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MANAGING THE FUSION BURN TO IMPROVE SYMBIOTIC SYSTEM PERFORMANCE

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Symbiotic power systems, in which fissile fuel is produced in fusion-powered factories and burned in thermal reactors characterized by high conversion ratios, constitute an interesting near-term fusion application. It is shown that the economic feasibility of such systems depend on adroit management of the fusion burn. The economics of symbiotes is complex : reprocessing and fabrication of the fusion reactor blankets are important components of the production cost of fissile fuel, but burning fissile material in the breeder blanket raises overall costs and lowers the support ratio. Analyses of factories which assume that the fusion power is constant during an irradiation cycle underestimate their potential. To illustrate the effect of adroit engineering of the fusion burn, this paper analyzes systems based on D-T and semi-catalyzed D-D fusion-powered U-233 breeders. To make the D-T symbiote self-sufficient, tritium is bred in separate lithium blankets designed so as to minimize overall costs. All blankets are assumed to have spherical geometry, with 85% closure. Neutronics depletion calculations were performed with a revised version of the discrete ordinates code XSDRN-PM, using multigroup (100 neutron, 21 gamma-ray groups) coupled cross-section libraries. Initially, 500 Mwatt are injected into the plasma, and U-233 is allowed to build up in the blanket until: 1. a maximum power density (e.g. 400 watt/cc) is reached, 2. the overall U-233 production cost reaches a minimum, or 3. a given total blanket power level is attained. Costs were calculated based on the indifference method, using US INFCE preliminary guidelines. Shaping the pulse so as to keep constant the blanket maximum power density permits a higher U-233 inventory and a lower fissile fuel production cost.

[Symbiotic energy system, CTR, U-233 production, fuel cycle, economics, denatured fuel, power coastdown, D-T and semi-catalyzed D-D cycles, advanced converter reactors, support ratios , fusion-fission hybrid]

Introduction

Pure fusion must meet some serious challenges before it can make a contribution to the world's energy needs. The most obvious one is that the plasma performance parameter Q (defined as the ratio of fusion energy released to the energy injected) must be large enough. Other challenges are the high capital cost of the fusion devices which are now envisioned, and the fact that large recirculating powers imply much thermal waste if the achievable plasma performance is modest.[1] Also, fusion reactors based on the so-called primary cycles (involving hydrogen isotopes) are strong neutron sources, and therefore have the potential to act as breeders for weapon-grade fissile material.

These difficulties can be alleviated by symbiotic systems. Attractive energy scenarios can be identified for modest fusion driver performances, and high overall energy conversion efficiencies can be attained in systems where most of the power is generated in advanced fission reactors. Also, in such systems, high breeder costs do not necessarily mean high overall power costs. Finally, the centralization of sensitive facilities may simplify the problem of safeguarding.

The idea of using fusion neutrons to generate fissile material is old.[2] The recent interest in symbiotic systems has been spurred by revisions of the national policies on the nuclear fuel cycle.[3] Although mixing Pu-239 with its isotopes[4] or with fission products may make it unattractive for weapon use, it is apparent that the thorium cycle has some interesting advantages[5] from the point of view of safeguarding (e.g. denatured U-233 fuel cycles, presence of U-232, possibility of high conversion ratios in thermal reactors, etc.) This paper will concentrate on U-233 rather than Pu-fissile factories.

Bender et al.[6] analyzed the performance of symbiotic systems, and their report served as basis for a straightforward statement of the goals of the factory blanket designs.[7] Woodruff[8] pointed out the possible advantages of the D-D cycles, which were also explored by Saltmarsh et al[9], Renier et al.[10] and others. Some of the methodology for calculating the capital costs of the fusion powered factory which has been used in this paper, was adapted from Kostoff.[11]

The capital cost and the antiproliferation resistance of symbiotic systems are enhanced by minimizing the amount of energy generated in the fusion breeder,[12] which implies the desirability of low neutron energy multiplication in the breeder blanket. This must be balanced against the negative effect of short irradiation times on fusion blanket fabrication and reprocessing costs.

Neutronic Analysis

The neutronic calculations were performed with a revised version of the discrete ordinates code XSDRN-PM[16], which incorporates a fuel depletion option. A S_4P_3 approximation was used in all the calculations, and was verified with several $S_{16}P_8$ runs.

ENDF/B-IV based multigroup cross-section sets and kerma factors for ^{6}Li, ^{7}Li, Pb, Fe, Ni, Cr, ^{233}U, ^{232}Th. etc. were taken from the DLC-37 (100 neutron, 21 gamma ray groups) coupled cross-section library.[17] The effect of neutron captures in protactinium is neglected.

Thorium and Lithium Blankets

Two fusion cycles are of interest to power the factory, the deuterium-tritium (D-T) cycle and the so-called "semi-catalyzed" deuterium cycle (D-D) with simultaneous burning of the generated tritium. Although the D-T cycle has the obvious advantage of a greater interaction rate, the need to make the system self-supporting in tritium imposes a heavy economic penalty.

In many designs reported in the literature tritium and U-233 are bred in the same blanket or in blankets which are neutronically coupled. Coupling the blankets may introduce some engineering difficulties and conflicting neutronics requirements for optimum tritium and U-233 breeding. Coupling is justified if it improves the economics or the safeguards, but separate blankets do lead to attractive overall performances.[14] If on the other hand, neither economics nor the centralization of sensitive facilities are enhanced by coupling, the two blankets may be separate; in fact, they may belong to different reactors altogether. Uncoupling makes the goals of blanket design much more obvious: each blanket may be optimized by itself.

Because of endothermic reactions in ^{7}Li or neutron-multiplying reactions in other materials, it is possible to design tritium blankets in which the neutron energy multiplication is not appreciably greater than one. From the point of view of system evaluation, separating the blanket makes the penalties associated with tritium breeding very clear. A given reactor can have separate blankets for tritium and U-233 breeding[15] The time-dependence of the energy deposition is quite different in the two blankets, however: it is practically constant in the lithium blanket, and it increases with time in the thorium blanket. Since we are interested in investigating the effect of time managing of the burn, we shall assume separate reactors to breed the two fuels.

A scheme for a symbiotic energy system based on the D-T or D-D cycles is shown in Figure 1. Note that the injector to the CTR U233-driver is "manageable" : it is possible to reduce the injection power, or to change the plasma amplification.

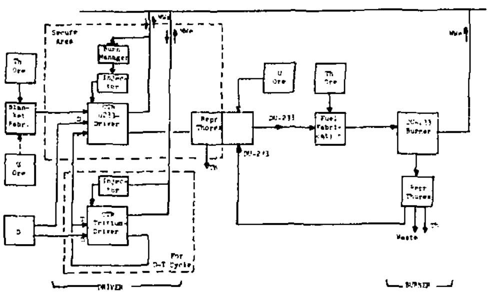

Fig. 1. Conceptual Symbiotic Energy System based on D-T and D-D Fusion Driven CTR's.

Tritium-Driver

In all the discussions that follow, when referring to the D-T cycle, it is implied that the systems are self-supporting in tritium, and that the tritium is bred in a standard blanket configuration which was identified as conceptually acceptable.[14] Preproduction of tritium within the symbiotic scenarios is also done when the injected power to the plasma of the U233-driver is coasted down.

That blanket is a spherical, 5-m to the inner wall, with 1.2 cm steel first wall, 100 cm thick region of Pb-Li^{Nat} metal alloy, and a 10 cm outer steel region. Assuming 85% blanket closure, and 2% tritium recuperation losses, the total tritium yield per D-T fusion neutron was calculated to be 1.41, and 16.1 MeV of energy are deposited in the blanket per fusion neutron.

The sensitivity of the tritium production yield to cross-section uncertainties (particularly the ^{7}Li(n,n'α)T reaction) is rather high for Li^{Nat} metal blankets, smaller for Pb-Li^{Nat} alloys.[14] The effect of the nuclear data uncertainties on tritium breeding and CTR symbiotic performance was previously[14] analyzed.

U233-Driver

Although the energy multiplication in the lithium blanket is practically constant, it can be a strong function of time in the thorium blanket. In the clean thorium blanket, fast thorium fissions compete with capture. As soon as the U-233 inventory builds up, however, fissions in U-233 deposit more and more energy into the blanket : at constant fusion neutron wall loading, the blanket neutron energy multiplication increases with time.

To illustrate this effect, we considered spherical breeder blankets, 5-m. inner radius, 1.2 cm steel first wall, with a 40 cm thick thorium metal blanket. A 5 cm Pb region, used as an endothermic neutron multiplier, and 1.2 cm of steel, separate the thorium region from the first wall; 10 cm of steel backs it. Heat is removed with helium gas. Energy is injected into the plasma with an efficiency of 50% : in most cases which we analyzed, the gross injected power at the beginning-of-cycle (BOC) of the U233-driver is 1000 Mwe.

The energy deposition for clean blankets per fusion neutron, as a function of radial position, is shown in Figure 2a for a typical D-T case with Pb as neutron multiplier. The deposition after eight quar-

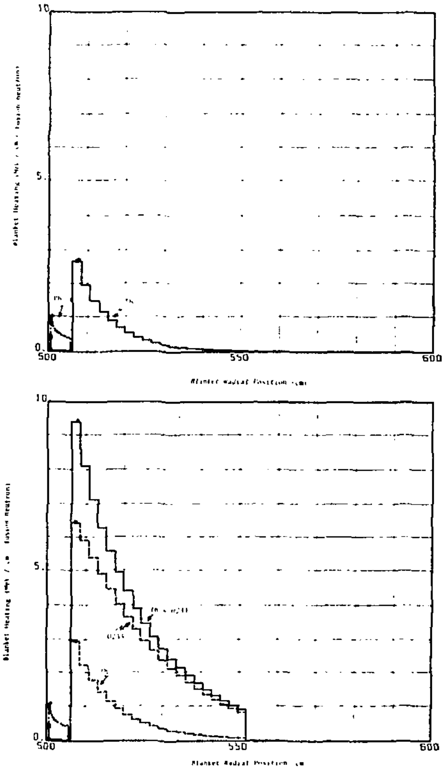

Fig. 2. Blanket Heating in a typical Blanket of a D-T U233-Driver.

ters of irradiation (100% capacity factor) is shown in Figure 2b : the maximum power density and the total blanket power have increased sharply. As the U-233 inventory builds up, fissions in U-233 deposit more and more energy into the blanket. This effect changes the radial profile of the power density, while making the maximum power density and the overall blanket energy multiplication increase with time.

The maximum local power density in the thorium blanket occurs in the zone closest to the plasma. For constant injected power, the maximum power densities as a function of irradiation time are shown in Figure 3a for a D-T driver, and in Figure 3b for a D-D driver, for values of Q ranging from 1 to 10 (or effective $Q' \equiv Q \times$ injection efficiency, ranging from 0.5 to 5.0). A capacity factor of 75% and 85% closure are assumed in all cases. Figure 4a and 4b show the overall blanket neutron energy multiplication, with the same assumptions regarding closure and capacity factor. The rates of increase of power density and overall blanket heating, for constant injected power, are higher for higher Q's. Materials considerations and the need for heat removal will determine a maximum allowable power density and a maximum total blanket power, beyond which continuous irradiation may lead to loss of blanket integrity. When this limit is reached, either the blanket elements will have to be removed or the first wall neutron loading will have to be lowered. We shall explore this in detail later. First, consider cases in which those constraints are ignored. Second, explore the effect of irradiation time on costs and support ratios.

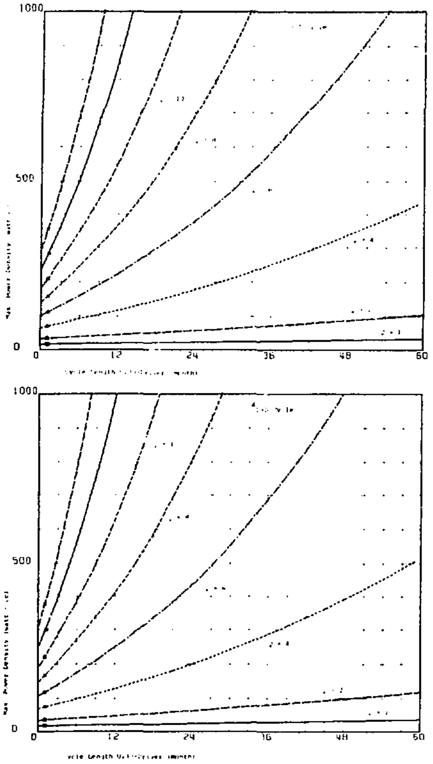

Fig. 3. Maximum Power Density of a D-T and D-D Fusion-Driven Blanket.

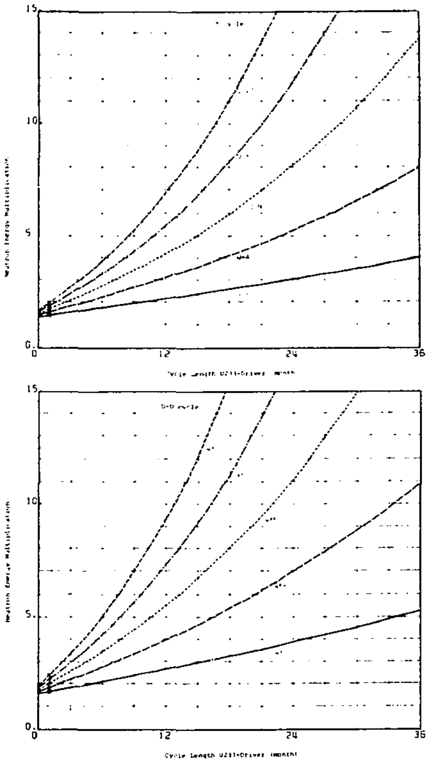

Fig. 4. Neutron Energy Multiplication of a D-T and D-D Fusion-Driven Blanket.

As a result of neutron-multiplying reactions in U-233, the blanket neutron flux increases with time and the gross fissile production rate increases. However part of the generated U-233 is burned in situ. As a result, the calculations showed that the net production rate varies slowly with time, as has been pointed out by other authors.[18]

The net U-233 monthly production as a function of irradiation time, for D-T and D-D drivers is shown in Figures 5a and 5b respectively. Since the monthly fuel production rate varies slowly with irradiation time while the blanket energy multiplication increases, the "power support ratio" (defined as the ratio of the thermal power from the fission reactors to the total maximum factory thermal power) decreases when the fertile fuel is allowed to remain in the thorium blanket for long periods. For the D-T drivers, support ratio as a function of blanket irradiation time is shown in Figure 6, when the fissile fuel is burned in advanced converter reactors characterized by a conversion ratio, CR = 0.9, and a ratio of capture-to-fission cross-section, $\alpha = 0.1$. Figure 7 displays the "unit support ratio" of the U233-driver (defined as the number of one Gwe U233-burners supported by one U233-driver). It increases slowly with irradiation time, in correlation with the U-233 production rate. The increase in the blanket power has therefore an important implication from the point of view of safeguards : it decreases the power support ratio. To meet a given power demand, sensitive facilities with a larger balance of plant are needed.

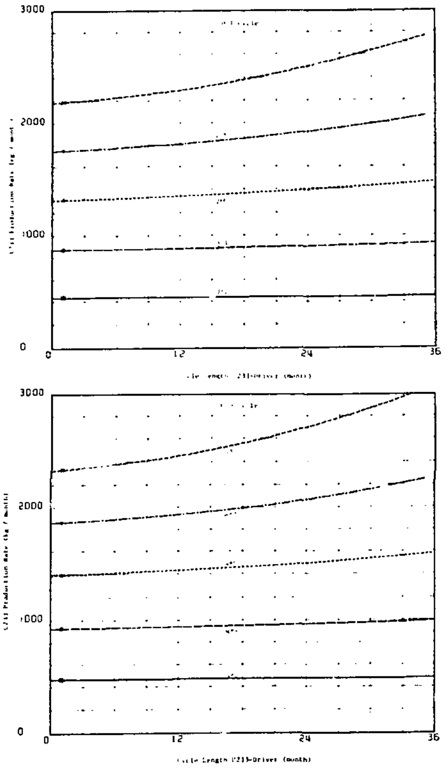

Fig. 5. Net U-233 Monthly Production Rate of a D-T and D-D Fusion-Driven Blanket.

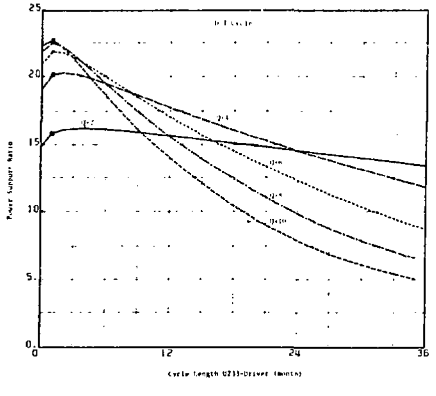

Fig. 6. Power Support Ratio of a D-T Fusion-Driven System.

In addition, the blanket power increase has an important economic implication : the capacity for heat removal from the blanket is underutilized at the beginning of cycle (BOC). This, in turn, implies a higher capital cost per unit of installed thermal power, when averaged over the irradiation period. It will be shown later that, if the total blanket power is held constant by managing the burn of the U233-driver, the net U-233 production cost decreases.

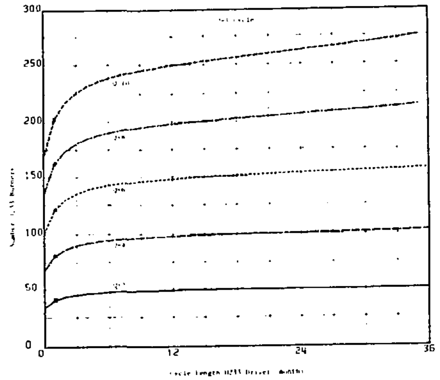

Fig. 7. Unit Support Ratio of a U233-Driver in a D-T Fusion-Driven Symbiotic Energy System.

The problem of balance of plant underutilization is minimized in designs where the blanket is continuously refuelled, such as moving pebble beds or molten salts, but these schemes introduce new engineering challenges. Also, the poor tritium breeding[19] attainable in molten salt reactors penalizes schemes based on the D-T cycle. We shall concentrate on blankets which are not continuously refuelled, for analyzing the possibilities of minimizing the penalties caused by the increasing U-233 inventory.

Note that most of the reported work on the evaluation of symbiotic systems, implicitly assumes that the fusion drivers operate in a steady state mode during the blanket irradiation cycle. The resulting blanket power increase causes the factory design performance to be limited by the maximum power density in the blanket, rather than by the first wall loading, as is the case for pure fusion reactors.

Fuel Cycle and Power Costs

The goal of minimizing the blanket energy deposition while maintaining high fissile fuel production seems best served by schemes where U-233 fuel is taken away from the reactor soon after it is produced.

However, reprocessing and fabrication of the blankets represent important fractions of the U-233 production cost. They increase as the irradiation period is made shorter. The combined effects of irradiation time on capital cost, net fuel generation, reprocessing, and fabrication costs imply that there exists an optimum irradiation period that yields the lowest overall U-233 production cost.

The analyses of fuel cycle, power cost and support ratios, are based on detailed mass and energy flow balances, assuming 85% blanket closure for the fusion breeders, and 2% fissile fuel losses in reprocessing and refabrication.

The computer code that is used to analyze the scenarios, is a complex cost analysis and optimization code[20], that incorporates US INFCE and NASAP preliminary economic guidelines. An effective interest rate (without inflation) of 4.525%, and an appropriate sinking fund depreciation, are used. The method of indifference pricing is applied. Operations-and-Maintenance, and taxes are not included in this analysis. The fusion drivers and the fission burners are operated at 75% capacity factor, with a 40% heat-electrical conversion thermal efficiency. A refueling down-time of two weeks is used for the U233-drivers. A 30 year lifetime is assumed for the CTR drivers and the fissile burners.

The following cost assumptions have been made :

DU-233 Fissile Burner. The burners are advanced converter reactors (ACR), one Gwe, burning denatured U-233 fuel, CR = 0.9 and α = 0.1. The following unit cost values are used :

Balance of plant :	$690 / kwe-installed
Nuclear island :	$170 / kwe-installed
Fuel fabrication :	$590 / kg-HM
Fuel reprocessing :	$240 / kg-HM

U233-Driver. The method used for the capital unit cost calculations of the CTR's is similar to the one reported by Kostoff[11] of the Office of Energy Research of DOE. Beam injector cost is assumed proportional to the electric power that goes into the neutral beams. Injection efficiency is assumed to be 50%. The cost components are estimated as follows :

Beam injector : β(1.5) x ACR balance of plant=$1030/kw
Nuclear island : 0.7 x ACR balance of plant= $480/kwe
Balance of plant:1.0 x ACR balance of plant= $690/kwe
Fabrication thorium metal fuel : $130 / kg-Th
Reprocessing thorium metal fuel :$275 / kg-Th
Cost of thorium ore : $30 / kg-Th

Tritium-Driver. For the driver for the tritium factory, the costs are estimated as follows :

Beam injector : β(1.5) x ACR balance of plant=$1030/kw
Nuclear island : 0.7 x ACR balance of plant= $480/kwe
Balance of plant:1.0 x ACR balance of plant= $690/kwe
Tritium recuperation : 0.8 x ACR balance of plant = $550/kwe

Each CTR is driven by 1000 MWe, injected at 50% efficiency. The amount of injected power can be lowered for the "managed" cases, to be considered later.

The calculated cost of the produced U-233 as a function of irradiation time, for the D-T driven factories, is shown in Figure 8 for Q' ranging from 1 to 5. It can be seen that, because of the combined effects of the decreasing fixed charge and the increasing fuel cycle cost of the U233-driver, there exists an optimum irradiation period for each Q. The fuel cycle component of the U-233 production cost is also shown in the Figure for one of the cases (Q = 8). The total U-233 production cost reflects fabrication and reprocessing costs of the U-233 producing blanket. The net power generated (or consumed) in the driver at BOC is sold (or bought) at the symbiotic system indifference power cost. It has been assumed that the minimum power from the factory - i.e., before U-233 builds up - is converted to electricity and sold to the grid, while any later extra power is wasted, at the CTR balance-of-plant cost.

The minimum U-233 production cost is tabulated in Table 1 for typical D-T and D-D fusion driven symbiotic energy systems for the cases analyzed. Table 1 also lists two measures of system performance,
1. unit support ratio : ratio of the number of U233-burners per CTR or per U233-driver.
2. power support ratio : ratio of the global power of the U233-burners to the maximum total power of the CTR's. [Note that for the D-T driven scenarios, we imply a combined system of one U233-driver and an appropriate number of tritium-drivers, so as to keep the overall system self-sufficient in tritium.] The capital and fuel cycle components of the U-233 production costs are also tabulated. (The two components do not add up to the total cost because the latter reflects the effect of selling the net CTR produced power at the BOC level at the symbiotic system indifference power cost).

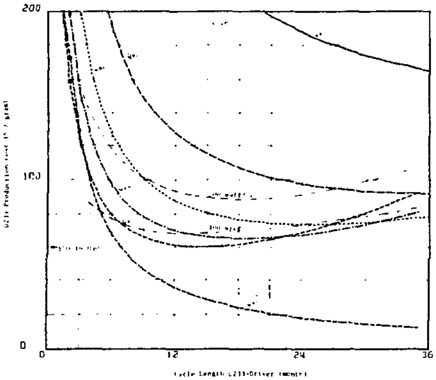

Fig. 8. Indifference U-233 Production Cost of a D-T Fusion-Driven Symbiotic System.

Q	U233 Cost Total ($/gr)	U233 Cost Fixed ($/gr)	U233 Cost Fuel ($/gr)	Unit Support Ratio per U233-Driver	Unit Support Ratio per CTR	Power Support Ratio	Max. Power Density (watt/cc)
D-T Cycle*							
2	148	97	26	52	15.3	10.1	128
4	92	71	25	103	30.4	11.8	250
6	74	63	24	153	45.7	11.9	395
8	65	59	24	203	60.7	12.7	514
10	60	56	24	252	75.7	12.7	635
D-D Cycle*							
2	69	37	26	55		17.0	135
4	54	31	25	109		18.0	270
6	49	29	24	163		17.1	415
8	46	28	24	216		17.8	524

* At minimum U233 Production Cost, no coastdown, no material limitations.

Table 1. Results for D-T and D-D Fusion-Driven Symbiotic Energy Systems.

Figure 8 and Table 1 display the high potential of CTR-driven symbiotic systems. For example, for the D-T cycle operating at Q = 8, the indifference cost is $65 per gram U-233 for an irradiation period of 19 months. This production cost corresponds to an equivalent yellowcake cost of approximately $60 / lb-$U_3O_8$ (at $75 / SWU, 0.2 w% SW tails, 20 w% U-235 in U enrichment, and assuming 1.4 equivalence U-233/U-235).

Unfortunately, engineering limitations make this case improbable, under the implied assumption of constant neutron wall loading. Figure 3 shows that for Q = 8, the maximum power density in the blanket is approximately 515 watt/cc, probably too high to be compatible with blanket integrity. If the blanket is refuelled earlier, the costs would be much higher. Suppose that we set a limit of 200 watt/cc for the maximum allowable power density in the U233-driver blanket. For Q = 8, this limit will be reached in the fifth month. The fuel cycle cost with such a scheme is $125 / gr-U233, and the overall U-233 indifference production cost is $152 / gr-U233. However, if we increase the limit on the maximum allowable power density in the blanket to 400 watt/cc, the fuel cycle cost component can be reduced sharply. The U-233 production cost is then $68 / gram. The costs and support ratios for all D-T and D-D runs, assuming the 200 and 400 watt/cc limits, are shown in Tables 2 and 3.

Managing the Burn

A straightforward way to lower the U-233 production cost is to manage the burn so that fewer neutrons reach the first wall. This can be done by reducing the injection power, the injection efficiency, or the plasma performance parameter Q, when :

1. the maximum power density in the blanket exceeds a specified maximum.
2. the total blanket power increases above a specified rating.

These two conventions will not give the same results since the blanket power profile does not remain constant as the U-233 inventory builds up. At constant total blanket power, the maximum power density decreases slowly.

Consider that the neutron wall loading is allowed to decrease by reducing the power injected into the plasma, so as to maintain the maximum power density in the blanket below 200 watt/cc. Figure 9 shows a) the power into the injector of the U233-driver, b) the maximum power density, and c) the total blanket power as a function of irradiation period, when Q is held constant during the burn. Note that the total blanket power increases slowly with time, because of the continuing U-233 build-up.

Coasting down may take place under the condition that the total blanket power remain constant. The maximum power density for the D-T driver is shown in Figure 10 for such a condition. The results are listed in Table 2.

Figure 11 shows the U-233 monthly production with a 200 watt/cc coastdown. While the production rate with no coastdown and no limits increases slowly with irradiation time (see Figure 5), it decreases rapidly with time once coastdown of the burn is started. However, coastdown allows further generation of U-233 once the maximum allowable power density or total power level is reached in the blanket.

Figure 12 shows a) the power support ratio, b) the unit support ratio of the U233-driver as a function of the cycle length of the driver, when the blanket maximum power density is held below 200 watt/cc. Comparison of Figures 6 (no coastdown) with 12 shows that for a given irradiation period, coasting down tends to affect the thermal power support ratio positively, and the unit support ratio negatively. For irradiation parameters of Q = 8, 24 months irradiation, and coastdown at 200 watt/cc, the power support ratio improves from 10 to 15, and the unit support ratio of the U233-driver decreases from 205 to 140. However, with these irradiation parameters (Q = 8, 24 months irradiation), the blanket maximum power density would reach 580 watt/cc if no coastdown is introduced. The minimum U-233 cost increases from $65 / gram to $74 / gram. At these minimum production values for Q = 8, the power support ratio increases from 12.7 to 17.9, and the unit support ratio of the U233-driver decreases from 203 to 160.

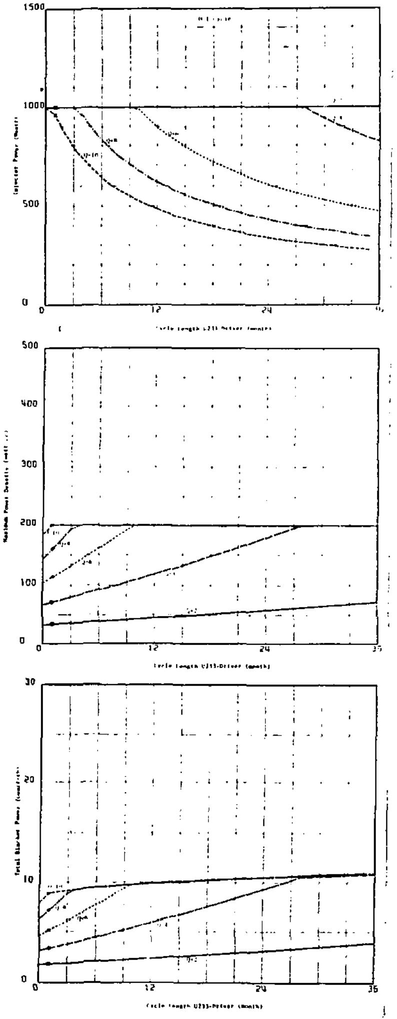

Fig. 9. Managing the Burn of a D-T Fusion-Driven Blanket, with a 200 watt/cc limit.

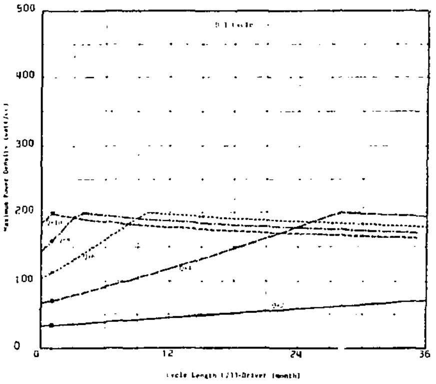

Fig. 10. Maximum Power Density of a D-T Fusion-Driven Blanket, when Total Blanket Power is limited.

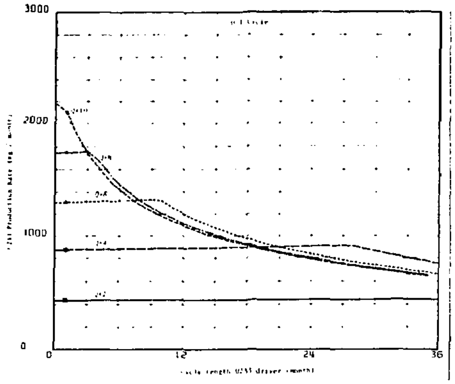

Fig. 11. U-233 Monthly Production Rate of a D-T Fusion-Driven Blanket with a Coastdown at 200 watt/cc.

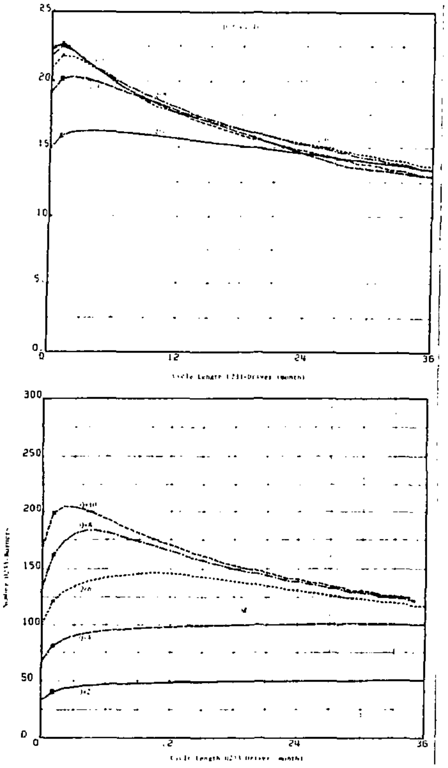

Fig. 12. Power Support Ratio and U233-Driver Unit Support Ratio of a D-T Fusion-Driven Symbiotic System.

Figure 13 shows the overall U-233 production cost under this scheme. For Q = 8, the cost bottoms off at a flat minimum of approximately $65 / gram-U233 after 1.5 years. This is a marked improvement over the $150 calculated when no fusion burn management is allowed.

The calculated minimum costs and the support ratios for all D-T runs are listed in Table 2 for a maximum power density of 200 watt/cc, and also if the limit is raised to 400 watt/cc. It is desirable to have the lowest U-233 production cost with the higher possible unit support ratios and optimum cases may be chosen in terms of a "figure of merit", such as the ratio of U-233 production cost to the number of U233-burners per CTR-driver. The results for cases which are optimum in the sense that they give the lowest values for this ratio are listed in Table 2. For the case discussed (Q = 8), a power support ratio of 17.9 is compatible with a U-233 production cost of $74 / gram-U233.

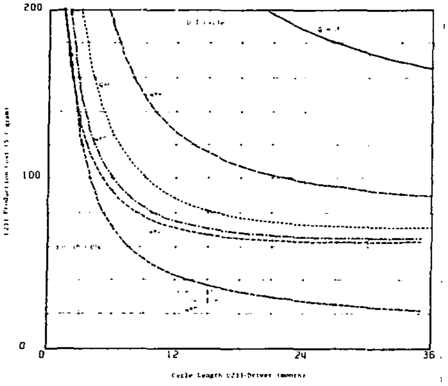

Fig. 13. Indifference U-233 Production Cost of a D-T Fusion-Driven Symbiotic System, with a coastdown at 200 watt/cc.

An alternative scheme to manage the burn is starting at a lower injection power, and then allowing coasting down after the maximum power density is reached. This scheme has a disadvantage of a lower rate of fuel generation at the beginning of the irradiation period : when less fusion power is generated, less fuel is produced. Table 2 shows the results for the case of Q = 8, when the initial injection power is 500 MWe rather than 1000 MWe. Upon reaching the maximum allowable power density of 200 watt/cc, the burn is allowed to coast down. In this case the overall minimum U-233 cost is $63 / gram, and the power support ratio is 14.4. When taken at a production cost of $74 / gram, the power support ratio is 17.0. These values do not differ much from those at which the BOC injected power is 1000 MWe. However, the number of burners per U233-driver has decreased to 100 (i.e. 37% decrease) because of the lower rate of fuel production at BOC. When taken at a minimum production cost per number of U233-burners, the power support ratio decreases by 20%, the unit support ratio of the U233-driver decreases by 37%, the U-233 cost decreases by 15%. Therefore there may be an advantage in starting the burn at relatively high levels and allowing it to coast down later.

A 100% increase in the injection cost of the CTR's (U233-driver and tritium-driver) causes a 16% increase in the production cost of U-233, when the plasma is operated at Q = 8, and the coastdown is done at 400 watt/cc and constant blanket power (see Table 2).

Q	No Coastdown and 200 watt/cc limit				Coastdown at 200 watt/cc and Constant Power								Coastdown at 200 watt/cc							
					At minimum $/gr-U233				At minimum $/gr-U233*				At minimum $/gr-U233				At minimum $/gr-U233*			
	U233 Cost ($/gr)	Unit Support Ratio of U233-Driver	Unit Support Ratio of CTR	Power Support Ratio	U233 Cost ($/gr)	Unit Support Ratio of U233-Driver	Unit Support Ratio of CTR	Power Support Ratio	U233 Cost ($/gr)	Unit Support Ratio of U233-Driver	Unit Support Ratio of CTR	Power Support Ratio	U233 Cost ($/gr)	Unit Support Ratio of U233-Driver	Unit Support Ratio of CTR	Power Support Ratio	U233 Cost ($/gr)	Unit Support Ratio of U233-Driver	Unit Support Ratio of CTR	Power Support Ratio
2	148	52	15.3	9.4																
4	95	101	30.2	13.8	87	93	29.7	12.2	90	100	30.2	13.1	88	95	29.9	11.9	90	100	30.2	13.0
6	101	146	44.4	18.5	71	109	40.9	13.7	77	138	43.8	16.5	71	117	41.9	13.7	75	136	43.7	16.0
8	151	181	57.6	21.5	66	124	50.9	14.7	74	159	55.6	17.9	65	126	51.3	14.1	71	160	55.5	17.1
4(1)	95	51	23.4	13.4																
6(1)	74	77	35.3	12.0																
8(1)	68	101	46.5	15.2	63	100	46.4	14.4	63	100	46.4	14.4								

Q	No Coastdown and 400 watt/cc limit				Coastdown at 400 watt/cc and Constant Power								Coastdown at 400 watt/cc							
					At minimum $/gr-U233				At minimum $/gr-U233*				At minimum $/gr-U233				At minimum $/gr-U233*			
2	148	52	15.3	9.4																
4	92	104	30.4	11.8																
6	74	153	45.7	11.9	71	146	45.5	11.0	72	153	45.8	11.	71	150	45.8	11.0	72	153	45.8	11.5
8	68	199	60.0	15.0	60	182	59.1	13.2	62	194	60.0	1 .0	61	185	59.4	12.7	62	195	60.0	13.7
10	74	241	74.0	17.7	55	196	70.2	13.8	59	231	73.4	16.0	56	202	71.0	13.2	59	233	73.6	15.6
6(2)									85	153	45.8	11.6								
8(2)									72	194	60.0	14.0								
10(2)									67	231	73.4	16.0								

* At minimum ratio of ($/gr-U233) per Unit Support Ratio of CTR.
(1) Injection at 500 Mwatt at BOC, otherwise at 1000 Mwatt at BOC.
(2) Injection cost at $2030/kw, otherwise at $1030/kw.

Table 2. Results for D-T Fusion-Driven Symbiotic Energy Systems with Coastdown.

Q	No Coastdown and 200 watt/cc limit			Coastdown at 200 watt/cc and Constant Power						Coastdown at 200 watt/cc					
				At minimum $/gr-U233			At minimum $/gr-U233*			At minimum $/gr-U233			At minimum $/gr-U233*		
	U233 Cost ($/gr)	Unit Support *Ratio*	Power Support *Ratio*	U233 Cost ($/gr)	Unit Support *Ratio*	Power Support *Ratio*	U233 Cost ($/gr)	Unit Support *Ratio*	Power Support *Ratio*	U233 Cost ($/gr)	Unit Support *Ratio*	Power Support *Ratio*	U233 Cost ($/gr)	Unit Support *Ratio*	Power Support Ratio
2	70	55.0	17.0												
4	58	107.6	24.5	49	96.5	19.6	50	103.7	21.8	49	99.3	19.4	50	104.0	21.4
6	78	154.5	37.9	46	114.5	22.0	49	136.3	28.0	46	120.6	21.9	49	138.0	27.3
8	170	185.3	51.0	47	123.1	22.4	52	155.8	30.5	46	128.6	21.5	52	160.0	29.8

Q	No Coastdown and 400 watt/cc limit			Coastdown at 400 watt/cc and Constant Power						Coastdown at 400 watt/cc					
2	70	55.0	17.0												
4	57	111.4	12.0	54	109.3	18.0	54	109.3	18.0	54	109.3	18.0	54	109.3	18.0
6	49	162.6	18.6	45	155.7	16.6	46	161.2	17.7	46	156.7	16.0	47	162.0	17.6
8	52	210.6	26.1	41	183.6	19.4	43	201.8	22.3	42	190.0	18.7	43	203.2	21.6

* At minimum ratio of ($/gr-U233) per (Burners per CTR Driver).

Table 3. Results for D-D Fusion-Driven Symbiotic Energy Systems with Coastdown.

Finally, the results for the D-D cycle, for similar constraints and plasma performance parameters, are listed in Table 3. Figure 14 shows the unit support ratio of the U233-driver operated on the D-D cycle. The fact that this cycle does not require tritium breeding blankets result in attractive U-233 production costs, power and unit support ratios. Note that the difficulties associated with achieving high Q's for a deuterium plasma do not concern us here. (It is likely that the most important fuel bred in a high Q D-D reactor may be ^{3}He rather than any fissile material). The results of the calculations are tabulated without more commentary, for ready reference.

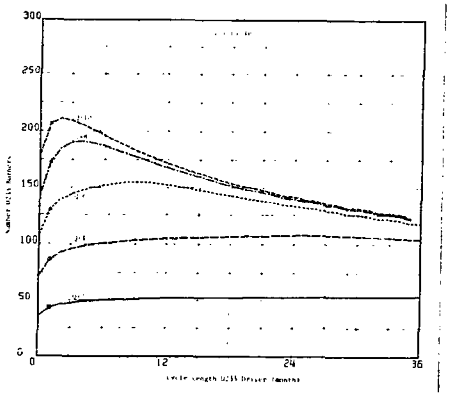

Fig. 14. U233-Driver Unit Support Ratio of a D-D Fusion-Driven System.

Conclusions

It has been shown that economic analyses of symbiotic systems which assume steady operation of the fusion driver overestimate the cost of generating U-233 in the fusion-powered factory. Although blankets which are continuously refuelled avoid the problem of high increases in blanket energy multiplication, it is possible to identify attractive factory schemes even if the blanket elements remain in place for long periods, by managing the fusion burn so as to lower the effect of reprocessing and fabrication of the U233-driver blanket on the U-233 production cost.

For a symbiotic system based on the D-T cycle, which is self-supporting in tritium, and a relatively modest performance parameter (Q x injection efficiency ∿ 4), the minimum calculated cost of U-233, utilizing "state of the art" cost numbers, is of the order of \$75 / gram, the power support ratio may be approximately 18, and the unit support ratio of the U233-driver 160. Assuming \$75 / SWU, 0.2 w% SW tails, 20 w% U-235 enrichment in U, and 1.4 equivalence U-233 / U-235, \$75 / gram-U233 corresponds to an equivalent cost of approximately \$70 / lb-U_3O_8. Lower U-233 production costs, higher power support ratios and higher unit support ratios can be achieved with drivers based on the D-D cycle.

Thus, CTR-driven scenarios may become competitive with U-235 driven cycles in the near future, but the economic analysis must keep track of the possibility to manage the driver to enhance the potential of those scenarios.

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