for dedicated tritium production reactors[1] which varied from $56,000 to $100,000/g of tritium in fission reactors to $10,000 to $49,000/g of tritium in conceptual designs of fusion D/T production reactors.

Although this is a preliminary study, the results indicate that it is significantly less expensive to incorporate breeding as an integral part of the fusion reactors than to purchase it from any proposed production reactor. Additionally, it is shown that the major capital cost differential is associated with the type of breeder utilized and whether or not Be is needed as a neutron multiplier.

One factor decreasing the cost of tritium breeding in this fusion power reactor study is that the cost of tritium containment, monitoring, etc., is borne by the D/T fuel cycle and no additional cost has been assigned to these factors in the breeding cycle. Although such factors have not been considered, they are probably not major cost drivers, as shown by the fact that doubling the cost of the tritium processor in the V/Li system resulted in only a small cost increase as compared to the He/Li_2O system. A potentially significant cost driver would probably be elucidated if the blanket and shield design were otpimized for the steel insert configuration. If the steel permitted a thinning of the shield, then significant cost savings could be obtained by shrinking the blanket and the toroidal field magnets. Such information could also be used to better quantify the energy multiplication with the steel insert.

The design of fusion reactors has reached a sophisticated stage in which concerns regarding safety, disposal of radioactive waste products, and high temperature operations to improve plant efficiency are being incorporated into the initial reactor designs. The ARIES-I reactor typifies this trend and if isotopically tailored breeders and neutron multipliers are required, then this study indicates that the cost of tritium production will be $\sim$ $1000/g(T).

This cost of tritium breeding in a fusion power reactor is within the range of that being considered for ^{3}He fuel in a D-^{3}He power tokamak reactor, such as ARIES-III. When costs are compared on an equal basis the COE for ARIES-I is 80 mills/kWh but only 70 mills/kWh for ARIES-III, using ^{3}He at a cost of $1000/g. Both the D/T and D-^{3}He reactions yield similar nuclear energy release, and apparently comparable costs for the fuels are obtained even though the plasma confinement equipment requires some major changes. Perhaps we do have, now, a valid fuel cost for tritium in a fusion economy.

CONCLUSION

This study presents a method to estimate the cost of tritium production in a fusion power reactor, when the Li-bearing breeder is removed from the blanket and replaced with RAF steel. The cost of tritium breeding is in the range of \$260 $\pm$ 40/g of tritium for a simple Li breeder but up to \$1420/g of tritium in a high temperature blanket. This cost is much less than the cost of tritium produced in a dedicated tritium production reactor and shows the economic justification for including tritium breeding in the fusion reactor design.

This study represents the present state-of-the-art in fusion reactor costing of the tritium breeding systems which are chiefly conceptual designs based upon limited experimental information. Experimental verification is sorely needed to demonstrate that the Li-bearing tritium breeders can yield TBR's > 1.0 and that neutron multipliers, such as Be, are effective in power-producing tokamak reactors.

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