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D-T AND D-D CYCLES FOR FUSION-POWERED U-233 FACTORIES

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In spite of a low reaction parameter, the "semicatalyzed" D-D cycle constitutes an interesting alternative for symbiotic systems because it eliminates the need for blanket tritium breeding. Previous work on D-D fusion-fission hybrids concluded that blanket energy multiplication is low and that this cycle may be of interest for ignited plasmas only[1]. Here, we show that low multiplication does not penalize the symbiotic system.

Burning fuel in the breeder has a negative effect on costs and the support ratio R (R ≡ converter thermal power / breeder thermal power). For example, references 2 and 3 estimate R and overall symbiote capital costs, based on steady operation and simple mass-flow considerations. These estimates may be rewritten in terms of blanket multiplication M (M ≡ energy deposited in blanket / neutron energy reaching first wall). For converters with conversion ratio C and ratio of capture to fission cross section α, the support ratio R (M) becomes:

$$R(M) = \frac{E\,G}{(f_n M + f_c + \frac{1}{Q})\,(1 - C)\,(1 + \alpha)}\,, \qquad (1)$$

where G is the net number of fissile atoms generated in the breeder per fusion neutron, f_n and f_c are the neutron and charged-particle fusion energy fractions, and the "energy value ratio" E is, approximately, 10.8 for the D-T cycle and 15.3 for the semi-catalyzed D-D cycle. Also, the expression for the capital cost, S (M), for the overall system relative to the converters may be estimated as

$$S\ (M) = \frac{1 + P/R\ (M)}{1 + \frac{n_b}{n_c}\ \frac{1}{R(M)} - \frac{(1 - C)\ (1 + \alpha)}{E\ G\ Q\ n_c\ n_I}}\ , \qquad (2)$$

where P is the capital cost for breeder thermal power relative to the converter, n_I is the efficiency for plasma injection, and n_b and n_c are the breeder and converter thermal efficiencies. From (1) and (2), it can be seen that support ratio decreases with M and, for constant p, the capital cost increases with M if

$$P > \frac{n_b}{n_c}\ \frac{1}{1 - \frac{(1 - C)\ (1 + \alpha)}{E\ G\ Q\ n_c\ \ n_I}}\ . \qquad (3)$$

This condition is automatically satisfied for the "pure" factory ($n_b = 0$). The above expressions are intended only as a rough illustration of the penalty associated with M in the symbiote: more parameters are needed to evaluate the system (the results of detailed calculations are given below). The expressions indicate that if a D-D-fueled breeder can achieve high G at low M, it is at an advantage.

In fact, for judiciously designed blankets, it is not clear that a D-D reactor can achieve lower M. Consider a simplified spherical breeder, 5 m inner radius, with a 1.3 cm steel first wall. Table I shows the results of neutronics calculations for 100% closure using the discrete ordinates code, XSDRN-PM[4], and the DLC-37 multigroup (100 neutron, 21 gamma-ray groups) cross-section library[5]. A P_3S_4 approximation was used and verified with several P_8P_{16} calculations. Line (a) refers to a metallic thorium blanket, 45 cm thick, for the D-D cycle. A 5 cm layer of Pb and 1.3 cm of steel separate the thorium from the first wall, and 10 cm of steel backs it. A 14.06 MeV and a 2.45 MeV neutron deposit a total of

32.7 MeV on the blanket, representing an effective M = 1.98, while the number of captures in thorium is 1.43 per neutron.

Item (b) represents a similar blanket, without the Pb and the second steel layer, for a D-T reactor. M is 3.14. Tritium is bred in a separate $\text{Pb-Li}^{\text{nat}}$ blanket, 80 cm. wide: here, 1.7 tritium atoms are bred per neutron, and 16.1 MeV deposited. Thus, the overall M for a viable system is 1.97, not very different from the D-D cycle.

The D-T cycle M can be further decreased by adding lead to the thorium blanket. Item (c) shows the effect of 5 cm of Pb and 1.3 more cm of stainless steel. The net M for the coupled blankets becomes 1.45, less than for the D-D system, but with a loss in breeding.

Clean blankets give an incomplete indication of the heat removal requirements in the factory. Reprocessing and fabrication are important cost components, and the breeder may be shut down for refueling. These factors lengthen the optimum irradiation time, and fuel build-up increases M. The Table also shows the results of calculations for the maximum power density in the above blankets as a function of irradiation time. Eventually, some maximum power density in the blanket may be reached, and refueling take place. It can be shown that, although irradiation time tends to increase the support ratio, the power costs pass through a minimum. The choice of the best period involves a tradeoff between these two effects.

Overall power costs, the potential for grid expansion, and resource utilization, were calculated for several types of burners, and compared with results reported earlier for the D-T cycle[6]. The calculations were based on US INFCE[7] preliminary cost data and economic guidelines, assuming 85% closure for the fusion breeders and 2% fuel losses in reprocessing and fabrication. The results indicate that the elimination of the need to breed tritium does in fact lead to lower costs and higher support ratios for the D-D fueled cycle - even if actual ignition ($Q \rightarrow \infty$) is never achieved.

Table 1. Results of Neutronics Calculations of Thorium Blankets for D-T and Semi-Catalyzed D-D Fusion Neutrons

	Quarter	Net U-23 Production per Quarter (MT)	Source Eigen-value	Per Fusion Neutron								Maximum Power* Density (Watt/cc)
				U-233 Nuclei		First Wall Heat (n+γ) (MeV)	Thorium Blanket		Total Blanket		Overall Multipli-cation	
				Gross	Net		Heat (MeV)	Multipli-cation	Heat (MeV)	Multipli-cation		
Pb(5 cm)/Th(45 cm) D - D	1	6.10	0.160	1.43	1.43	0.30	14.2	1.71	16.3	1.98	1.98	110.
	2	6.17	0.236	1.49	1.44	0.30	24.0	2.81	26.2	3.18	3.18	148.
	4	6.34	0.373	1.63	1.47	0.31	46.7	5.66	49.0	5.94	5.94	230.
	6	6.54	0.488	1.81	1.50	0.31	75.7	9.17	78.0	9.45	9.45	329.
	8	6.81	0.587	2.04	1.55	0.32	112.4	13.62	114.8	13.91	13.91	445.
	9	6.98	0.631	2.19	1.57	0.32	136.2	16.50	138.7	16.80	16.80	516.
No Pb/Th(45 cm) D - T	1	6.20	0.373	2.06	2.06	0.36	43.7	3.11	44.2	3.14	1.97	203.
	2	6.25	0.438	2.15	2.08	0.36	58.4	4.16	58.9	4.19	2.40	236.
	4	6.38	0.549	2.37	2.12	0.37	93.4	6.64	93.9	6.68	3.42	311.
	6	6.55	0.639	2.65	2.20	0.38	137.0	9.78	138.0	9.32	4.71	401.
	8	6.76	0.714	3.00	2.28	0.39	195.0	13.90	196.0	13.90	6.40	513.
Pb(5 cm)/Th(45 cm) D - T	1	5.66	0.234	1.88	1.88	0.50	22.8	1.62	26.4	1.88	1.45	132.
	2	5.70	0.312	1.95	1.89	0.50	34.4	2.45	38.1	2.71	1.79	151.
	4	5.80	0.443	2.12	1.93	0.50	61.6	4.38	65.3	4.65	2.59	220.
	6	5.92	0.549	2.33	1.97	0.51	95.2	6.77	98.9	7.04	3.57	301.
	8	6.07	0.636	2.60	2.02	0.52	138.0	9.78	141.4	10.10	4.81	396.
	9	6.16	0.674	2.76	2.05	0.52	163.0	11.60	167.2	11.90	5.57	451.
	1**	5.43	0.211	1.80	1.80	0.50	20.8	1.48	24.5	1.74	1.39	112.
	2**	5.46	0.293	1.87	1.81	0.50	32.5	2.31	36.2	2.57	1.73	143.

* At Q=5.64, CTR Injection 500 MW,
100% Capacity Factor, 100% Closure

** Replace 10% thorium volume by SS

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