**Thorium Assessment Study Quarterly Progress
Report for Third Quarter Fiscal 1977**

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MASTER

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OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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THORIUM ASSESSMENT STUDY QUARTERLY PROGRESS REPORT
FOR THIRD QUARTER FISCAL 1977

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ABSTRACT

The objective of this program is to contribute to the ongoing assessment of the potential role of thorium fuel cycles for alleviating safeguards concerns. Scenarios include (1) no fuel recycle permitted, (2) fuel recycle permitted only in secure regions ("energy parks") with denatured (chemically non-separable) fuels only outside these regions, and (3) no limits on fuel recycle. A further objective is to provide nuclear mass balance data on HTGRs required by ERDA contractors for comparative cost-benefit studies.

1. HIGHLIGHTS

D. E. Bartine

During the third quarter of FY 77, a normalized summary of mass balance information for thermal reactor fuel cycles was prepared from data supplied by various TAP participants. Mass balances were generated for 8 LMFBR fuel cycles, indicating decreased breeding ratios for the substitution of ^{233}U for Pu fissile material and for the substitution of ^{232}Th for ^{238}U fertile material. Studies continued on the symbiotic relationship coupling dispersed fast reactors operating on denatured fuel ($^{233}\text{U}/^{238}\text{U}$) with ^{233}U production reactors operating in centralized energy centers. The existence of an asymptotic outside to inside power ratio for defined symbiotic systems was determined, and a compound system doubling time definition was developed for the combined system. A trade-off was noted between outside/inside power ratio and doubling time. Cross section sensitivity calculations were performed to determine the effect of estimated uncertainties in the ^{232}Th capture cross section on symbiotic system performance, indicating significant lowering of the breeding ratio and sharp increases in the compound system doubling time. These potential losses may be recaptured by reactor designs which are optimized for Th cycle fuels.

A preliminary investigation of the utilization of Th base metal fuels in LMFBRs indicates a potential role for a Th/U/Pu trinary metal system.

A description of the flow of nuclear materials for restricted fuel cycle scenarios was generated, including detailed flow charts.

2. THERMAL REACTOR CALCULATIONS

J. C. Cleveland
W. E. Thomas

2.1 Standard HTGR Reference Design Fuel Cycle Information

Thirty years of mass flow data was generated for a Th-HEU HTGR. The reactor design is for a 3000 MW(t), 1160 MW(e) plant with a core power density of 8.4 w/cc. The carbon to thorium ratio is 214 for the initial core and 238 for reload batches. More detailed core design information is given in ref. 1. The fuel management scheme involves self-generated recycle of the bred uranium with one recycle of the fully enriched make-up uranium. Recycle of uranium bred from thorium continues throughout the history of the reactor. The calculations assumed annual refueling with a constant capacity factor of 80%. With the exception of the initial core, fuel in each of four approximately equal volume segments remains in the reactor for four cycles. The calculated average conversion ratio for the equilibrium cycle is 0.65. Mass balance information is provided in Tables 2.1 and 2.2. Information presented here represents a more detailed calculation of mass flows from that presented in ref. 1.

2.2 Mass Balances for Thermal Reactors

A summary of mass balance information for various thermal reactor fuel cycle combinations as determined by various Thorium Assessment Program participants has been prepared and is presented in Table 2.3. The source of the information for each case is given in the last column of the table. Mass balance information for all cases has been put on the same

Table 2.1 Mass balance equilibrium discharge information
for the 1160 MW(e) standard HTGR

HEAVY METAL DISCHARGED (KG)											
CYCLE	THORIUM	*FRESH MAKEUP*		**BRED URANIUM REMOVED*		SPENT U RETIRED		TOTAL U REMOVED		***PLUTONIUM***	
		U-235	URANIUM	U-233	U-235 URANIUM	U-235	URANIUM	FISSILE	TOTAL	FISSILE	TOTAL
1	9906.0	221.6	294.0	149.5	0.9	161.4	0.0	371.9	455.5	0.8	1.4
2	8760.2	104.0	180.7	194.8	3.5	222.9	0.0	302.3	403.6	0.9	2.7
3	8590.6	56.4	135.1	223.4	7.3	269.6	0.0	287.2	404.7	1.1	4.8
4	8426.7	31.6	108.1	237.6	11.6	300.7	0.0	280.8	408.7	1.4	7.2
5	8444.0	72.1	222.1	241.0	11.2	302.5	0.0	324.3	524.6	2.7	13.5
6	7623.6	32.7	95.8	227.8	15.0	301.8	21.1	296.6	497.6	2.7	14.6
7	7627.4	41.3	117.2	232.2	18.7	319.0	10.5	302.7	513.2	2.8	15.1
8	7629.1	42.3	118.3	235.0	22.2	334.2	5.9	305.4	520.1	2.7	15.0
9	8457.9	43.3	119.9	260.8	26.3	376.3	3.4	333.8	556.5	2.7	14.8
10	7632.0	39.7	108.9	237.7	25.0	346.6	7.9	310.4	576.6	3.8	21.5
11	7632.1	43.4	118.9	236.5	26.6	351.1	3.6	310.0	521.4	2.4	13.5
12	7632.5	43.6	119.1	236.9	28.5	358.9	4.5	313.6	540.3	2.7	15.0
13	8460.4	44.6	121.9	261.4	31.4	396.2	4.6	342.1	580.7	2.7	15.4
14	7632.2	34.5	94.3	239.1	33.2	379.3	4.7	311.6	536.9	2.5	14.3
15	7633.3	41.6	112.9	238.2	31.7	372.7	4.4	315.9	542.9	2.5	14.4
16	7634.1	41.9	113.2	238.5	32.4	376.1	4.8	317.6	552.0	2.7	15.3
17	8462.8	43.1	116.0	262.9	34.3	410.4	4.9	345.2	589.2	2.7	15.6
18	7636.0	39.4	105.2	241.2	35.6	392.3	5.1	321.3	561.8	2.6	15.5
19	7636.3	41.9	111.7	239.6	35.6	391.7	3.9	321.0	553.3	2.4	14.3
20	7636.8	42.1	111.9	239.8	34.8	398.7	4.8	321.4	560.2	2.6	15.3
21	8465.8	47.0	124.4	264.3	36.1	420.8	4.8	352.2	604.8	2.8	16.1
22	7638.0	37.2	98.1	242.4	37.0	401.0	5.0	321.6	560.3	2.5	15.2
23	7638.7	43.1	113.3	240.9	36.7	399.8	4.6	325.4	568.4	2.6	15.4
24	7639.2	43.4	113.6	241.0	36.6	400.5	4.9	325.8	572.8	2.7	16.0
25	8468.2	48.3	126.1	265.4	37.2	428.7	4.9	355.8	613.7	2.8	16.5
26	7640.0	37.9	98.7	243.4	37.9	407.6	5.5	324.7	571.7	2.6	16.1
27	7640.3	43.7	113.8	241.7	37.4	405.2	4.4	327.2	570.5	2.5	15.3
28	7640.6	43.9	113.9	241.8	37.1	405.5	5.1	327.9	578.8	2.7	16.4
29	8469.8	48.9	126.5	266.3	38.1	436.2	5.2	358.4	622.2	2.9	17.2
30	32319.9	490.5	747.9	992.9	150.0	1653.9	53.7	1687.2	2695.3	8.1	37.0

Table 2.2 Mass balance equilibrium charge information
for the 1160 MW(e) standard HTGR

HEAVY METAL CHARGED (KG)										
CYCLE	THORIUM	*FRESH MAKEUP*		*** RECYCLED BRED U ***			*RECY. SPENT U*		TOTAL U CHARGED	
		U-235	UFANIUM	U-233	U-235	URANIUM	U-235	URANIUM	FISSILE	URANIUM
1	37482.8	1701.8	1827.0	0.0	0.0	0.0	0.0	0.0	1701.8	1827.0
2	9127.9	808.4	867.9	0.0	0.0	0.0	0.0	0.0	808.4	867.9
3	8234.7	338.4	363.3	146.4	0.9	158.2	217.2	288.2	702.9	809.6
4	8234.7	406.3	436.1	190.8	3.4	218.4	101.9	177.1	702.5	831.7
5	8234.7	406.3	436.1	218.9	7.2	264.2	55.3	132.4	687.7	832.7
6	9127.9	410.0	440.1	232.8	11.4	294.6	30.9	105.9	685.1	840.7
7	8234.7	369.9	397.1	236.2	11.0	296.4	70.6	217.7	687.7	911.2
8	8234.7	403.2	432.8	223.2	14.7	295.7	32.1	93.9	673.2	822.5
9	8234.7	403.2	432.8	227.6	18.3	312.6	40.5	114.9	689.5	860.3
10	9127.9	412.5	442.8	230.3	21.8	327.5	41.5	115.9	706.0	886.2
11	8234.7	319.5	343.0	255.5	25.7	368.7	42.4	117.5	643.2	829.3
12	8234.7	381.0	409.0	232.9	24.5	339.7	39.0	106.8	677.4	855.5
13	8234.7	381.0	409.0	231.7	26.0	344.1	42.5	116.5	681.3	869.6
14	9127.9	389.6	418.3	232.2	27.9	351.7	42.7	116.7	692.5	886.7
15	8234.7	351.5	377.4	256.2	30.8	388.2	43.8	119.4	682.2	885.0
16	8234.7	372.8	400.2	234.3	32.6	371.7	33.8	92.4	673.4	864.3
17	8234.7	372.8	400.2	233.4	31.1	365.2	40.7	110.6	678.0	876.0
18	9127.9	413.2	443.6	233.7	31.7	368.5	41.1	111.0	719.7	923.1
19	8234.7	325.4	349.3	257.6	33.6	402.2	42.2	113.7	658.9	865.2
20	8234.7	374.8	402.3	236.3	34.9	384.4	38.6	103.1	684.7	889.9
21	8234.7	374.8	402.3	234.7	34.9	383.9	41.1	109.5	685.5	895.7
22	9127.9	415.4	446.0	234.9	34.1	380.9	41.3	109.7	725.7	936.6
23	8234.7	324.9	348.8	259.0	35.4	412.3	46.0	121.9	665.3	883.0
24	8234.7	373.9	401.4	237.5	36.3	393.0	36.5	96.2	684.2	890.5
25	8234.7	373.9	401.4	236.1	36.0	391.8	42.3	111.1	688.3	904.2
26	9127.9	414.4	444.9	236.1	35.8	392.5	42.5	111.3	728.9	948.7
27	8234.7	321.9	345.6	260.1	36.5	420.2	47.3	123.6	665.8	889.3
28	8234.7	377.3	405.0	238.5	37.1	399.5	37.1	95.8	690.1	901.3
29	8234.7	377.3	405.0	236.8	36.7	397.1	42.3	111.5	693.7	913.7
30	9127.9	418.2	449.0	236.9	36.4	397.4	43.0	111.7	734.5	958.0

Table 2.3. Summary of mass balance information for various reactor fuel cycle combinations

Case Number	Reactor	Cycle	Power	Enrichment ^a	Initial fissile loading [kg (fissile)/GE(e)] ^b	Initial core fertile material loading [MT/GW(e)yr] ^b	Conversion ratio	30-year totals		Capacity factor	Burnup (MWD/T)	Fuel reload scheme	Power density ^c (w/cc)	Pu production [kg/GW(e)yr] ^b	Equilibrium annual makeup requirements [kg/GW(e)yr] ^b	Reference
								ST/GW(e) ^b U ₃ O ₈	MT(SWU)/GW(e) ^b SWU							
1	PWR	LEU No recycle	3800 MW(t) 1300 MW(e)	3.0 w/o	1693 U ²³⁵	74.3 U ²³⁸	0.60	5989	3555	0.75	30363	1/3 of core reloaded annually	95.6	165 (fissile) 232 (total)	790 kg U ²³⁵	EPRI NP-359
2	PWR	LEU U recycle Pu stowaway	3800 MW(t) 1300 MW(e)		1693 U ²³⁵	74.3 U ²³⁸	0.60	4946	3452	0.75	30363	1/3 of core reloaded annually	95.6			EPRI NP-359
3	PWR	LEU U + Pu recycle	3800 MW(t) 1300 MW(e)	3.6 w/o net fissile	1693 U ²³⁵	74.3 U ²³⁸	0.61	4089	2690	0.75	30363	1/3 of core reloaded annually	95.6		478 kg U ²³⁵	EPRI NP-359
4	PWR ^d	Th-HEU U ²³⁵ makeup U recycle Pu stowaway	3800 MW(t) 1300 MW(e)		2354 U ²³⁵	69.4 Th	0.68	3453	3436	0.75	33400	1/3 of core reloaded annually	95.6	~0	340 kg U ²³⁵	EPRI NP-359
5	PWR ^d	Th-den U 20%/12% U ²³⁵ makeup U recycle	3800 MW(t) 1300 MW(e)	4.4 w/o makeup 4.2 w/o recycle	2537 U ²³⁵	59.3 Th 10.1 U ²³⁸	0.67	4121	3940	Calculation performed for variable CF	32521	1/3 of core reloaded annually	95.6	76 (fissile)	421 kg U ²³⁵	ORNL Quarterly Q-2, 1977
6	PWR ^f	Pu/Th LWR Pu makeup Pu recycle	3800 MW(t) 1300 MW(e)		2400 kg Pu (fissile)	68.5 Th	~0.63	NA		0.75	33400	1/3 of core reloaded annually	95.6		~690 kg Pu (fissile)	Letter from R. A. Matzie (CE) to J. C. Cleveland, 5/10/77
7	PWR ^c	Th-den U U ²³⁵ startup U ²³³ makeup U recycle	3800 MW(t) 1300 MW(e)		2537 kg U ²³⁵	59.3 Th 10.1 U ²³⁸		NA		0.75	33400	1/3 of core reloaded annually	95.6	67 (fissile)	290 kg U ²³³	Letter from R. A. Matzie (CE) to J. C. Cleveland, 5/10/77
8	PWR ^e	Th-den U ²³³ U ²³³ startup U ²³³ makeup U recycle	3800 MW(t) 1300 MW(e)		1840 kg U ²³³	56.5 Th 13.5 U ²³⁸		NA		0.75	33400	1/3 of core reloaded annually	95.6	65 (fissile)	290 kg U ²³³	Letter from R. A. Matzie (CE) to J. C. Cleveland, 5/10/77
9	PWR ^e	Th-den U ²³³ U ²³³ startup U ²³³ makeup U recycle	1150 MW(e)	3.2 w/o net fissile				NA	NA	0.75	33000	1/3 of core reloaded annually	95.6	60 (fissile)	294 kg U ²³³	Letter from Yoon Chang to K. Dance, 4/11/77

Table 2.3 Continued

Case Number	Reactor	Cycle	Power	Enrichment ^a	Initial fissile loading [kg (fissile) /GW(e)] ^b	Initial core fertile material loading [MT/GW(e)yr] ^b	Conversion ratio	30 year totals		Capacity factor	Burnup (MWD/T)	Fuel reload scheme	Power density ^c (w/cc)	Pu production [kg/GW(e)yr] ^b	Equilibrium annual makeup requirements [kg/GW(e)yr] ^b	Reference
								ST/GW(e) ^b U ₃ O ₈	MT(SWU) ^b GW(e) SWU							
10	CANDU ^d	Th-den U U ²³⁵ makeup Self-generated U recycle	1000 MW(e)	1.7 w/o net fissile	2121 U ²³⁵					Calculation performed for variable CF	16000			30 (fissile)	151 kg U ²³⁵	ANL Quarterly Q-1, 1977
11	CANDU ^e	Th-den U ²³³ U ²³³ makeup U recycle	1000 MW(e)	1.6 w/o net fissile	1648 U ²³³			NA	NA	Calculation performed for variable CF	16000			32 (fissile)	102 kg U ²³³	ANL Quarterly Q-1, 1977
12	CANDU	Natural U No recycle		0.711			0.74	~4600	0.0	0.75	7500	Online refueling		323 (fissile)	851 kg U ²³⁵	ORNL/TM-5565 by P. R. Kasten
13	HTGR ^d	Th-HEU U recycle	3000 MW(t) 1160 MW(e)	7.5 w/o net fissile	1375 kg U ²³⁵	30.3 Th	0.65	2690	2684	Calculation performed at 0.8	94000 for 0.8 capacity	1/4 of core re- loaded annually	8.4	2.2 (fissile) 12.9 (total)	300 kg U ²³⁵	ORNL Quarterly Q-1, 1977
14	HTGR ^d	Th-HEU U ²³⁵ makeup U recycle	4000 MW(t) 1600 MW(e)	4.1 w/o net fissile	2772 kg U ²³⁵	63.4 Th	0.83	2076	2073	Calculation performed at 0.8	41000 for 0.8 capacity	1/4 of core re- loaded annually	7.0	1.1 (fissile) 3.5 (total)	155 kg U ²³⁵	Letter from Dick Lane (GA) to P. R. Kasten, 2/18/77
15	HTGR ^e	Th-U ²³³ U ²³³ makeup	4000 MW(t) 1600 MW(e)	3.4 w/o net fissile	2615 kg U ²³³ 260 kg U ²³⁵	96.9 Th	~0.93	NA		Calculation performed at 0.8	27000 for 0.8 capacity	1/4 of core re- loaded annually	5.0	~0	82 kg U ²³³ 8 kg U ²³⁵	Letter from Dick Lane (GA) to P. R. Kasten, 2/18/77
16	HTGR	LEU No recycle	3000 MW(t) 1160 MW(e)	11 w/o net fissile	956 kg U ²³⁵	16.9 Th		5100	4235	Calculation performed at 0.8	119300 for 0.8 capacity	1/3 of core re- loaded annually	8.4	55 (fissile) 100 (total)	652 kg U ²³⁵	Letter from Dick Lane (GA) to P. R. Kasten, 2/18/77
17	SSCR	LEU No recycle	3800 MW(t) 1300 MW(e)	2.6 w/o	1600 kg U ²³⁵			5000		0.75	30363	1/3 of core re- loaded annually	95.6	206 (fissile)	677 kg U ²³⁵	Letter from R. A. Matzie (CE) to J. C. Cleveland, 5/10/77
18	SSCR	Th HEU U recycle	3800 MW(t) 1300 MW(e)		2100 kg U ²³⁵			2200		0.75	33400	1/3 of core re- loaded annually	95.6		165 kg U ²³⁵	Letter from R. A. Matzie (CE) to J. C. Cleveland, 5/10/77
19	SSCR	Th-HEU U recycle	3800 MW(t) 1300 MW(e)					2200		0.75		1/3 of core re- loaded annually				CE Quarterly Q-1, 1977
20	SSCR	Th-den U U recycle	3800 MW(t) 1300 MW(e)					2500		0.75		1/3 of core re- loaded annually				CE Quarterly Q-1, 1977
21	SSCR	LEU No recycle	3800 MW(t) 1300 MW(e)					5000		0.75		1/3 of core re- loaded annually				CE Quarterly Q-1, 1977

^aEquilibrium requirement, for given reactor power and capacity factor.^bAt 75% capacity factor.^cAt full power.^dAssumes no exogenous ²³³U source.^eAssumes exogenous ²³³U source.^fEquilibrium annual ²³³U production = 265 kg/GW(e) at 75% capacity factor.

basis of a 1000 MW(e) plant operating at 75% capacity. Since the original calculations were performed for plants of various electrical ratings and assumed capacity factors, the normalization to the same basis required an adjustment of the original data. For this reason the information in the table should be considered approximate.

Cases 4 and 13 are directly comparable cases for Th-HEU fuel in PWRs and HTGRs respectively. Four reasons have been identified for the lower initial core fissile inventory in the HTGR case by comparing results from ORNL calculations for a Th-HEU PWR with results from the ORNL calculations given in case 13. They are

1. the thermal efficiency of .34 for the PWR compared to .39 for the HTGR,
2. parasitic neutron absorption of $\sim 6.4\%$ in the PWR clad and coolant vs $\sim 1.6\%$ in the HTGR particle coatings, moderator and coolant,
3. reduced core leakage in the HTGR due to its larger volume which is ~ 10 times that of the PWR, and
4. reduced ^{233}Pa burnout in the HTGR due to the lower flux levels in the HTGR.

The increased fissile requirement in HTGRs for a higher conversion ratio system is evident by comparing cases 13 and 14. To achieve the higher conversion ratio HTGR the thorium loading is increased.

This table will be expanded as more information is received from the various ERDA contractors.

3. FAST REACTOR CALCULATIONS

T. J. Burns

J. R. White

3.1 Mass Balances for Alternate LMFBR Fuel Cycles

Mass balances (initial loading through equilibrium cycle) have been generated for eight LMFBR fissile/fertile combinations. The following cases are included:

Case	Core/Axial Blanket/ Radial Blanket	Comments
1.	(Pu- ²³⁸ U)O ₂ / ²³⁸ UO ₂ / ²³⁸ UO ₂	run as a reference case
2.	(²³³ U- ²³⁸ U)O ₂ / ²³⁸ UO ₂ /ThO ₂	12% denatured U core assemblies
3.	(²³³ U- ²³⁸ U)O ₂ /ThO ₂ /ThO ₂	12% denatured U core assemblies
4.	(²³³ U- ²³⁸ U-Th)O ₂ /ThO ₂ /ThO ₂	20% denatured U in core assemblies
5.	(²³³ U- ²³⁸ U-Th)O ₂ /ThO ₂ /ThO ₂	40% denatured U in core assemblies
6.	(Pu-Th)O ₂ /ThO ₂ /ThO ₂	possible energy center ²³³ U source
7.	(Pu- ²³⁸ U)O ₂ / ²³⁸ UO ₂ /ThO ₂	possible energy center ²³³ U source
8.	(²³³ U-Th)O ₂ /ThO ₂ /ThO ₂	possible energy center ²³³ U source

The reactor model utilized evolved from that proposed by the Large Core Code Evaluation Working Group.² Although the model does not correspond to a particular commercial design, it is felt to be "representative" of a large core commercial LMFBR. An axial blanket (at the same oxide density as the core) was added since the original model consisted only of the reactor midplane. Table 3.1 summarizes some of the relevant design parameters of the model. Mass balances for each reactor were calculated by replacing the PuO₂/²³⁸UO₂ fuel of the reference case with the fissile/fertile combination under consideration (and in some cases replacement

Table 3.1.. LMFBR design basis

Power [MW(th)]	3085
Output [MW(e)]	1200
Efficiency	0.389
Core Height (cm)	108
Axial Blanket Length (cm)	33
Clad and Structure	SS316
Reactor ΔP (psi)	132
Average Flow Velocity (m/sec)	8.6
T out ($^{\circ}F$)	1050
ΔT ($^{\circ}F$)	300
Mixed Oxide Density (% TD)	92
Assembly Pitch (cm)	13.9
Duct Thickness (cm)	.2
Duct Gap (cm)	.2
Assemblies:	
Core	360
Radial Blanket	234
Control	<u>19</u>
Total	613
Core Assembly:	
Pin OD (cm)	.660
Clad Thickness (cm)	.030
Fuel Pin Gap (cm)	.014
Spacers	wire
Pins/Assembly	271
Pitch/Diameter	1.20
Target Peak Linear Power (kw/ft)	16.61
Target Avg Linear Power (kw/ft)	8.35
Target Peak Burnup (MWD/kg)	120
Target Avg Burnup (MWD/kg)	100
V _{fuel}	0.43
V _{na}	0.38
V _{ss}	0.19
Radial Blanket Assembly:	
Pin OD (cm)	1.229
Clad Thickness (cm)	0.030
Fuel Pin Gap (cm)	0.014
Spacers	wire
Pins/Assembly	91
Pitch/Diameter	1.16
V _{fuel}	0.57
V _{na}	0.30
V _{ss}	0.13
Fuel Management:	
Refueling Interval (days)	365.3
Fuel Residence Time (full power days)	821.8
Blanket Residence Time (full power days)	1643.6
Fraction of Assemblies Replaced/Refueling	
Core	1/3
Radial Blanket	1/6

of the depleted UO_2 blanket material with ThO_2). The original heavy metal volume fraction was maintained for all the reactors, the only correction being for the reduced density of ThO_2 . (Hence, the calculations do not address the possibility of modifying the fuel elements to account for the higher melting point and thermal conductivity of ThO_2 relative to UO_2 .) For all calculations, a fuel management scheme which replaced 1/3 of each core zone and 1/6 of the radial blanket each year was employed. A capacity factor of 0.75 was assumed.

The results of these calculations are summarized in Table 3.2. Cases 2 and 3 are distinguished only by different axial blankets. In case 2 the axial blanket extension of the core fuel contains only Pu and U isotopes at discharge as does the core region. In case 3 the axial blanket also contains Th.

Certain characteristics of the denatured reactors are evident from Table 3.2. The decreased breeding ratios of the denatured reactors reflect two primary effects: the substitution of ^{233}U for fissile Pu and corresponding reduction in the average number of neutrons produced per fission, and a reduction in the number of fertile nuclei fissions (due to the significantly smaller fission cross section of ^{232}Th relative to ^{238}U). One especially noteworthy feature of the denatured reactors is the marked reduction in the amount of fissile Pu discharged per cycle compared to that of the reference system. Additionally, the ^{233}U -fueled systems typically require a smaller fissile inventory than does the corresponding Pu-fueled system (over and above the $\sim 2.5\%$ correction for different atomic weights of the nuclides).

Cases 6, 7, and 8 represent possible ^{233}U sources. Since ^{233}U is not a naturally occurring isotope, it must be "manufactured" from ^{232}Th .

Table 3.2. Equilibrium cycle summary for
alternate LMFBR fuel cycles

Case	1	2	3	4	5	6	7	8
Breeding Ratio (Mid cycle)	1.288	1.143	1.137	1.096	1.056	1.158	1.271	1.030
Reactor Charge (kg)								
Fissile Pu	965	-	-	-	-	1104	964	-
Total Pu	1248	-	-	-	-	1427	1254	-
Fissile U	35	977	975	1009	1054	-	23	1093
Total U	17521	12447	7679	5094	2661	-	11197	1093
Thorium	-	5982	10513	12955	15271	16449	5850	16743
Total HM	18769	18429	18192	18048	17932	17876	18302	17836
Reactor Discharge (kg)								
Fissile Pu	1189	544	416	244	94	513	1001	-
Total Pu	1555	586	453	264	101	856	1362	-
Fissile U	21	541	662	841	1003	699	197	1111
Total U	16340	11155	6664	4516	2453	699	10434	1111
Thorium	-	5782	10168	12347	14447	15412	5628	15789
Total HM	17895	17523	17284	17127	17002	16967	17424	16900

Three possible means of generating a ^{233}U inventory have been considered: a Pu/Th LMFBR, the reference Pu/ ^{238}U system with a ThO_2 radial blanket, and a ^{233}U /Th LMFBR. (These reactors must operate within a secure energy center since they are not denatured.) In particular, comparing the reference case with the data for the Pu/Th LMFBR indicates the breeding ratio penalty associated with the fast fission cross section of ^{232}Th relative to ^{238}U . Tables 3.3-3.18 tabulate the 30 year mass balances for each reactor adjusted for a variable capacity factor.³

3.2 Symbiotic Reactor Systems

As indicated by Table 3.2, the four denatured reactors considered (cases 2-5) are net ^{233}U consumers. Although the overall breeding ratio in each case is greater than 1, a portion of the bred fissile material (i.e., the Pu bred from the denaturant ^{238}U) cannot be recycled back into the denatured reactors. This effect is illustrated by Fig. 3.1 which schematically depicts the isotopic components of the overall breeding ratio. All the denatured reactors considered require a ^{233}U source for makeup requirements (in addition to the initial ^{233}U inventory required for startup). A symbiotic system is therefore envisioned which would couple the dispersed denatured reactors to a centralized energy center ^{233}U production reactor.⁴ Figure 3.2 indicates the relative fissile production/destruction rates for the three possible energy center reactors considered. From the viewpoint of overall fissile production, the Pu/ ^{238}U system with a ThO_2 radial blanket is clearly superior. However, from the standpoint of ^{233}U production, the Pu/Th LMFBR has a distinct advantage.

One symbiotic parameter of particular importance is the ratio of power produced in the dispersed reactors to that produced in the energy

Table 3.3

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 * DISCHARGE MASS FLOW FOR ENTIRE REACTOR (KG) *
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REACTOR IDENTIFICATION : PU-U/U LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 PU/UO2 CORE, UO2 AXIAL AND RADIAL BLANKETS (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	0.0	0.0	24.1	13822.8	666.9	185.3	66.9	30.6	733.7	14796.5
2	0.6600	0.0	0.0	22.7	14751.4	859.3	257.1	70.0	39.3	929.3	15999.7
3	0.7200	0.0	0.0	21.6	15787.1	982.0	297.9	65.2	41.5	1047.2	17195.2
4	0.7200	0.0	0.0	21.1	15732.7	1018.7	304.8	67.2	42.6	1085.8	17187.0
5	0.7200	0.0	0.0	20.6	15699.9	1046.2	306.5	67.3	42.7	1113.5	17183.2
6	0.7200	0.0	0.0	20.1	15668.5	1071.6	308.4	67.4	42.7	1139.1	17178.8
7	0.7200	0.0	0.0	20.1	15669.3	1071.8	308.3	67.5	42.7	1139.3	17179.6
8	0.7200	0.0	0.0	20.1	15668.2	1072.8	308.3	67.5	42.7	1140.2	17179.5
9	0.7200	0.0	0.0	20.1	15666.8	1073.7	308.4	67.5	42.7	1141.2	17179.1
10	0.7200	0.0	0.0	20.1	15666.2	1074.2	308.4	67.5	42.7	1141.7	17179.0
11	0.7200	0.0	0.0	20.1	15665.9	1074.3	308.4	67.5	42.7	1141.8	17178.9
12	0.7200	0.0	0.0	20.1	15665.9	1074.4	308.4	67.5	42.7	1141.9	17178.9
13	0.7200	0.0	0.0	20.1	15665.9	1074.4	308.4	67.5	42.7	1141.9	17178.9
14	0.7200	0.0	0.0	20.1	15665.9	1074.4	308.4	67.5	42.7	1141.9	17178.9
15	0.7200	0.0	0.0	20.1	15665.9	1074.4	308.4	67.5	42.7	1141.9	17178.9
16	0.7200	0.0	0.0	20.1	15665.9	1074.4	308.4	67.5	42.7	1141.9	17178.9
17	0.7040	0.0	0.0	19.7	15317.7	1050.5	301.6	66.0	41.7	1116.5	16797.2
18	0.6890	0.0	0.0	19.2	14991.4	1028.1	295.2	64.6	40.8	1092.7	16439.3
19	0.6730	0.0	0.0	18.8	14643.2	1004.2	288.3	63.1	39.9	1067.3	16057.5
20	0.6570	0.0	0.0	18.3	14295.1	980.4	281.5	61.6	38.9	1042.0	15675.8
21	0.6410	0.0	0.0	17.9	13947.0	956.5	274.6	60.1	38.0	1016.6	15294.0
22	0.6260	0.0	0.0	17.5	13620.6	934.1	268.2	58.7	37.1	992.8	14936.1
23	0.6100	0.0	0.0	17.0	13272.5	910.2	261.3	57.2	36.1	967.4	14554.4
24	0.5940	0.0	0.0	16.6	12924.3	886.4	254.5	55.7	35.2	942.0	14172.6
25	0.5790	0.0	0.0	16.2	12598.0	864.0	248.0	54.3	34.3	918.2	13814.7
26	0.5630	0.0	0.0	15.7	12249.8	840.1	241.2	52.8	33.4	892.9	13433.0
27	0.5470	0.0	0.0	15.3	11901.7	816.2	234.3	51.3	32.4	867.5	13051.2
28	0.5310	0.0	0.0	14.8	11553.6	792.4	227.5	49.8	31.5	842.1	12669.5
29	0.5160	0.0	0.0	14.4	11227.2	770.0	221.0	48.4	30.6	818.3	12311.6
30	0.5000	0.0	0.0	71.3	45727.1	2274.7	594.8	166.5	89.3	2441.2	48923.6

Table 3.4

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 * CHARGE MASS FLOW FOR ENTIRE REACTOR (KG)
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REACTOR IDENTIFICATION : PU-U/O LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 PU/UO2 CORE,UO2 AXIAL AND RADIAL BLANKETS (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	0.0	0.0	115.3	57213.2	1891.6	542.6	287.2	96.6	2178.7	60146.4
2	0.6600	0.0	0.0	31.0	15387.2	737.2	211.4	111.9	37.6	849.1	16516.4
3	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
4	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
5	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
6	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
7	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
8	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
9	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
10	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
11	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
12	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
13	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
14	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
15	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
16	0.7200	0.0	0.0	33.9	16786.0	804.2	230.6	122.1	41.1	926.3	18017.9
17	0.7040	0.0	0.0	33.1	16413.0	786.4	225.5	119.4	40.2	905.7	17617.5
18	0.6890	0.0	0.0	32.4	16063.3	769.6	220.7	116.8	39.3	886.4	17242.2
19	0.6730	0.0	0.0	31.7	15690.3	751.7	215.6	114.1	38.4	865.8	16841.8
20	0.6570	0.0	0.0	30.9	15317.3	733.9	210.5	111.4	37.5	845.3	16441.4
21	0.6410	0.0	0.0	30.2	14944.2	716.0	205.3	108.7	36.6	824.7	16041.0
22	0.6260	0.0	0.0	29.4	14594.5	699.2	200.5	106.1	35.7	805.4	15665.6
23	0.6100	0.0	0.0	28.7	14221.5	681.4	195.4	103.4	34.8	784.8	15265.2
24	0.5940	0.0	0.0	27.9	13848.5	663.5	190.3	100.7	33.9	764.2	14864.8
25	0.5790	0.0	0.0	27.2	13498.8	646.7	185.5	98.2	33.0	744.9	14489.4
26	0.5630	0.0	0.0	26.5	13125.8	628.9	180.4	95.5	32.1	724.3	14089.0
27	0.5470	0.0	0.0	25.7	12752.7	611.0	175.2	92.7	31.2	703.7	13688.6
28	0.5310	0.0	0.0	25.0	12379.7	593.1	170.1	90.0	30.3	683.2	13288.2
29	0.5160	0.0	0.0	24.3	12030.0	576.4	165.3	87.5	29.4	663.9	12912.8
30	0.5000	0.0	0.0	23.5	11657.0	558.5	160.2	84.8	28.5	643.3	12512.5

Table 3.5

 *
 * DISCHARGE MASS FLOW FOR ENTIRE REACTOR (KG) *
 *

REACTOR IDENTIFICATION : U/U-TH MIN. DENATURED LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 UO2 CORE,UO2 AXIAL BLANKETS,THO2 RADIAL BLANKET (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PJ	TOTAL HM
1	0.6000	4760.6	387.7	15.5	9176.8	198.4	5.6	0.1	0.0	198.5	14544.8
2	0.6600	5208.7	438.9	13.8	9647.5	368.8	20.0	0.7	0.0	369.5	15698.5
3	0.7200	5651.4	417.5	12.5	10179.9	527.7	42.4	2.1	0.1	529.7	16833.4
4	0.7200	5620.0	450.5	12.5	10179.7	523.8	41.3	2.0	0.1	525.8	16829.9
5	0.7200	5588.5	476.3	12.5	10181.7	523.2	41.1	1.9	0.1	525.1	16825.4
6	0.7200	5557.0	501.3	12.6	10185.7	521.5	40.7	1.9	0.1	523.4	16820.8
7	0.7200	5554.4	503.9	12.6	10187.7	520.7	40.5	1.9	0.1	522.6	16821.7
8	0.7200	5552.7	505.4	12.6	10188.6	520.3	40.4	1.9	0.1	522.2	16822.0
9	0.7200	5551.4	506.4	12.6	10188.9	520.2	40.4	1.9	0.1	522.1	16821.9
10	0.7200	5550.8	506.9	12.6	10189.0	520.1	40.4	1.9	0.1	522.0	16821.8
11	0.7200	5550.5	507.1	12.6	10189.1	520.1	40.4	1.9	0.1	522.0	16821.8
12	0.7200	5550.5	507.1	12.6	10189.1	520.1	40.4	1.9	0.1	522.0	16821.8
13	0.7200	5550.5	507.1	12.6	10189.1	520.1	40.4	1.9	0.1	522.0	16821.8
14	0.7200	5550.5	507.1	12.6	10189.1	520.1	40.4	1.9	0.1	522.0	16821.8
15	0.7200	5550.5	507.1	12.6	10189.1	520.1	40.4	1.9	0.1	522.0	16821.8
16	0.7200	5550.5	507.1	12.6	10189.1	520.1	40.4	1.9	0.1	522.0	16821.8
17	0.7040	5427.1	455.5	12.3	9562.7	508.5	39.5	1.8	0.1	510.4	16448.0
18	0.6890	5311.5	485.3	12.1	9750.4	497.7	38.6	1.8	0.1	499.5	16097.5
19	0.6730	5188.2	474.0	11.8	9524.0	486.1	37.7	1.8	0.1	487.9	15723.7
20	0.6570	5064.8	462.8	11.5	9297.6	474.6	36.8	1.7	0.1	476.3	15349.9
21	0.6410	4941.5	451.5	11.2	9071.1	463.0	36.0	1.7	0.1	464.7	14976.1
22	0.6260	4825.8	440.9	11.0	8858.9	452.2	35.1	1.6	0.1	453.8	14625.6
23	0.6100	4702.5	429.7	10.7	8632.4	440.6	34.2	1.6	0.1	442.2	14251.8
24	0.5940	4579.1	418.4	10.4	8406.0	429.1	33.3	1.6	0.1	430.6	13878.0
25	0.5790	4463.5	407.8	10.1	8193.8	418.2	32.5	1.5	0.1	419.8	13527.5
26	0.5630	4340.2	396.6	9.9	7967.3	406.7	31.6	1.5	0.1	408.2	13153.7
27	0.5470	4216.8	385.3	9.6	7740.9	395.1	30.7	1.4	0.1	396.6	12779.9
28	0.5310	4093.5	374.0	9.3	7514.5	383.6	29.8	1.4	0.1	385.0	12406.1
29	0.5160	3977.8	363.5	9.0	7302.2	372.7	28.9	1.4	0.1	374.1	12055.6
30	0.5000	23458.2	1442.7	31.9	21786.0	786.1	46.1	1.9	0.1	788.0	47553.0

Table 3.6

 *
 * CHARGE MASS FLOW FOR ENTIRE REACTOR (KG)
 *

REACTOR IDENTIFICATION : U/L-TH MIN. DENATURED LMFBR @ 1200 NWE (RZ MODEL) (6/09/77)
 UO2 COPE,UO2 AXIAL BLANKETS,THO2 RADIAL BLANKET (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	28712.8	1956.8	56.4	27868.0	0.0	0.0	0.0	0.0	0.0	58594.0
2	0.6600	5264.0	839.1	20.4	10094.0	0.0	0.0	0.0	0.0	0.0	16217.6
3	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
4	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
5	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
6	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
7	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
8	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
9	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
10	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
11	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
12	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
13	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
14	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
15	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
16	0.7200	5742.6	915.4	22.3	11011.7	0.0	0.0	0.0	0.0	0.0	17691.9
17	0.7040	5614.5	855.0	21.8	10767.0	0.0	0.0	0.0	0.0	0.0	17298.7
18	0.6890	5495.3	876.0	21.3	10537.6	0.0	0.0	0.0	0.0	0.0	16930.2
19	0.6730	5367.7	855.6	20.8	10292.9	0.0	0.0	0.0	0.0	0.0	16537.0
20	0.6570	5240.1	835.3	20.3	10048.2	0.0	0.0	0.0	0.0	0.0	16143.9
21	0.6410	5112.5	814.9	19.8	9803.5	0.0	0.0	0.0	0.0	0.0	15750.7
22	0.6260	4992.8	795.9	19.4	9574.0	0.0	0.0	0.0	0.0	0.0	15382.1
23	0.6100	4865.2	775.5	18.9	9329.3	0.0	0.0	0.0	0.0	0.0	14989.0
24	0.5940	4737.6	755.2	18.4	9084.6	0.0	0.0	0.0	0.0	0.0	14595.8
25	0.5790	4618.0	736.1	17.9	8855.2	0.0	0.0	0.0	0.0	0.0	14227.2
26	0.5630	4490.4	715.8	17.4	8610.5	0.0	0.0	0.0	0.0	0.0	13834.1
27	0.5470	4362.7	695.4	16.9	8365.8	0.0	0.0	0.0	0.0	0.0	13440.9
28	0.5310	4235.1	675.1	16.4	8121.1	0.0	0.0	0.0	0.0	0.0	13047.8
29	0.5160	4115.5	656.0	16.0	7891.7	0.0	0.0	0.0	0.0	0.0	12679.2
30	0.5000	3987.9	635.7	15.5	7647.0	0.0	0.0	0.0	0.0	0.0	12286.0

Table 3.7

 *
 * CHARGE MASS FLOW FOR ENTIRE REACTOR (KG)
 *

REACTOR IDENTIFICATION : U/TH MIN. DENATURED LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 UO2 CORE, THO2 AXIAL AND RADIAL BLANKETS (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	39588.4	1973.4	33.4	16430.0	0.0	0.0	0.0	0.0	0.0	58025.3
2	0.6600	9251.7	846.2	12.0	5895.4	0.0	0.0	0.0	0.0	0.0	15009.3
3	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
4	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
5	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
6	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
7	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
8	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
9	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
10	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
11	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
12	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
13	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
14	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
15	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
16	0.7200	10092.8	923.2	13.1	6435.7	0.0	0.0	0.0	0.0	0.0	17464.7
17	0.7040	9868.5	902.6	12.8	6292.6	0.0	0.0	0.0	0.0	0.0	17076.6
18	0.6890	9658.3	883.4	12.5	6158.6	0.0	0.0	0.0	0.0	0.0	16712.8
19	0.6730	9434.0	862.9	12.2	6015.6	0.0	0.0	0.0	0.0	0.0	16324.6
20	0.6570	9209.7	842.4	11.9	5872.5	0.0	0.0	0.0	0.0	0.0	15936.5
21	0.6410	8985.4	821.9	11.7	5729.5	0.0	0.0	0.0	0.0	0.0	15548.4
22	0.6260	8775.1	802.6	11.4	5595.4	0.0	0.0	0.0	0.0	0.0	15184.6
23	0.6100	8550.8	782.1	11.1	5452.4	0.0	0.0	0.0	0.0	0.0	14796.5
24	0.5940	8326.6	761.6	10.8	5309.4	0.0	0.0	0.0	0.0	0.0	14408.4
25	0.5790	8116.3	742.4	10.5	5175.3	0.0	0.0	0.0	0.0	0.0	14044.5
26	0.5630	7892.0	721.9	10.2	5032.3	0.0	0.0	0.0	0.0	0.0	13656.4
27	0.5470	7667.7	701.3	9.9	4889.3	0.0	0.0	0.0	0.0	0.0	13268.3
28	0.5310	7443.4	680.8	9.7	4746.3	0.0	0.0	0.0	0.0	0.0	12880.2
29	0.5160	7233.2	661.6	9.4	4612.2	0.0	0.0	0.0	0.0	0.0	12516.4
30	0.5000	7008.9	641.1	9.1	4469.2	0.0	0.0	0.0	0.0	0.0	12128.3

Table 3.8

 *
 * DISCHARGE MASS FLOW FOR ENTIRE REACTOR (KG) *
 *

REACTOR IDENTIFICATION : U/TH MIN. DENATURED LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 UO2 CORE, THO2 AXIAL AND RADIAL BLANKETS (2 CORE ZONES)

	CAPACITY									FISSILE	TOTAL
YEAR	FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	PU	HM
1	0.6000	8346.6	427.4	8.5	5406.9	160.9	5.1	0.1	0.0	161.0	14355.5
2	0.6600	9110.4	519.5	6.9	5543.4	290.2	17.8	0.7	0.0	290.9	15488.9
3	0.7200	9861.0	540.5	5.6	5751.0	404.7	37.2	1.9	0.1	405.6	16601.8
4	0.7200	9829.2	574.1	5.7	5752.4	400.7	36.1	1.8	0.1	402.5	16600.0
5	0.7200	9797.6	600.1	5.7	5754.8	399.9	35.8	1.8	0.1	401.7	16595.8
6	0.7200	9766.7	624.7	5.7	5758.3	398.6	35.5	1.8	0.1	400.4	16591.3
7	0.7200	9764.4	627.0	5.7	5759.9	398.0	35.3	1.8	0.1	399.8	16592.3
8	0.7200	9762.9	628.4	5.7	5760.7	397.7	35.2	1.7	0.1	399.5	16592.5
9	0.7200	9761.7	629.4	5.7	5760.9	397.7	35.2	1.7	0.1	399.4	16592.4
10	0.7200	9761.1	629.9	5.7	5761.0	397.6	35.2	1.7	0.1	399.4	16592.3
11	0.7200	9760.8	630.1	5.7	5761.1	397.6	35.2	1.7	0.1	399.3	16592.3
12	0.7200	9760.8	630.1	5.7	5761.1	397.6	35.2	1.7	0.1	399.3	16592.3
13	0.7200	9760.8	630.1	5.7	5761.1	397.6	35.2	1.7	0.1	399.3	16592.3
14	0.7200	9760.8	630.1	5.7	5761.1	397.6	35.2	1.7	0.1	399.3	16592.3
15	0.7200	9760.8	630.1	5.7	5761.1	397.6	35.2	1.7	0.1	399.3	16592.3
16	0.7200	9760.8	630.1	5.7	5761.1	397.6	35.2	1.7	0.1	399.3	16592.3
17	0.7040	9543.9	616.1	5.6	5633.1	388.8	34.4	1.7	0.1	390.5	16223.6
18	0.6890	9340.5	603.0	5.5	5513.0	380.5	33.7	1.7	0.1	382.1	15877.9
19	0.6730	9123.6	589.0	5.4	5385.0	371.6	32.9	1.6	0.1	373.3	15509.2
20	0.6570	8906.7	575.0	5.2	5257.0	362.8	32.1	1.6	0.1	364.4	15140.5
21	0.6410	8689.8	561.0	5.1	5129.0	354.0	31.3	1.5	0.1	355.5	14771.8
22	0.6260	8486.5	547.8	5.0	5008.9	345.7	30.6	1.5	0.1	347.2	14426.1
23	0.6100	8269.6	533.8	4.9	4880.9	336.8	29.8	1.5	0.1	338.3	14057.4
24	0.5940	8052.7	519.8	4.7	4752.9	328.0	29.0	1.4	0.1	329.4	13688.6
25	0.5790	7849.3	506.7	4.6	4632.9	319.7	28.3	1.4	0.1	321.1	13343.0
26	0.5630	7632.4	492.7	4.5	4504.9	310.9	27.5	1.4	0.1	312.3	12974.3
27	0.5470	7415.5	478.7	4.4	4376.8	302.1	26.7	1.3	0.1	303.4	12605.5
28	0.5310	7198.6	464.7	4.2	4248.8	293.2	25.9	1.3	0.1	294.5	12236.8
29	0.5160	6995.2	451.6	4.1	4128.8	284.9	25.2	1.2	0.1	286.2	11891.1
30	0.5000	32326.5	1624.6	16.1	12459.0	610.0	40.4	1.7	0.1	611.7	47078.3

Table 3.9

 *
 * CHARGE MASS FLOW FOR ENTIRE REACTOR (KG) *
 *

REACTOR IDENTIFICATION : U-TH/TH 20% ENRATED LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 U/THO2 CORE, THO2 AXIAL AND RADIAL BLANKETS (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	46862.2	2119.2	17.6	8644.0	0.0	0.0	0.0	0.0	0.0	57643.0
2	0.6600	11400.3	881.3	6.9	3594.2	0.0	0.0	0.0	0.0	0.0	15882.6
3	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
4	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
5	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
6	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
7	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
8	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
9	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
10	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
11	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
12	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
13	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
14	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
15	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
16	0.7200	12436.6	961.4	7.5	3920.9	0.0	0.0	0.0	0.0	0.0	17326.4
17	0.7040	12160.3	940.0	7.3	3833.8	0.0	0.0	0.0	0.0	0.0	16941.4
18	0.6890	11901.2	920.0	7.2	3752.1	0.0	0.0	0.0	0.0	0.0	16580.4
19	0.6730	11624.8	898.6	7.0	3665.0	0.0	0.0	0.0	0.0	0.0	16195.4
20	0.6570	11348.4	877.3	6.8	3577.9	0.0	0.0	0.0	0.0	0.0	15810.4
21	0.6410	11072.1	855.9	6.7	3490.7	0.0	0.0	0.0	0.0	0.0	15425.3
22	0.6260	10813.0	835.9	6.5	3409.0	0.0	0.0	0.0	0.0	0.0	15064.4
23	0.6100	10536.6	814.5	6.3	3321.9	0.0	0.0	0.0	0.0	0.0	14679.3
24	0.5940	10260.2	793.1	6.2	3234.8	0.0	0.0	0.0	0.0	0.0	14294.3
25	0.5790	10001.1	773.1	6.0	3153.1	0.0	0.0	0.0	0.0	0.0	13933.3
26	0.5630	9724.8	751.8	5.8	3066.0	0.0	0.0	0.0	0.0	0.0	13548.3
27	0.5470	9448.4	730.4	5.7	2978.8	0.0	0.0	0.0	0.0	0.0	13163.3
28	0.5310	9172.0	709.0	5.5	2891.7	0.0	0.0	0.0	0.0	0.0	12778.2
29	0.5160	8912.9	689.0	5.4	2810.0	0.0	0.0	0.0	0.0	0.0	12417.3
30	0.5000	8636.6	667.6	5.2	2722.9	0.0	0.0	0.0	0.0	0.0	12032.3

Table 3.10

 *
 * DISCHARGE MASS FLOW FOR ENTIRE REACTOR (KG) *
 *

REACTOR IDENTIFICATION : U-TH/TH 20% DENATURED LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 U/THO2 CORE, THO2 AXIAL AND RADIAL BLANKETS (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	11069.9	596.6	3.9	2455.0	69.2	2.0	0.0	0.0	69.2	14196.7
2	0.6600	11465.5	676.1	3.9	3038.1	152.2	8.8	0.3	0.0	152.5	15344.9
3	0.7200	12130.7	715.7	3.4	3364.1	227.5	19.7	1.0	0.0	228.5	16462.0
4	0.7200	11915.7	748.0	3.3	3521.6	235.8	20.0	1.0	0.0	236.8	16445.7
5	0.7200	11886.4	774.4	3.4	3524.4	234.8	19.8	0.9	0.0	235.8	16444.1
6	0.7200	11857.6	798.9	3.4	3526.9	233.9	19.5	0.9	0.0	234.8	16441.1
7	0.7200	11856.7	800.6	3.4	3527.7	233.6	19.4	0.9	0.0	234.5	16442.3
8	0.7200	11855.3	802.1	3.4	3528.1	233.4	19.4	0.9	0.0	234.3	16442.6
9	0.7200	11854.0	803.1	3.4	3528.2	233.4	19.3	0.9	0.0	234.3	16442.4
10	0.7200	11853.4	803.6	3.4	3528.3	233.3	19.3	0.9	0.0	234.2	16442.3
11	0.7200	11853.2	803.8	3.4	3528.3	233.3	19.3	0.9	0.0	234.2	16442.3
12	0.7200	11853.2	803.8	3.4	3528.4	233.3	19.3	0.9	0.0	234.2	16442.3
13	0.7200	11853.2	803.8	3.4	3528.4	233.3	19.3	0.9	0.0	234.2	16442.3
14	0.7200	11853.2	803.8	3.4	3528.4	233.3	19.3	0.9	0.0	234.2	16442.3
15	0.7200	11853.2	803.8	3.4	3528.4	233.3	19.3	0.9	0.0	234.2	16442.3
16	0.7200	11853.2	803.8	3.4	3528.4	233.3	19.3	0.9	0.0	234.2	16442.3
17	0.7040	11589.6	786.0	3.3	3450.0	228.1	18.9	0.9	0.0	229.0	16076.9
18	0.6890	11342.6	769.2	3.2	3376.4	223.3	18.5	0.9	0.0	224.1	15734.4
19	0.6730	11079.4	751.3	3.2	3298.0	218.1	18.1	0.8	0.0	218.9	15369.0
20	0.6570	10816.0	733.5	3.1	3219.6	212.9	17.6	0.8	0.0	213.7	15003.6
21	0.6410	10552.6	715.6	3.0	3141.2	207.7	17.2	0.8	0.0	208.5	14638.2
22	0.6260	10305.7	698.9	3.0	3067.7	202.9	16.8	0.8	0.0	203.7	14295.7
23	0.6100	10042.3	681.0	2.9	2989.3	197.7	16.4	0.8	0.0	198.4	13930.3
24	0.5940	9778.9	663.2	2.8	2910.9	192.5	16.0	0.7	0.0	193.2	13564.9
25	0.5790	9531.9	646.4	2.7	2837.4	187.6	15.5	0.7	0.0	188.4	13222.4
26	0.5630	9268.5	628.5	2.7	2759.0	182.4	15.1	0.7	0.0	183.2	12857.0
27	0.5470	9005.1	610.7	2.6	2680.6	177.3	14.7	0.7	0.0	178.0	12491.6
28	0.5310	8741.7	592.8	2.5	2602.2	172.1	14.3	0.7	0.0	172.7	12126.2
29	0.5160	8494.8	576.1	2.4	2528.7	167.2	13.9	0.6	0.0	167.9	11783.7
30	0.5000	36854.2	1921.4	9.4	7615.9	356.3	22.1	0.9	0.0	357.2	46781.2

Table 3.11

 *
 * CHARGE MASS FLOW FOR ENTIRE REACTOR (KG) *
 *

REACTOR IDENTIFICATION : U-TH/TH 40% DENATURED LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 U/THO2 CORE, THO2 AXIAL AND RADIAL BLANKETS (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	51733.3	2229.2	6.9	3411.1	0.0	0.0	0.0	0.0	0.0	57380.5
2	0.6600	13438.5	924.4	2.9	1414.5	0.0	0.0	0.0	0.0	0.0	15780.3
3	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
4	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
5	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
6	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
7	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
8	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
9	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
10	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
11	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
12	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
13	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
14	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
15	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
16	0.7200	14660.2	1008.5	3.1	1543.0	0.0	0.0	0.0	0.0	0.0	17214.9
17	0.7040	14334.4	986.1	3.1	1508.8	0.0	0.0	0.0	0.0	0.0	16832.3
18	0.6890	14029.0	965.0	3.0	1476.6	0.0	0.0	0.0	0.0	0.0	16473.7
19	0.6730	13703.2	942.6	2.9	1442.3	0.0	0.0	0.0	0.0	0.0	16091.1
20	0.6570	13377.5	920.2	2.9	1406.0	0.0	0.0	0.0	0.0	0.0	15708.6
21	0.6410	13051.7	897.8	2.8	1373.7	0.0	0.0	0.0	0.0	0.0	15326.0
22	0.6260	12746.3	876.8	2.7	1341.6	0.0	0.0	0.0	0.0	0.0	14967.4
23	0.6100	12420.5	854.4	2.7	1307.3	0.0	0.0	0.0	0.0	0.0	14584.8
24	0.5940	12094.7	832.0	2.6	1273.0	0.0	0.0	0.0	0.0	0.0	14202.3
25	0.5790	11789.3	811.0	2.5	1240.9	0.0	0.0	0.0	0.0	0.0	13843.6
26	0.5630	11463.5	788.6	2.5	1206.6	0.0	0.0	0.0	0.0	0.0	13461.1
27	0.5470	11137.7	766.2	2.4	1172.3	0.0	0.0	0.0	0.0	0.0	13078.5
28	0.5310	10811.9	743.7	2.3	1138.0	0.0	0.0	0.0	0.0	0.0	12696.0
29	0.5160	10506.5	722.7	2.2	1105.8	0.0	0.0	0.0	0.0	0.0	12337.3
30	0.5000	10180.7	700.3	2.2	1071.6	0.0	0.0	0.0	0.0	0.0	11954.8

Table 3.12

 *
 * DISCHARGE MASS FLOW FOR ENTIRE REACTOR (KG) *
 *

REACTOR IDENTIFICATION : U-TH/TH 40% DENATURED LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 U/THO2 CORE, THO2 AXIAL AND RADIAL BLANKETS (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	12428.0	669.5	1.6	583.8	27.1	0.8	0.0	0.0	27.1	14110.8
2	0.6600	13190.7	790.2	1.5	1197.2	58.6	3.3	0.1	0.0	58.7	15241.7
3	0.7200	14051.4	867.1	1.4	1317.9	87.1	7.3	0.4	0.0	87.4	16342.6
4	0.7200	13925.5	907.6	1.4	1389.4	90.7	7.5	0.4	0.0	91.1	16322.5
5	0.7200	13895.3	933.2	1.5	1390.6	90.2	7.3	0.3	0.0	90.6	16322.5
6	0.7200	13872.9	956.9	1.5	1391.6	89.8	7.2	0.3	0.0	90.2	16320.3
7	0.7200	13872.4	958.4	1.5	1391.9	89.7	7.2	0.3	0.0	90.1	16321.5
8	0.7200	13871.3	959.8	1.5	1392.1	89.7	7.2	0.3	0.0	90.0	16321.7
9	0.7200	13870.1	960.7	1.5	1392.1	89.7	7.2	0.3	0.0	90.0	16321.6
10	0.7200	13869.6	961.2	1.5	1392.1	89.6	7.2	0.3	0.0	90.0	16321.5
11	0.7200	13869.4	961.4	1.5	1392.1	89.6	7.2	0.3	0.0	90.0	16321.5
12	0.7200	13869.3	961.4	1.5	1392.1	89.6	7.2	0.3	0.0	90.0	16321.5
13	0.7200	13869.3	961.4	1.5	1392.1	89.6	7.2	0.3	0.0	90.0	16321.5
14	0.7200	13869.3	961.4	1.5	1392.1	89.6	7.2	0.3	0.0	90.0	16321.5
15	0.7200	13869.3	961.4	1.5	1392.1	89.6	7.2	0.3	0.0	90.0	16321.5
16	0.7200	13869.3	961.4	1.5	1392.1	89.6	7.2	0.3	0.0	90.0	16321.5
17	0.7040	13551.1	940.0	1.4	1361.2	87.6	7.0	0.3	0.0	88.0	15958.8
18	0.6890	13272.2	920.0	1.4	1332.2	85.8	6.9	0.3	0.0	86.1	15618.8
19	0.6730	12964.0	898.7	1.4	1301.3	83.8	6.7	0.3	0.0	84.1	15256.1
20	0.6570	12655.6	877.3	1.3	1270.3	81.8	6.6	0.3	0.0	82.1	14893.4
21	0.6410	12347.6	855.9	1.3	1239.4	79.8	6.4	0.3	0.0	80.1	14530.7
22	0.6260	12058.6	835.9	1.3	1210.4	77.9	6.3	0.3	0.0	78.2	14190.6
23	0.6100	11750.4	814.5	1.2	1179.5	75.9	6.1	0.3	0.0	76.2	13827.9
24	0.5940	11442.2	793.2	1.2	1148.5	74.0	5.9	0.3	0.0	74.2	13465.2
25	0.5790	11153.3	773.1	1.2	1119.5	72.1	5.8	0.3	0.0	72.3	13125.2
26	0.5630	10845.0	751.8	1.1	1088.6	70.1	5.6	0.3	0.0	70.3	12762.5
27	0.5470	10536.6	730.4	1.1	1057.6	68.1	5.5	0.3	0.0	68.3	12399.8
28	0.5310	10228.6	709.0	1.1	1026.7	66.1	5.3	0.2	0.0	66.4	12037.1
29	0.5160	9939.7	689.0	1.1	997.7	64.2	5.2	0.2	0.0	64.5	11697.1
30	0.5000	41200.7	2169.4	4.0	3002.6	136.6	8.2	0.3	0.0	136.9	46541.9

Table 3.13

 *
 * CHARGE MASS FLOW FOR ENTIRE REACTOR (KG)
 *

REACTOR IDENTIFICATION : PU-TH/TH LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 PU/THO2 CORE, THO2 AXIAL AND RADIAL BLANKETS (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	53892.4	0.0	0.0	0.0	2263.1	646.2	340.5	114.7	2603.6	57256.8
2	0.6600	14475.4	0.0	0.0	0.0	844.8	241.2	127.1	42.8	971.9	15731.3
3	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
4	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
5	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
6	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
7	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
8	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
9	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
10	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
11	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
12	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
13	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
14	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
15	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
16	0.7200	15791.4	0.0	0.0	0.0	921.6	263.1	138.6	46.7	1060.2	17161.4
17	0.7040	15440.5	0.0	0.0	0.0	901.1	257.3	135.6	45.6	1036.7	16780.0
18	0.6890	15111.5	0.0	0.0	0.0	881.9	251.8	132.7	44.7	1014.6	16422.5
19	0.6730	14760.6	0.0	0.0	0.0	861.4	245.9	129.6	43.6	991.0	16041.1
20	0.6570	14409.6	0.0	0.0	0.0	840.9	240.1	126.5	42.6	967.5	15659.8
21	0.6410	14058.7	0.0	0.0	0.0	820.5	234.2	123.4	41.6	943.9	15278.4
22	0.6260	13729.7	0.0	0.0	0.0	801.3	228.7	120.5	40.6	921.8	14920.9
23	0.6100	13378.8	0.0	0.0	0.0	780.8	222.9	117.5	39.6	898.3	14539.5
24	0.5940	13027.9	0.0	0.0	0.0	760.3	217.1	114.4	38.5	874.7	14158.1
25	0.5790	12698.9	0.0	0.0	0.0	741.1	211.6	111.5	37.5	852.6	13800.6
26	0.5630	12348.0	0.0	0.0	0.0	720.6	205.7	108.4	36.5	829.0	13419.3
27	0.5470	11997.1	0.0	0.0	0.0	700.1	199.9	105.3	35.5	805.5	13037.9
28	0.5310	11646.1	0.0	0.0	0.0	679.7	194.0	102.3	34.4	781.9	12656.5
29	0.5160	11317.2	0.0	0.0	0.0	660.5	188.6	99.4	33.5	759.8	12299.0
30	0.5000	10966.2	0.0	0.0	0.0	640.0	182.7	96.3	32.4	736.3	11917.6

Table 3.14

 *
 * DISCHARGE MASS FLOW FOR ENTIRE REACTOR (KG) *
 *

REACTOR IDENTIFICATION : PU-TH/TH LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 PU/THO2 CORE, THO2 AXIAL AND RADIAL BLANKETS (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	12932.1	227.2	0.0	0.0	555.8	225.2	85.9	38.7	641.7	14064.9
2	0.6600	13910.9	422.2	0.0	0.0	482.7	260.0	79.6	44.2	562.3	15199.5
3	0.7200	14885.4	599.4	0.0	0.0	403.7	279.1	73.3	47.5	477.0	16288.4
4	0.7200	14854.8	622.0	0.0	0.0	413.7	281.4	74.5	47.9	488.2	16294.3
5	0.7200	14826.1	646.4	0.0	0.0	415.8	281.6	74.6	47.9	490.4	16292.3
6	0.7200	14796.8	669.5	0.0	0.0	416.9	281.6	74.7	47.9	491.6	16287.4
7	0.7200	14798.6	668.7	0.0	0.0	417.4	281.7	74.8	47.9	492.2	16289.0
8	0.7200	14797.7	669.5	0.0	0.0	417.6	281.7	74.8	47.9	492.4	16289.2
9	0.7200	14796.4	670.5	0.0	0.0	417.6	281.7	74.8	47.9	492.4	16288.9
10	0.7200	14795.9	670.9	0.0	0.0	417.7	281.7	74.8	47.9	492.5	16288.8
11	0.7200	14795.6	671.1	0.0	0.0	417.7	281.7	74.8	47.9	492.5	16288.8
12	0.7200	14795.6	671.1	0.0	0.0	417.7	281.7	74.8	47.9	492.5	16288.8
13	0.7200	14795.6	671.1	0.0	0.0	417.7	281.7	74.8	47.9	492.5	16288.8
14	0.7200	14795.6	671.1	0.0	0.0	417.7	281.7	74.8	47.9	492.5	16288.8
15	0.7200	14795.6	671.1	0.0	0.0	417.7	281.7	74.8	47.9	492.5	16288.8
16	0.7200	14795.6	671.1	0.0	0.0	417.7	281.7	74.8	47.9	492.5	16288.8
17	0.7040	14466.8	656.2	0.0	0.0	408.4	275.4	73.1	46.8	481.5	15926.8
18	0.6890	14158.6	642.2	0.0	0.0	399.7	269.5	71.6	45.8	471.3	15587.4
19	0.6730	13829.8	627.3	0.0	0.0	390.4	263.3	69.9	44.8	460.3	15225.5
20	0.6570	13501.0	612.4	0.0	0.0	381.2	257.0	68.2	43.7	449.4	14863.5
21	0.6410	13172.2	597.5	0.0	0.0	371.9	250.8	65.6	42.6	438.4	14501.5
22	0.6260	12864.0	583.5	0.0	0.0	363.2	244.9	65.0	41.6	428.2	14162.2
23	0.6100	12535.2	568.6	0.0	0.0	353.9	238.6	63.4	40.6	417.2	13800.2
24	0.5940	12206.4	553.7	0.0	0.0	344.6	232.4	61.7	39.5	406.3	13438.2
25	0.5790	11898.1	539.7	0.0	0.0	335.9	226.5	60.1	38.5	396.0	13098.9
26	0.5630	11569.3	524.8	0.0	0.0	326.6	220.3	58.5	37.4	385.1	12736.9
27	0.5470	11240.6	509.9	0.0	0.0	317.3	214.0	56.8	36.4	374.2	12374.9
28	0.5310	10911.8	495.0	0.0	0.0	308.1	207.7	55.2	35.3	363.2	12013.0
29	0.5160	10603.5	481.0	0.0	0.0	299.4	201.9	53.6	34.3	352.9	11673.6
30	0.5000	43255.0	1210.2	0.0	0.0	1157.3	588.2	188.8	100.5	1346.1	46500.0

Table 3.15

 *
 * CHARGE MASS FLOW FOR ENTIRE REACTOR (KG) *
 *

REACTOR IDENTIFICATION : PU-U/U-TH LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 PU/UO2 CORE,UO2 AXIAL BLANKETS,THO2 RADIAL BLANKET (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	28082.2	0.0	54.7	27041.3	1909.6	547.6	290.0	97.5	2199.6	58022.9
2	0.6600	5148.4	0.0	19.9	9833.9	734.0	216.4	114.6	38.4	848.6	16105.6
3	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
4	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
5	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
6	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
7	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
8	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
9	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
10	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
11	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
12	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
13	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
14	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
15	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
16	0.7200	5616.4	0.0	21.7	10727.9	800.7	236.1	125.0	41.9	925.7	17569.8
17	0.7040	5491.6	0.0	21.2	10485.5	792.9	230.9	122.3	41.0	905.2	17179.3
18	0.6890	5374.6	0.0	20.8	10266.0	766.2	225.9	119.6	40.1	885.9	16813.3
19	0.6730	5249.8	0.0	20.3	10027.6	748.4	220.7	116.9	39.2	865.3	16422.8
20	0.6570	5125.0	0.0	19.8	9789.2	730.6	215.4	114.1	38.2	844.7	16032.4
21	0.6410	5000.2	0.0	19.3	9550.8	712.8	210.2	111.3	37.3	824.2	15642.0
22	0.6260	4883.2	0.0	18.9	9327.3	696.2	205.3	108.7	36.4	804.9	15275.9
23	0.6100	4758.4	0.0	18.4	9088.9	678.4	200.0	105.9	35.5	784.3	14885.5
24	0.5940	4633.6	0.0	17.9	8850.5	660.6	194.8	103.1	34.6	763.7	14495.1
25	0.5790	4516.6	0.0	17.5	8627.0	643.9	189.9	100.5	33.7	744.4	14129.0
26	0.5630	4391.7	0.0	17.0	8388.6	626.1	184.6	97.8	32.8	723.9	13738.6
27	0.5470	4266.9	0.0	16.5	8150.2	608.3	179.4	95.0	31.8	703.3	13348.1
28	0.5310	4142.1	0.0	16.0	7911.8	590.5	174.1	92.2	30.9	682.7	12957.7
29	0.5160	4025.1	0.0	15.6	7688.3	573.8	169.2	89.6	30.0	663.4	12591.7
30	0.5000	3900.3	0.0	15.1	7449.9	556.0	164.0	86.8	29.1	642.9	12201.2

Table 3.16

 *
 * DISCHARGE MASS FLCW FOR ENTIRE REACTOR (KG) *
 *

REACTOR IDENTIFICATION : PU-U/U-TH LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 PU/UO2 CORE,UO2 AXIAL BLANKETS,THO2 RADIAL BLANKET (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	4652.6	26.8	14.5	8807.2	648.9	189.3	68.5	31.3	717.4	14439.2
2	0.6600	5087.5	57.3	12.7	9302.6	794.5	252.6	68.8	38.6	863.3	15614.6
3	0.7200	5516.3	51.6	11.3	9834.9	893.4	301.3	66.5	42.4	959.9	16757.7
4	0.7200	5481.6	115.8	11.4	9813.8	893.5	304.5	68.3	43.5	961.7	16736.4
5	0.7200	5446.7	146.6	11.4	9818.3	893.3	304.2	68.3	43.5	961.7	16732.4
6	0.7200	5411.8	171.8	11.5	9823.1	892.8	303.7	68.4	43.5	961.1	16726.5
7	0.7200	5409.1	173.7	11.5	9825.3	892.5	303.6	68.4	43.5	961.0	16727.6
8	0.7200	5406.4	175.5	11.5	9826.3	892.4	303.5	68.4	43.5	960.9	16727.6
9	0.7200	5404.5	176.8	11.5	9826.7	892.4	303.5	68.4	43.5	960.8	16727.2
10	0.7200	5403.6	177.4	11.5	9826.9	892.4	303.4	68.4	43.5	960.8	16727.1
11	0.7200	5403.3	177.6	11.5	9826.9	892.4	303.4	68.4	43.5	960.8	16727.1
12	0.7200	5403.2	177.7	11.5	9827.0	892.4	303.4	68.4	43.5	960.8	16727.1
13	0.7200	5403.2	177.7	11.5	9827.0	892.4	303.4	68.4	43.5	960.8	16727.1
14	0.7200	5403.2	177.7	11.5	9827.0	892.4	303.4	68.4	43.5	960.8	16727.1
15	0.7200	5403.2	177.7	11.5	9827.0	892.4	303.4	68.4	43.5	960.8	16727.1
16	0.7200	5403.2	177.7	11.5	9827.0	892.4	303.4	68.4	43.5	960.8	16727.1
17	0.7040	5283.1	173.6	11.2	9608.5	872.5	296.7	66.9	42.6	939.4	16355.4
18	0.6890	5170.5	170.0	11.0	9403.9	853.9	290.4	65.5	41.7	919.4	16006.9
19	0.6730	5050.4	166.1	10.7	9185.5	834.1	283.6	64.0	40.7	898.1	15635.2
20	0.6570	4930.4	162.2	10.5	8967.1	814.3	276.9	62.4	39.7	876.7	15263.4
21	0.6410	4810.3	158.2	10.2	8748.7	794.4	270.1	60.9	38.8	855.4	14891.7
22	0.6260	4697.7	154.5	10.0	8544.0	775.9	263.8	59.5	37.8	835.4	14543.3
23	0.6100	4577.7	150.6	9.7	8325.5	756.0	257.1	58.0	36.9	814.0	14171.5
24	0.5940	4457.6	146.6	9.5	8107.3	736.2	250.3	56.5	35.9	792.7	13799.8
25	0.5790	4345.0	142.9	9.2	7902.5	717.6	244.0	55.0	35.0	772.6	13451.3
26	0.5630	4225.0	139.0	9.0	7684.2	697.8	237.3	53.5	34.0	751.3	13079.6
27	0.5470	4104.9	135.0	8.7	7465.8	677.9	230.5	52.0	33.1	729.9	12707.9
28	0.5310	3984.8	131.1	8.5	7247.4	658.1	223.8	50.5	32.1	708.6	12336.2
29	0.5160	3872.3	127.4	8.2	7042.7	639.5	217.5	49.0	31.2	688.6	11987.7
30	0.5000	22860.5	456.0	29.8	21082.7	1811.4	587.8	169.5	91.1	1980.9	47108.7

Table 3.17

 *
 * CHARGE MASS FLOW FOR ENTIRE REACTOR (KG) *
 *

REACTOR IDENTIFICATION : U233-TH/TH LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 U233/THO2 CORE,THO2 AXIAL AND RADIAL BLANKETS (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	54839.1	2322.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	57161.4
2	0.6600	14734.2	961.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15695.6
3	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
4	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
5	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
6	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
7	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
8	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
9	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
10	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
11	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
12	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
13	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
14	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
15	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
16	0.7200	16073.6	1048.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17122.5
17	0.7040	15716.4	1025.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16742.0
18	0.6890	15381.6	1003.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16385.3
19	0.6730	15024.4	980.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16004.8
20	0.6570	14667.2	957.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15624.3
21	0.6410	14310.0	933.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15243.8
22	0.6260	13975.1	912.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14887.1
23	0.6100	13617.9	888.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14506.6
24	0.5940	13260.7	865.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14126.1
25	0.5790	12925.9	843.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13769.4
26	0.5630	12568.7	820.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13388.9
27	0.5470	12211.5	796.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13008.4
28	0.5310	11854.3	773.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12627.9
29	0.5160	11519.4	751.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12271.1
30	0.5000	11162.2	728.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11890.6

Table 3.18

 *
 * DISCHARGE MASS FLOW FOR ENTIRE REACTOR (KG) *
 *

REACTOR IDENTIFICATION : U233-TH/TH LMFBR @ 1200 MWE (RZ MODEL) (6/09/77)
 U233/THO2 CORE, THO2 AXIAL AND RADIAL BLANKETS (2 CORE ZONES)

YEAR	CAPACITY FACTOR	TH232	U233	U235	U238	PU239	PU240	PU241	PU242	FISSILE PU	TOTAL HM
1	0.6000	13324.9	715.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14040.8
2	0.6600	14289.2	867.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15157.0
3	0.7200	15276.0	968.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16244.5
4	0.7200	15211.3	1013.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16224.5
5	0.7200	15186.1	1038.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16224.7
6	0.7200	15160.3	1062.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16222.5
7	0.7200	15160.4	1063.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16223.8
8	0.7200	15159.3	1064.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16224.0
9	0.7200	15158.2	1065.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16223.9
10	0.7200	15157.7	1066.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16223.8
11	0.7200	15157.5	1066.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16223.8
12	0.7200	15157.5	1066.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16223.8
13	0.7200	15157.5	1066.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16223.8
14	0.7200	15157.5	1066.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16223.8
15	0.7200	15157.5	1066.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16223.8
16	0.7200	15157.5	1066.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16223.8
17	0.7040	14820.7	1042.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15863.3
18	0.6890	14504.9	1020.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15525.3
19	0.6730	14168.0	996.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15164.8
20	0.6570	13831.2	973.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14804.2
21	0.6410	13494.4	949.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14443.7
22	0.6260	13178.6	927.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14105.7
23	0.6100	12841.8	903.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13745.2
24	0.5940	12504.9	879.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13384.6
25	0.5790	12189.1	857.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13046.6
26	0.5630	11852.3	833.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12686.1
27	0.5470	11515.5	810.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12325.6
28	0.5310	11178.6	786.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11965.1
29	0.5160	10862.9	764.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11627.1
30	0.5000	43969.3	2375.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	46344.5

Fig. 3.1. Breeding ratio isotopes composition for various denatured reactors.

Fig. 3.2. Net fissile production for various energy center "transmuters."

center "transmuters." Since two fissile species are involved in the symbiotic relationship, a "window" of allowable outside/inside ratios is present. The symbiotic power ratio is constrained by ^{233}U production on one side and by Pu production on the other. One interesting aspect of the symbiosis is the existence of an asymptotic value of the outside/inside power ratio. Assuming that the inventory of each fissile isotope is compounded annually (in a manner similar to that used to calculate a reactor's compound doubling time), the time dependent behavior of the symbiotic power ratio can be determined. Figure 3.3 illustrates the behavior for the two extreme initial values of the power ratio (no denatured reactors and the maximum number which can be maintained by the transmuter) for one such system. As Fig. 3.3 indicates, the asymptotic value is approached regardless of the starting configuration. The asymptotic value is also the point where the growth rates of the two fissile inventories are identical. Hence, each component of the system (i.e., dispersed reactors and centralized reactors) is growing at the same rate, and a compound symbiotic system doubling time can be determined for this value of the power ratio. The doubling time can be determined by considering either fissile inventory, i.e.,

$$\begin{aligned}
 \text{CSSDT} &= \frac{0.693 \left(M_{\text{Initial}}^{\text{D}} + M_{\text{External}}^{\text{D}} \right) P_{\infty}}{L \left(M_{\text{Discharge}}^{\text{T}} + P_{\infty} M_{\text{Discharge}}^{\text{D}} \right) - P_{\infty} M_{\text{Charge}}^{\text{D}}} \quad ^{233}\text{U}, \\
 &= \frac{0.693 \left(M_{\text{Initial}}^{\text{T}} + M_{\text{External}}^{\text{T}} \right)}{L \left(M_{\text{Discharge}}^{\text{T}} + P_{\infty} M_{\text{Discharge}}^{\text{D}} \right) - M_{\text{Charge}}^{\text{T}}} \quad \text{Pu},
 \end{aligned}$$

Fig. 3.3. Symbiotic power ratio for system of 20% denatured LMFBR's and energy center Pu/Th transmuters (2% fuel cycle losses, 1 year out of reactor time).

where the superscripts indicate the type of reactor (Denatured or Transmuter), P_{∞} is the asymptotic power ratio and L is a loss factor. Table 3.19 indicates the various symbiotic system parameters for a variety of transmuter and dispersed reactor combinations ($L = 0.98$; 1 year out of reactor time). Also indicated are the corresponding values for a reference $(\text{Pu}/^{238}\text{U})\text{O}_2$ system operating with no fuel cycle restrictions. As the values given in Table 3.19 indicate, maximizing the outside/inside ratio adversely effects the system doubling time. Similarly minimizing the system doubling time would adversely impact the symbiotic power ratio. As expected, the systems based on the $\text{Pu}/^{238}\text{U} + \text{ThO}_2$ RB reactor have shorter doubling times than the corresponding system based on the Pu/Th LMFBR, reflecting the lower overall fissile production of the latter. Conversely, the power ratio of the systems based on the Pu/Th LMFBR are significantly better than those attained by the $\text{Pu}/^{238}\text{U} + \text{ThO}_2$ RB, reflecting the much higher ^{233}U production. For a given transmuter, increasing the denaturing constraint (i.e., decreasing the ^{238}U and increasing the Th) increases the symbiotic power ratio (due to the lower ^{233}U makeup requirements) and also increases the doubling time (due to the lower overall system fissile production).

3.3 Cross-Section Sensitivity

A primary concern in assessing various parameters pertaining to alternate fuel cycles is the adequacy of the nuclear data, especially when a detailed design/optimization effort is envisioned. Of particular concern is the ^{232}Th capture cross-section due to the use of ^{233}U as fuel in the proposed denatured reactors. Recent measurements⁵ of the ^{232}Th

Table 3.19. Equilibrium cycle symbiotic parameters
(2% losses, 1 year out-of-reactor time)

Energy Center Reactor LMFBR	Dispersed LMFBR	Asymptotic Dispersed Outside/Energy Center Power Ratio	Compound System Doubling Time (Years)
(Pu/U)O ₂ + ThO ₂ RB	~ 12% Denatured	0.35	14.3
(Pu/U)O ₂ + ThO ₂ RB	20% Denatured	0.52	16.5
(Pu/U)O ₂ + ThO ₂ RB	40% Denatured	0.94	21.9
Pu/Th	~ 12% Denatured	1.67	24.7
Pu/Th	20% Denatured	2.83	33.8
Pu/Th	40% Denatured	6.91	66.0
<hr/>			
-	(Pu/U)O ₂	∞	11.8

Table 3.20. Effect of revised ²³²Th capture
cross sections

	ENDF/B-IV	Revised Th Capture
20% Denatured		
Initial Inventory [KG/GW(e)]	2192	2050
Equilibrium Reload [KG/GW(e)]	813	796
Breeding Ratio	1.096	1.050
Pu/Th "Transmuter"		
Initial Inventory [KG/GW(e)]	2517	2280
Equilibrium Reload [KG/GW(e)]	894	865
Breeding Ratio	1.158	1.078
Symbiotic Power Ratio	2.83	2.59
Compound System Doubling Time (years)	33.8	89.7
Nuclear Energy Growth (%/year)	2.1	0.8

capture cross section indicate marked differences from that derived from ENDF/B-IV in the region between 4 KeV and 800 KeV (ranging up to a 25% decrease). To assess the possible impact of a decrease of this magnitude, the 20% denatured LMFBR and the Pu/Th LMFBR were recalculated using a cross-section library adjusted for the decreased ^{232}Th capture. The results are given in Table 3.20. The lower ^{232}Th capture results in slightly smaller fissile inventories in both reactors and, more significantly, markedly reduces the breeding ratio (breeding gain) in both systems. The asymptotic power ratio is essentially unchanged since the percentage decrease in the breeding gain in each reactor is comparable. The revised ^{232}Th capture data does effect the symbiotic system doubling time, increasing it by a factor of 2.65. Although the lower ^{232}Th cross section can possibly be compensated for by increasing the fertile loading, it is evident that, in view of the large uncertainties in the nuclear data, all alternate fuel cycle results should be regarded as scoping calculations pending measurement and/or reevaluation of the pertinent nuclear data.

4. ADVANCED LMFBR SYSTEMS

D. L. Selby

4.1 General Considerations

In addition to the ThO_2 base fuels there are two major thorium systems under consideration as fuels for fast reactor systems. These two systems are the Th base metal alloys and the Th carbide base fuels. It appears that both systems offer both advantages and disadvantages over the ThO_2 fuels.

4.2 Thorium Base Metal Fuels

In general Th base metal fuels are characterized by high breeding ratios (relative to ThO_2), high thermal conductivity, negative sodium voiding coefficient, Doppler similar to oxide cores, and an energy spectrum much higher than equivalent oxide systems. Several Th alloys have been considered as fuels for fast breeder reactors. The most noted ones are:

1. Th-Pu
2. Th-U
3. Th-U-Pu

The Th-Pu alloy fuel exhibits a very high breeding ratio (relative to oxide systems). Unfortunately, the metallurgical properties of this alloy eliminate it as a potential fuel for fast reactors. Above 450°C Pu-Th alloys with at least 10% Pu have been found to undergo severe swelling.⁶ A Th-Pu alloy containing 15 wt % plutonium increased in volume by 14% when irradiated at 500°C to .54 atom percent burnup.

In order to take advantage of the resistance to swelling under irradiation exhibited by Th metal, it has been found that the U content of the U-Th alloy must not exceed 25% by weight.^{7,8,9} Above 25% by wt U Th-U, alloys irradiated up to 700°C exhibited severe distortions and swellings up to 8%ΔV per atom percent burnup.

Simple calculations for a Th-20%wtU alloy have shown a relatively low breeding ratio. However, the breeding ratio is greatly affected by the amount of total cladding in the core. The use of large fuel pins could decrease the amount of cladding needed and thus could increase the breeding ratio to as much as 1.35.

It appears that the Th-U-Pu trinary represents the better of the three fuels considered. It has been shown that up to 10% U in the Th-20%wt U alloy can be replaced by Pu with little or no effect on the irradiation behavior.¹⁰ Furthermore, the addition of the Pu substantially increases the breeding ratio. Preliminary calculations have shown that breeding ratios as high as 1.65 can be obtained depending on the fuel pin size.

4.3 Thorium Base Carbide Fuels

A lot less information is known about the carbide fuels than the metal fuels. Preliminary calculations have not been completed, but it appears that the breeding ratios obtained for the carbide fuels will be more similar to those obtained for the oxide fuels than those obtained for the metal fuels.

5. FLOW OF NUCLEAR MATERIAL FOR RESTRICTED FUEL CYCLE SCENARIOS

J. C. Cleveland

This report describes the flow of nuclear material for various restricted fuel cycle scenarios intended to alleviate safeguards concerns through the use of thorium fuel cycles. These scenarios, and the corresponding objectives for the safeguards related thorium assessment studies have been listed in an ORNL Quarterly Progress Report¹¹ and are reported in Table 5.1.

The first fuel cycle to be considered, as is indicated in Table 5.1, is the throwaway cycle HTGR. The throwaway cycle would be required if reprocessing of spent reactor fuel is judged to lead to unacceptable proliferation risks and therefore not allowed. Based on information presented in Ref. 12, the HTGR fuel cycle which is optimized for throwaway conditions involves the use of fully enriched uranium in thorium. If security considerations prohibit the use of fully enriched uranium, the HTGR throwaway cycle would be a LEU (~11 to 13% enriched uranium) cycle or a denatured ^{235}U -thorium cycle. Under no-reprocessing restrictions, no exogenous source of ^{233}U would be available for denatured cycles.

A simplified diagram of this HTGR throwaway cycle scenario is given in Fig. 5.1. More detail concerning the fuel fabrication process is shown in Fig. 5.2. For the optimized throwaway cycle, highly enriched material would be handled throughout the fuel element fabrication process.¹³ The security problems would be reduced significantly if the throwaway cycle were a LEU cycle or a denatured cycle.

Table 5.1. Suggested scenarios, objectives and criteria
for safeguarded-related thorium assessment studies

Restricted Fuel Cycle Scenarios	Objectives	Criteria
1. Throwaway Cycle - HTGR	1. Determine effects of employing HTGR on power cost and fuel resources under no-reprocessing conditions.	1. Comparison of HTGR parameters with LWR parameters.
2. Safeguarded reprocessing and non-denatured cycles with dispersed and denatured cycles.	2. Create a symbiotic system which would maximize resource utilization and power dispersal for the reactor mix considered; determine neutronic, capital cost, and safety implications.	2. Create safeguarded nuclear fuel cycles which compete with coal over the long-term, and which are consistent with the nuclear fuel resource base. Maximize U_{233} component over Pu component. Maximize power production in dispersed reactors.
a. All LWR symbiotic system	a. For current, all LWR	
b. LMFBR + LWR symbiotic systems	b. Introduction of the LMFBR	
c. LMFBR, HTGR, HWR, LWR + LWR, HTGR, HWR symbiotic systems	c. Introduction of HTGR, HWR.	

ORNL-DWG-77-17382

Fig. 5.1. HTGR throwaway cycle.

ORNL-DWG 75-1929 R

Fig. 5.2. Process for HTGR fuel element fabrication.

The scenarios to be considered in which reprocessing of spent fuel is allowed involve the use of fuel cycle centers containing nondenatured reactors, fuel reprocessing, refabrication and waste management facilities. Within these centers, denatured fuel would be fabricated for use in the dispersed reactors.

The first of these scenarios, as listed in Table 5.1, is the all LWR symbiotic system. Under this scenario there can be two types of fuel for the dispersed reactors:

1. LEU of ~ 3.0 w/o ^{235}U ,
2. Denatured uranium in thorium.

The fuel composition involving ^{233}U of ~ 2.5 w/o in ^{238}U with no thorium component is not considered because of the preference to breed ^{233}U rather than plutonium. Within the secured area, the primary reactor fuel composition will be plutonium in thorium. The conventional "mixed oxide" fuel composition involving plutonium in natural or depleted uranium will not be considered--again because of the preference to breed ^{233}U rather than plutonium. The fuel compositions involving fully enriched ^{235}U in thorium and nondenatured bred ^{233}U in thorium will also be considered as candidates for fueling reactors within the secured area. However, if this available ^{235}U and bred ^{233}U were denatured and used to fuel dispersed reactors, plutonium production in the total system would be somewhat increased, which is contrary to the objectives; but the ratio of dispersed reactors to secured reactors would be increased, which is an objective. The study will attempt to arrive at a reasonable trade-off.

A simplified diagram for the flow of fuel in this all LWR symbiotic system is shown in Fig. 5.3. As shown, spent elements from the dispersed

Fig. 5.3. Fuel flow schematic for LWR symbiotic system.

reactors are shipped to the fuel cycle centers for reprocessing. Within the reprocessing plant, the uranium and plutonium are separated from the spent LEU fuel: the uranium being converted to UF_6 for shipment to the cascade and the plutonium being sent as PuO_2 to the fuel refabrication plant located within the fuel cycle center. Uranium separated from the denatured fuel would be re-enriched to the allowable limit by addition of fully enriched ^{235}U or, if available, by addition of bred ^{233}U . Plutonium separated from the spent denatured fuel would also be sent to the fabrication facility. Within the secured area, the plutonium would be fabricated into $\text{PuO}_2/\text{ThO}_2$ fuel elements used to fuel LWRs within the secure area. Bred uranium from these reactors would have a high fissile content. It could be blended with thorium and burned within the center or denatured and burned at dispersed reactors. The fuel fabrication plant for LEU fuel elements and for denatured fuel elements could be located either inside or outside the center since the fissile material used in this fuel could not be converted for use in explosive devices by chemical separation techniques.

Process flow sheets for LWR fuel reprocessing are shown in Ref. 14. The separation of uranium, plutonium and thorium occurs in the solvent extraction process. The plutonium containing partition column is highly purified and concentrated. Uranium bred in denatured fuel would contain a large ^{238}U component as would uranium discharged from LEU fuel. However, the uranium bred from $\text{PuO}_2/\text{ThO}_2$ fuel would be highly fissile as would uranium discharged from fully enriched $^{235}\text{UO}_2/\text{ThO}_2$ fuel. The ^{232}U component of the bred ^{233}U stream offers some safeguard advantages after a sufficient time interval has allowed buildup of radioactive ^{232}U .

daughter nuclides. The very low fissile content of the waste streams is judged to present no safeguards or proliferation concerns since the fissile material will have been removed to the limit of available technology. Entrainment of fissile material in the off gas treatment steps is judged insufficient to result in safeguards or proliferation concerns. However, accidental or intentional diversion of purified fissile material via a waste stream is a distinct possibility.¹³

Figure 5.4 shows the steps for LWR fuel element fabrication. The uranium or plutonium is blended with thorium in the initial step; the chemical composition of the fuel remains the same through all remaining steps. The fuels containing plutonium as well as those containing uranium of a high fissile content blended with thorium will present a security problem since the high fissile content could be separated by chemical means. This would not be a problem for LEU fuel or denatured fuel. Fabrication of these fuels could possibly be performed outside the fuel cycle center. All reprocessing and refabrication steps could be carried out within the same physical facility if this were required in order to aid in security methods.¹⁵

The next scenario involves the introduction of the LMFBR. Within the secured area LMFBRs with plutonium-thorium cores and thorium blankets would be utilized for ^{233}U production. Some LMFBRs within the secured area could have plutonium-uranium cores and thorium blankets if it were desirable to breed some additional plutonium to be burned within the secured area for ^{233}U production. Denatured LMFBRs could be located at dispersed sites.

Fig. 5.4. LWR oxide fuel element fabrication.

The flow sheets for LMFBR fuel reprocessing are shown in Ref. 14. In the solvent extraction step, both the ^{233}U and the plutonium streams from the partition columns would be highly purified and concentrated. As in the reprocessing of LWR fuel, entrainment of fissile material in the off gas treatment is insufficient to cause safeguards or proliferation concerns. Accidental or intentional diversion of purified or fissile material via waste streams is, however, a distinct possibility.¹³

The flow sheets for FBR fuel fabrication are given in Fig. 5.5. Blanket rod fabrication presents no safeguard or proliferation concerns. Except for denatured LMFBR fuel, highly fissile material is handled throughout the fuel element fabrication process and could be converted to material useable in an explosive device by chemical separation techniques.

The final scenario involves the introduction of HTGRs and HWRs. At the dispersed sites these reactors would utilize denatured or LEU fuel. In addition, the HWR could utilize natural uranium fuel. The plutonium-thorium HTGR could be utilized within the secured area as a plutonium burner. The reprocessing and refabrication steps for the HWR do not differ significantly from those already presented for the LWR. The fabrication flow sheets for HTGR fuel have been presented in Fig. 5.2. Except for denatured and LEU HTGR fuel, highly fissile material is handled throughout the fabrication process.

Reference 14 shows the reprocessing steps for HTGR fuel. Due to the nature of HTGR fuel elements and particles, the fissile material is physically separable from the fertile material. However, this should not cause safeguards concern in the head end process because the

Fig. 5.5. FBR oxide fuel element fabrication.

irradiated fuel is highly radioactive. Furthermore, a different particle design involving the same particle size and coating for fissile and fertile particles could preclude diversion by physical separation in the head end process.¹³ As in the reprocessing of LWR and LMFBR fuel, the solvent extraction step produces separate uranium and plutonium streams which are highly purified and concentrated. Entrainment of fissile material in off gas treatment is judged to be sufficiently small as to result in no safeguards concerns. Also, as in the reprocessing of other reactor fuel types, accidental or intentional diversion of purified fissile material via waste streams is a distinct safeguards concern.¹³

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