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The "Best" ²³³U-Producing Blanket for
the Tandem Mirror Hybrid

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MEMORANDUM

TO: Distribution
FROM: Dave Bender
SUBJECT: The "Best" ²³³U-Producing Blanket
for the Tandem Mirror Hybrid

I. Summary

I have used the first-order system analysis I developed recently (UCRL-80589, Rev. 1) to evaluate various characteristics of ²³³U-producing hybrids. The notation used below is the same as in the above-cited paper. Also, in this memo I develop a cost model for the hybrid and incorporate it in the previously developed analysis.

II. Blanket Types

Figure 1 is a plot of the nuclear characteristics of various types of ²³³U-producing blanket. These values were taken from a variety of published and unpublished sources. Here, (C&M) is Cook and Maniscalco, (Lee) is J. D. Lee, (Lidsky) is Larry Lidsky, (C) is Cook, and (PPPL) is Princeton. The blankets represent five different basic design philosophies; a brief description and representative (optimistic?) nuclear characteristics (used in the later sections) are listed in Table 1. Blanket No. 4 does not appear in Figure 1 (off scale) and was developed by Su, Woodruff and McCormick (U. of Washington); it has very high production but $k_{eff} = 0.95$. I do not consider it reasonable for a reactor but include it for completeness.

III. Pertinent Performance Parameters

As measures of "goodness" for the reactor I consider two parameters:

- (1) R_c = Unit System Capital Cost
- (2) R_t = Support Ratio

The first, R_c , addresses economics (cost of electricity) and the second, R_t , is a measure of the number of (dispersed) burner reactors per hybrid and addresses the proliferation issue. As will be subsequently shown, there is no blanket (among the examples chosen) that optimizes both parameters. Therefore the "best" blanket is somewhat subjective.

To evaluate the fusion-fission system parameters I assume a high conversion ratio ²³³U burner (e.g., HTGR or CANDU); parameters are listed in

Table 2. The hybrid parameters imply fairly modest fusion technology: 50% injector efficiency and no direct conversion. Then, the system parameters to be evaluated are

$$R_t = r(0.2 + 0.8M + 1/Q_p)^{-1}, \quad (1)$$

$$R_c = \left(1 + \frac{\kappa}{R_t}\right) \left[1 + \frac{1}{R_t} - \frac{1}{\eta_h n_{tc} r Q_p}\right]^{-1}, \quad (2)$$

where

$$r = \frac{10.75(f/n)}{(1-C_r)(1+\alpha)}. \quad (3)$$

The support ratios for the five blankets are shown in Figure 2 as a function of plasma power amplification, Q_p . Note that the ordering of the blankets, with respect to R_t , follows the ordering of the parameter $(f/n)/M$ in Table 1, i.e., substituting Eq. (3) into (1)

$$R_t \sim \frac{(f/n)}{0.2 + 0.8M + 1/Q_p}.$$

The highest support ratio is for the blanket using Be/Pb for neutron multiplication; then, in descending order, Th-Fission, Th-Nonfission, ^{238}U -Fission and ^{238}U /Pu-Fission. The support ratio for the low M blankets does not become large until $Q_p > 1 - 2$. For $Q_p < 1$, R_t decreases rapidly as Q_p decreases for the low M blankets.

We now treat κ (unit capital cost for the hybrid) as a parameter by choosing $R_c = 1.2$ as an attractive economic target and solving Eq. 2 for the value of κ that will yield $R_c = 1.2$. The results are shown in Figure 3. For low Q_p , the high M blankets admit the highest hybrid capital costs. But for $Q_p > 1$, the low M blankets admit higher costs and for $Q_p > 2$, the ordering is the same as for R_t in Figure 2.

However, treating κ as purely a parameter is not the complete story; we anticipate that the hybrid capital costs will vary with the type of blanket and plasma performance. This point is addressed in the next section.

IV. Hybrid Capital Cost Model

I propose the following functional form for the hybrid capital cost,

$$(COST)_b = F(Q_p) P_{fus} + k_{tb} P_{tb} \quad (4)$$

That is, the cost of the reactor is divided into two terms. The first is the cost of the fusion components, where $F(Q_p)$ has units of $\$/kW_{fusion}$ (\$ per kW of fusion power) and P_{fus} is fusion power. The second term is BOP which is assumed proportional to hybrid plant thermal power, P_{tb} .

$$P_{tb} = (0.2 + 0.8 M + 1/Q_p) P_{fus} \quad (5)$$

The coefficient k_{tb} is a constant with units of $\$/kWt$.

To estimate the form of the function $F(Q_p)$, results from the standard mirror hybrid system model are used. This is shown in Figure 4; here I plot $\$/kW_{fusion}$ for the fusion components:

Magnet,
Injectors,
End Tanks,
Vacuum System,
Blanket Structure,
PCRV,
Refrigeration,

as a function of Q_p . To generate this curve with the code, I held P_{fus} and M constant and arbitrarily increased Q_p with an input multiplier. We see a significant decrease in this unit cost as Q_p increases. The reason is that as Q_p increases:

- (1) Injector costs decrease because of decreased injected current;
- (2) End-tank costs decrease because of lower power and current into the tanks;
- (3) Vacuum system costs decrease because of lower gas-handling capacity;
- (4) Refrigeration costs decrease because of less cryopanel area.

In general, for $Q_p \leq 2$, there is a substantial cost penalty for low Q_p . The effect on the plant unit capital cost is shown in Figure 5 (for the standard mirror hybrid).

I propose the following functional form for $F(Q_p)$,

$$F(Q_p) = k_{fus} + \frac{k'_{fus}}{Q_p^a}, \quad (6)$$

where k_{fus} , k'_{fus} and "a" are constants. Thus we have for the plant cost,

$$(COST)_b = (k_{fus} + \frac{k'_{fus}}{Q_p^a}) P_{fus} + k_{tb} P_{tb}. \quad (7)$$

The unit capital cost C_{tb} (\$/kWt), is then (using Eq. 5),

$$C_{tb} = \frac{(cost)_b}{P_{th}} = k_{tb} + \frac{(k_{fus} + k'_{fus} Q_p^{-a})}{0.2 + 0.8M + 1/Q_p}. \quad (8)$$

Normalizing to the unit capital cost of the burner, C_{tc} , we write this relation as

$$\kappa = \frac{C_{tb}}{C_{tc}} = C_1 + \frac{C_2(1 + C_3 Q_p^{-a})}{0.2 + 0.8M + 1/Q_p}. \quad (9)$$

The first term is BOP and the second is the fusion components (which are analogous to the nuclear steam supply system, NSSS, in a fission reactor). Typically, in an LWR, NSSS is 15% of the cost and BOP is 85%.

In Eq. 9, the numerator of the second term describes the decrease in the unit cost as Q_p increases, as specified by the coefficients C_3 and "a". Note that for an ignited reactor ($Q_p = \infty$),

$$\kappa = C_1 + \frac{C_2}{0.2 + 0.8M}. \quad (10)$$

Thus for pure fusion ($M = 1$),

$$\kappa = C_1 + C_2, \quad (11)$$

i.e., for pure fusion to be competitive with fission, $C_2 < 1$, assuming C_1 (BOP) is about the same for fusion and fission. Also, note that in Eq. 10, as M becomes large, the fractional plant unit cost attributal to the fusion components decreases, i.e.,

$$\lim_{M \rightarrow \infty} \kappa = C_1.$$

To evaluate this model for κ , I obtained the coefficients in Eq. 9 for the standard mirror hybrid; these values are given in Table 3, i.e.,

$$\kappa = 0.9 + \frac{2.45(1 + 1.05 Q_p^{-1.45})}{0.2 + 0.8M + 1/Q_p} \quad (12)$$

Note that for an ignited plasma, we have

$$\kappa = 0.9 + \frac{2.45}{0.2 + 0.8M}$$

which gives $\kappa = 3.35$ for pure fusion ($M = 1$), i.e., this is an expensive reactor because of the large value of C_2 . For a high-M hybrid, $M = 10$, we get $\kappa = 1.19$, i.e., the energy multiplication reduces the unit cost considerably.

In Figure 6, the plant unit cost is plotted for the five blankets as a function of Q_p . In all cases, we see the penalty associated with low Q_p (Fig. 4). And, because of the inverse dependence on M (as typified in Eq. 10), the low M blanket reactors have the highest unit costs (on a \$/kWh basis).

V. Power Cost

Comparing Figures 3 and 6, we see that the reactors with the low M blankets admit higher hybrid plant costs (Fig. 3) and indeed have higher cost (Figure 6). To compare the economics of reactors with the various blankets, we no longer treat κ as a parameter but rather substitute the cost model, Eq. 9, into Eq. 2 and solve for R_C .

The results for the five blankets are shown in Figure 7 as a function of Q_p . Blanket No. 4 (U-Pu Fission) has the best economics but is not attractive because of its near-criticality and low support ratio. Of the remaining blanket options, the best economic performer is No. 3 (U Fission); however, it has the lowest support ratio of the four blankets, high power density (due to high M), will generate Pu (possible undesirable political implications) and significant afterheat from fission products. Comparing Fig. 7 and Table 1, we see that the larger (f/n), the better the economics; blanket energy multiplication has a second order effect.

The surprising result (to me) in Figure 7 is that the low M blankets, No. 2 (Th Fission) and No. 5 (Be/Pb), have only slightly (~5%) poorer economics

than the U-Fission blanket for $Q_p \geq 2$. The Th-Fission blanket would avoid the possible objection to Pu. However, the Be/Pb blanket avoids both Pu and afterheat problems (assuming the ^{233}U can be removed before a significant fraction is fissioned) and has the highest support ratio of the five blankets. The non-fission Th blanket (No. 1) incurs a significant cost penalty relative to blanket No. 3 (U-Fission) and has a lower support ratio than blankets Nos. 2 and 5.

VI. Example Reactor Parameters

For the different blankets, I evaluated the hybrid power flow and economic parameters for $Q_p = 2$ (see Tables 4A and 4B). In all cases, I designed the hybrid to 2500 MWt (blanket and end-tanks). I chose this number because a 1000 MWe HTGR ($\eta_{tc} = 0.4$) is 2500 MWt.

In Table 4A, I have used "low" fusion technology, i.e., $\eta_h = 0.5$, $\eta_{DC} = 0$. Note that the U/Th blanket is a large net power producer, the Th-Fission blanket is just about break-even electrically and the Be/Pb blanket is a large power consumer.

In Table 4B, I used relatively optimistic fusion technology, i.e., $\eta_h = 0.75$ and $\eta_{DC} = 0.5$. Here, all three reactors are net power producers. Note that the fusion power went up (as compared to Table 4A) because the use of direct conversion reduces the relative amount of thermal energy in the end tanks.

Given these two limiting cases in fusion technology, it is my guess that a Be/Pb blanket could be designed to be just about an electrical break-even reactor at $Q_p = 2$.

VII. Conclusions and Comments

(1) For the hybrid, we want $Q_p \sim 2$ or greater because of the capital cost penalty. This is a generalization from a specific example, the standard mirror hybrid, but I have a strong conviction it will be true for most other confinement schemes.

(2) As I suspected when I started this analysis, the best economics result with a U-Fission blanket. However, the hybrid economics are almost as good with the Th-Fission and Be/Pb blankets, they yield high support ratios, and address Pu and afterheat problems.

(3) The non-fission Th blanket looks like a loser.

(4) To suppress the afterheat problem in the Be/Pb blanket will require very frequent reprocessing to avoid build-up and in-situ fission of the bred

²³³U. The economic penalty associated with frequent reactor shut-down for refueling (low capacity factor) and the cost of fabrication/reprocessing at low burnup will probably require some type of on-line refueling, e.g., molten salt.

(5) Before embarking on the tandem mirror hybrid point design next year, we should give strong consideration to the Be/Pb and Th-Fission blankets.

(6) With an intermediate level of fusion technology, a reactor with the Be/Pb blanket would be about break-even electrically, with the Th-Fission blanket would be a small net electrical producer and with the U/Th blanket would be a large net energy producer.

(7) One aspect of the system performance which I (or anyone else) have not yet addressed is the problem of supplying the fissile inventories of the reactor cores. With a Pu fuel cycle, this is not a major problem since there will be large amounts of Pu available from the once-through U fuel cycle. However, this is not the case with the ²³³U fuel cycle -- the hybrid will probably have to do the job. The overall system effect is to decrease the support ratio -- possibly by a large amount, because the reactor core inventory is large compared to the annual fuel make-up requirements. The questions to be answered are "does the inventory requirement favor one of the blankets considered or does it significantly increase the modest economic difference between the U/Th and Be/Pb blankets?" I will try to quantify the problem in another memo.

(8) Of the two blanket neutronic parameters, net fissile breeding ratio, (f/n), and energy multiplication, M, system economics are dominated by (f/n), e.g.,

$$R_c \sim 1/(f/n)$$

and the support ratio is dominated by

$$R_t \sim (f/n)/M.$$

These conclusions apply to $Q_p > 1$.

Blanket Types

Table 1

<u>Blanket No.</u>	<u>Type</u>	<u>M</u>	<u>f/n</u>	<u>(f/n)/M</u>
1	Th Non- Fission	1.5	0.5	0.33
2	Th Fission	2.3	0.84	0.37
3	U Fission	8.3	1.07	0.13
4	U + Pu Fission	80.9	3.54	0.044
5	Be or Pb (n, 2n)	1.6	0.8	0.5

Reactor Parameters

Table 2

Burner:	$C_R = 0.85$	Hybrid:	$\eta_h = 0.5$
	$\alpha = 0.1$		$\eta_{tb} = 0.35$
	$\eta_{tc} = 0.35$		$(\eta_{DC} = 0)$
	$C_{tc} = 1000 \text{ \$/kWe}$		

Coefficients for Capital Cost Model (from Standard Mirror Hybrid)

Table 3

$C_1 = 0.9$
$C_2 = 2.45$
$C_3 = 1.05$
$a = 1.45$

Reactor Parameters

Table 4A

$$\eta_h = 0.5, \eta_{tb} = 0.35, \eta_{DC} = 0, Q_p = 2$$

	(2)	Blanket (3)	(5)
Power Flow (MW)			
Injector Elec. Input	984	341	1263
Fusion	984	341	1263
Thermal	2500	2500	2500
Gross Elec. Output	875	875	875
Net Elec. Output	-109	534	-388
Recirculating Power Fraction	1.13	0.39	1.44
No. of 1 GWe HTGR's Supported	21.6	9.5	26.3
Economics			
Elec. Cost (mills/kwh)	23.73	22.87	23.94
Fuel Cost			
(\$/gm)	124	79	135
(mills/kwh)	2.23	1.42	2.43
Hybrid Cap. Cost (10 ⁹ \$)	1.87	1.13	2.17

Reactor Parameters

Table 48

$\eta_h = 0.75$, $\eta_{tb} = 0.35$, $\eta_{DC} = 0.5$, $Q_p = 2$

	<u>(2)</u>	<u>Blanket (3)</u>	<u>(5)</u>
Power Flow (MW)			
Injector Elec. Input	761	239	1028
Fusion	1142	357	1534
Thermal	2500	2500	2500
Gross Elec. Output	1275	1000	1412
Net Elec. Output	514	762	390
Recirculating Power Frac.	0.60	0.24	0.72
No. of 1 GWe HTGR's Supported	25.0	10.0	32.0
Economics			
Elec. Cost (mills/kwh)	23.00	22.62	23.09
Fuel Cost			
(\$/gm)	85.7	65.4	90.2
(mills/kwh)	1.54	1.18	1.62
Hybrid Cap. Cost (10^9 \$)	2.04	1.16	2.48

[Fig. 1]

NUCLEAR CHARACTERISTICS OF ^{233}U -PRODUCING BLANKETS

(AT BEGINNING OF LIFE)

KEY :

- TH NON-FISSION
- ▲ TH FISSION
- x Be or Pb ($n, 2n$)
- + U FAST-FISSION

[Fig. 2]

SUPPORT RATIO

ALLOWABLE
HYBRID UNIT CAPITAL COST
FOR $R_c = 1.2$

[Fig. 3]

[Fig. 4]

UNIT COST OF
FUSION COMPONENTS
FOR
STANDARD MIRROR HYBRID

AS $Q_p \uparrow$, COST FOR:

INJECTORS ↓

END TANKS ↓

VAC. SYS. ↓

REFRIG. ↓

UNIT CAPITAL COST
FOR
STANDARD MIRROR HYBRID

[Fig. 5]

HYBRID UNIT CAPITAL COST MODEL

[Fig. 6]

SYSTEM CAPITAL COST RATIO
WITH HYBRID UNIT
CAPITAL COST MODEL

[Fig. 7]