

FUEL CYCLE FOR A TRANSIENT REACTOR SYSTEM

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Introduction

In this paper reactor strategy considerations made by Häfele, Manne and Schikorr /1/, /2/ are extended. In papers /1/ and /2/, these authors gave a short review of the work on reactor strategies performed in the sixties, followed by a study on possible options for the future supply of energy. They took into account new functions of known reactor types and proposed one possible reactor strategy that is based on these functions. Special attention was paid to the timing problem. Both, an asymptotic solution to the long range phase and the conditions for the preceding transient phase of the energy problem were considered.

The purpose of this paper is an analysis of the nuclear fuel cycle in the transient phase: The material flows in the nuclear industry as well as the necessary separative work are calculated for the 66 year period under consideration.

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### General Assumptions

The assumptions made for such a transient phase can be summarized as outlined in the cited paper:

- All increased demands for electric power will be met by LWR's for the next one or two decades.
- No Pu-recycling in LWR's. All Pu produced shall be used to establish the first core inventories of new FBR's.
- The FBR does not double any more. The rate of its increase is proportional to the increase of the installed LWR capacity. The breeding gain of FBR's is used for the supply of U233 to the THTR.
- The THTR can be installed proportionally to the FBR. It produces by virtue of its high temperature hydrogen.

The aim of the following investigations is to calculate the consumption of natural uranium, the demand for separative work and the quantity of depleted uranium as a function of time.

A flow chart of the proposed reactor population is given in Fig.1.

### Time schedule

LWR's are built at a rate of 18GWe/y during the first 18 years followed by a period of constant LWR capacity with the FBR accounting for an increasing share of the nuclear energy supply. After a period of 40 years starting with the installation of the first LWR the capacity of nuclear industry is suggested to meet all the electrical power requirements. Now the

installation of FBR's continue at the same rate by replacing the LWR's until after an integral period of 58 years all LWR's are dismantled. At this very point the THTR capacity should be able to meet all the process heat requirements. Fig.2 shows the development of the reactor population in steps of three years. The methods of calculation and the used data have been established in discussion with Mr.McGrath, GfK Karlsruhe, and partially refer to /1/, /2/ and /3/.

#### LWR System

Assume:

- 1) average burnup is  $33 \text{ GW}_{\text{th}} \text{ d/t}$  /McGrath/
- 2) efficiency is 34%
- 3) 2,6% enriched uranium is required for initial loading, 3.2% for replacement /McGrath/
- 4) conversion to plutonium is  $0,17 \text{ t/GW}_{\text{e}} \text{ y}$  /1/
- 5) Np + Am + Cm content of elements is  $0,696 \text{ kg/t}$  /McGrath/ (per ton of original fresh fuel)
- 6) Losses in fabrication and reprocessing are for both, uranium and plutonium respectively 0,5% at each and total 1% /McGrath/.
- 7) The lifetime of the reactor is assumed to be 30 years.

Representing the increase of LWR capacity with time by a step function with a period of 3 years results in an initial and final step of 27 GWe at time  $t=0$  and  $t=18$  and  $54 \text{ GWe/y}$  at  $t=3,6, \dots$  (see Fig.2).

(a) annual replacement quantity for the first step:

$$27 \cdot \frac{1}{0,34} \text{ GW}_{\text{th}} * \frac{365 \text{ d/y}}{33 \text{ GW}_{\text{th}} \text{ d/t}} = 878 \text{ t/y}$$

(b) the ratio of UNat requirements for initial loading and annual replacement is 500:200 /1/. The demand of natural uranium for the production of 1t 2,6% U-235 is 5,092t and of 1t 3,2% U-235 6,392t.

Initial loading requirements for the first step

$$878 \cdot \frac{500}{5,092} : \frac{200}{6,392} = 2756 \text{ t}$$

(c) amount of fission products produced is:

$$27 \cdot \frac{1}{0,34} \text{ GW}_{\text{th}} \cdot \frac{365 \text{ d/y} \cdot 10^{-3} \text{ t/kg}}{0,95 \text{ GW}_{\text{th}} \text{ d/kg}} = 30,5 \text{ t}$$

use for calculations: 1gm fissions  $\hat{=}$  0,95 MW<sub>th</sub>d

(d) Quantity of plutonium: 27GWe  $\cdot$  0,17t/GWe = 4,6 t/y

(e) total amount of heavy metals out of reactor is:

$$(a) - (c) = 847,5 \text{ t/y}$$

(g) Uranium left in fuel elements must be (f)-(d)-(e)= 843t/y

(h) loss to waste in reprocessing are:

- 1) all fission products (c)
- 2) all Np + Am + Cm (e)
- 3) 0,5% of incoming plutonium quantity
- 4) 0,5% of incoming uranium quantity

However a return of the 1% enriched U-235 in the spent

fuel is not included in the present calculations.

(i) natural uranium demand for annual replacements

$$878 \cdot \frac{1}{0,995} \cdot \frac{e_o - e_t}{e_n - e_t} = 5643 \text{t/y} \quad 5643 \text{t/y}$$

$$e_o = 3,2\%, \quad e_t = 0,25\%, \quad e_n = 0,7115\%$$

(j) natural uranium demand for initial loading:

$$2756 \cdot \frac{1}{0,995} \cdot \frac{e_o - e_t}{e_n - e_t} = 14 \ 106 \text{t}$$

(k) production of tails:

$$\text{annual replacement: } 5643 - 878 = 4 \ 764 \text{t/y}$$

$$\text{initial loading } 14106 - 2756 = 11 \ 350 \text{t}$$

(l) separative work

$$\text{for initial loading: } 230 \cdot 27 \cdot \frac{522}{500} = 6 \ 507 \text{t}$$

$$\text{for annual replacement: } 110 \cdot 27 \cdot \frac{209}{200} = 3 \ 105 \text{t/y}$$

$$522 = \frac{14 \ 106}{27} ; \quad 209 = \frac{5 \ 643}{27}$$

The values 230 and 110 correspond to those given in /1/ for ore  $U_3O_8$  requirements of 500t/GWe for the initial loading and 200t/GWe for the annual replacement.

The natural uranium demand for the LWR system, the production of tails and the associated separative work as a function of time is shown in Fig.4. The corresponding values are listed in Tab.1,2 and 4.

The time delays between ore demand and fuel loading have been taken into account (3 years).

FBR System

- Assume: 1) 90% of energy production in core + axial blanket
- 2) Average burnup of core + axial blanket elements is 80.000 MW<sub>th</sub>d/t
  - 3) Average portion of plutonium to total heavy metal content of fresh elements is 8%.
  - 4) Losses in fabrication and reprocessing are for both, uranium and plutonium respectively 0,5% at each, in total 1%.
  - 5) Np + Cm + Am content of elements is 1,5kg/t (per ton of original fresh fuel).
  - 6) Radial blanket conversion is 0,3t U<sub>3</sub>/GWe
  - 7) FBR core + axial blanket is self-supporting in plutonium with a 1% over supply to account for losses.

Installation schedule: an initial step of 27GWe, followed by six steps of 54GWe and two final steps of respectively 42 GWe and 30GWe match the increase of 18GWe/y (see Fig.2).

(a) initial loading requirements for core + axial blanket:

In pile inventory of plutonium is 2,5t/GWe /1/. According to assumption 3) the total initial heavy metal re-

$$\text{requirements for the first step are: } 27 \cdot \frac{2,5}{0,08} = 844\text{t}$$

$$\text{total amount of uranium is } 844 - 844 \cdot 0,08 = 776\text{t}$$

$$\text{U}_3\text{O}_8 \text{ requirements for initial loading are: } 776 \cdot 1,005 = 780\text{t}$$



(b) fuel element quantity per year for core and axial blanket:

$$0,9 \cdot 27 \cdot \frac{1}{0,4} \text{ GW}_{\text{th}} \cdot \frac{365 \text{ d/y}}{80 \text{ GW}_{\text{th}} \text{ d/t}} = 277 \text{ t/y}$$

(c) total plutonium quantity per years:  $0,08 \cdot 277 = 22,2 \text{ t/y}$

(d) total amount of U8 is :  $277 - 22 = 255 \text{ t/y}$

(e) amounts of fission products produced is:

$$0,9 \cdot 27 \cdot \frac{1}{0,4} \text{ GW}_{\text{th}} \cdot \frac{365 \text{ d/y} \cdot 10^{-3} \text{ t/kg}}{0,95 \text{ GW}_{\text{th}} \text{ d/kg}} = 23 \text{ t/y}$$

(f) total amount of heavy metals out of reactor is:

$$(b) - (e) = 254 \text{ t/y}$$

(g) total plutonium out of reactor must equal (c)+1%

to account for fabrication and reprocessing losses:  $22,4 \text{ t/y}$

(h) total amount of Np + Am + Cm present in fuel

element equal  $1,5 \text{ kg/t} \cdot 277 \text{ t/y} = 0,4 \text{ t/y}$

(i) U8 left in fuel elements must be:  $(f) - (g) - (h) = 231 \text{ t/y}$

(j) annual U8 requirements for replacement are:

$$(d) \cdot 1,005 - (i) \cdot 0,995 = 26 \text{ t/y}$$

(k) initial loading requirements for radial blanket:

assume the following dimensions of core and blankets:

core:  $D = 163 \text{ cm}$

$H = 100 \text{ cm}$

axial blanket:  $D = 163 \text{ cm}$

$H = 2 \times 20 \text{ cm}$

radial blanket:  $D_1 = 163 \text{ cm}, D_2 = 243 \text{ cm}$

$H = 100 + 2 \times 20 = 140 \text{ cm}$

The calculated ratio of volumes of core + axial blanket and of the radial blanket is 2,92 : 3,57. According to this ratio, the initial requirements of thorium for the first 27 GWe step could be calculated:

$$844 \cdot \frac{3,57}{2,92} = 1031t$$

$$\text{at the fabrication facilities: } 1031 \cdot 1,005 = 1037t$$

(l) assuming a lifetime of 8 years for the radial blanket, the annual replacement requirements are:  $1031/8 = 129t/y$

(m) amount of fission products produced in the radial blanket is:

$$\frac{2,7}{0,4} \text{ GW}_{th} \cdot \frac{365d/y \cdot 10^{-3}t/kg}{0,95\text{GW}_{th}d/kg} = 2,6t/y$$

(n) quantity of U3 in radial blanket elements:  $0,3 \cdot 27 = 8,1t/y$

(o) total quantity of thorium remaining in radial blanket elements:

$$(l) - (m) - (n) = 118t/y$$

(p) annual makeup thorium required at fabrication facility for thorium radial blankets:  $(e) \times 1,005 - (o) \times 0,995 = 12t/y$

(q) quantity of U3 out of reprocessing facility to THTR:  
 $0,995 \cdot 8,1 = 8,06t/y$

The U8 and Th-requirements of the FBR system are shown in Fig.3 and the corresponding values are listed in table 2 and 3.

### THTR System

Assume: 1) average burnup of elements is  $95\text{GW}_{th}d/t$

2) losses in fabrication and reprocessing are for both, uranium and thorium respectively 0,5% at each, in total 1%

3) Pa + Np content of spent fuel is 1,9kg/t  
(fresh fuel)

4) conversion rate of THTR is sufficient to  
balance U3 needs

The installation schedule is given in Fig.2. Since the annual fissile requirements are met by the FBR, the first THTR is installed 3 years after the first FBR in order to allow for reprocessing and fabrication delay. An initial step of 27 GWe at time 21 is followed by 12 steps of 54GWe and two final steps of 42GWe and 3GWe. This step function matches a steady increase of 18GWe/y of installed THTR capacity.

(a) annual replacement requirements:

8t heavy isotopes/GWe \* 216t/y

(b) metric ton fissile purchased: 0,32 (U-235)\*

metric ton fissile recycled: 0,19 (U-233)\*

\* These figures are given in a paper by Simcha Golan and R.Salmon /2/ and correspond to a 1000MWe HTGR and thorium fuel with U-235 makeup and U-233 recycle.

The neutron ratio of the two fissiles U-235 and U-233 is 2,05:2,28 and 0,32t U-235 + 0,19t U-233 are equivalent to

$\frac{0,32 \cdot 2,05}{2,28} + 0,19 = 0,478t$  U-233 12,9t/y

(c) annual thorium replacement for the first step is:

27 (8-0,478) = 203t/y

(d) quantity of fission products produced:

$27 \cdot \frac{1}{0,4} GW_{th} \cdot \frac{365d/y \cdot 10^{-3}t/kg}{0,95GW_{th}d} = 26t/y$

(e) total thorium content of spent fuel:

8.27t/y heavy isotopes - 25,95t/yFP - 0,19·27t/yU3-

-8·27·0,0019t/y(Pa+Np) = 185t/y

- (f) annual demand for thorium is  
 $(c) \cdot 1,005 - (e) \cdot 0,995 = 21t/y$
- (g) initial loading requirements  
 heavy isotopes: 35t/GWe )  
 fissile: 2,025t/GWe ) /2/ 945t
- $U5(93\%) = 2,025/0,93 = 2,177t/GWe$  59t
- (h) initial thorium requirements:  $1,005 (945-58,78) = 891t$
- (i) natural uranium requirements for initial loading:  
 $540t/GWe /1/ 14580t$
- (j) tails are:  $540 - 540 \cdot \frac{0,7115-0,25}{93-0,25} = 540-2,687 =$   
 $537,31t/GWe 14507t$
- (k) separative work for initial loading is  $438t/GWe /1/ 11826t$

The natural uranium, thorium and separative work requirements are shown in Fig.3 and 4. The corresponding values are listed in Tab.1, 2, 3 and 4.

References

- /1/ Häfele, W., and W.Schikorr, "Reactor Strategies and the Energy Crisis", International Atomic Energy Agency Study Group on Reactor Strategy Calculations, Vienna (proceedings in press), November 1973
  
- /2/ Häfele, W., and A.S.Manne, "Strategies for a Transition from Fossil to Nuclear Fuels", Research Report of the International Institute for Applied Systems Analysis, June 1974
  
- /3/ Golan, S., and R.Salmon, "Nuclear fuel logistics", Nuclear News, February 1973

Table 1  
Natural Uranium Consumption

Time (Years)	LWR			THTR	TOTAL
	Annual (tons)	Initial (tons)	Cumulative (tons)	Initial (tons)	Cumulative
- 3		14 106	14 106		14 106
- 2	5 643		19 749		19 749
- 1	5 643		25 392		25 392
0	5 643	28 213	59 248		59 248
1	16 929		76 177		76 177
2	16 929		93 106		93 106
3	16 929	28 213	138 248		138 248
4	28 215		166 463		166 463
5	28 215		194 678		194 678
6	28 215	28 213	251 106		215 106
7	39 501		290 607		290 607
8	39 501		330 108		330 108
9	39 501	28 213	369 609		369 609
10	50 787		420 396		420 396
11	50 787		471 183		471 183
12	50 787	28 213	521 970		521 970
13	62 073		584 043		584 043
14	62 073		646 116		696 116
15	62 073	14 106	722 295		722 295
16	67 716		790 011		790 011
17			857 727		857 727
18			925 443	14 580	940 023
19			993 159	14 580	1 007 739
20			1 060 875	14 580	1 075 755
21			1 128 591	43 740	1 172 331
22			1 196 307	43 740	1 240 047
23			1 264 023	43 740	1 307 763
24			1 331 739	72 900	1 404 639
25			1 399 955	72 900	1 472 355
26			1 467 171	72 900	1 540 071
27		14 106	1 548 993	102 060	1 651 653
28			1 616 709	102 060	1 718 769
29	▽		1 684 425	102 060	1 786 485
30		28 213	1 780 354	131 220	1 911 574

Table 1 continued

31	67 716		1 848 078	131 220	1 979 298
32	↓		1 915 786	131 220	2 047 006
33		28 213	2 011 715	160 380	2 172 095
34			2 079 431	160 380	2 239 811
35	▽		2 147 147	160 380	2 307 527
36	65 308	21 943	2 234 298	189 540	2 423 838
37	65 208		2 299 506	189 540	2 489 046
38	65 208		2 364 714	189 540	2 554 254
39	54 549	1 567	2 420 830	218 700	2 639 530
40	54 549		2 475 379	218 700	2 694 079
41	54 549		2 529 928	218 700	2 748 628
42	43 263		2 573 191	247 860	2 821 651
43	43 263		2 616 459	247 860	2 864 314
44	43 263		2 659 717	247 860	2 907 597
45	31 977		2 691 694	277 020	2 968 714
46	31 977		2 723 671	277 020	3 000 691
47	31 977		2 755 648	277 020	3 032 668
48	20 691		2 776 339	306 180	3 082 519
49	20 691		2 797 630	306 180	3 103 210
50	20 691		2 817 721	306 180	3 123 901
51	9 405		2 827 126	335 340	3 162 466
52	9 405		2 836 531	335 340	3 171 871
53	9 405		2 845 936	335 340	3 181 276
54	627		2 846 563	364 500	3 211 063
55	627		2 847 190	364 500	3 211 690
56	627		2 847 817	364 500	3 212 317
57	0			387 176	3 234 993
58				387 176	3 234 993
59				387 176	3 234 993
60				388 797	3 236 614
61					
62					
63					
64					
65			▽	▽	▽
66					

Table 2

Depleted Uranium Balance

Time	Consumption (FBR)			Tails			
	Annual	Initial	Cumulative	LWR annual	LWR initial	THTR	Cumulative
- 3					11 350		
- 2				4 764			16 114
- 1				4 764			20 878
0				4 764	22 700		48 342
1				14 292			62 634
2				14 292			76 926
3				14 292	22 700		113 918
4				23 820			137 738
5				23 820			161 558
6				23 820	22 700		208 078
7				33 348			241 426
8				33 348			274 774
9				33 348	22 700		330 822
10				42 876			373 698
11				42 876			416 574
12				42 876	22 700		482 150
13				52 404			534 554
14				52 404			586 958
15		780	780	52 404	11 350		650 712
16	26		806	57 168			707 880
17	26		832				765 048
18	26	1 560	2 968			14 507	836 723
19	79		2 497				893 891
20	79		2 576				951 059
21	79	1 560	4 215			29 015	1 037 242
22	133		4 348				1 094 410
23	133		4 481				1 151 578
24	133	1 560	6 174			29 015	1 237 761
25	185		6 359				1 294 929
26	185		6 544				1 352 097
27	185	1 560	8 289		11 350	29 015	1 449 630
28	238		8 527				1 506 798
29	238		8 527				1 563 966
30	238	1 560	10 563	▽	22 700	29 015	1 672 849



Table 2 continued

31	290		10 853	57 168			1 730 017
32	290		11 143	↓			1 787 185
33	290	1 560	12 993		22 700	29 015	1 896 068
34	344		13 337	↓			1 953 236
35	344		13 681				2 010 404
36	344	1 560	15 585	55 051	17 655	29 015	2 112 125
37	396		15 981	55 051			2 167 176
38	396		16 377	55 051			2 222 227
39	396	1 560	18 333	46 052	1 261	29 015	2 298 555
40	449		18 782	46 052			2 344 607
41	449		19 231	46 052			2 390 659
42	449	1 560	21 240	36 524		29 015	2 456 198
43	503		21 743	36 524			2 492 722
44	503		22 246	36 524			2 529 246
45	503	1 560	24 306	26 996		29 015	2 585 257
46	555		24 864	26 864	26 996		2 612 253
47	555		25 419	26 996			2 639 249
48	555	1 560	27 534	17 468		29 015	2 685 732
49	608		28 142	17 468			2 703 200
50	608		28 750	17 468			2 720 668
51	608	1 560	30 918	7 940		29 015	2 757 623
52	660		31 578	7 940			2 765 563
53	660		32 238	7 940			2 773 503
54	660	1 213	34 111	529		29 015	2 803 077
55	701		34 812	529			2 803 576
56	701		35 513	529			2 804 105
57	701	87	36 301			22 567	2 826 672
58	704		37 005				2 826 672
59	↓		37 709				2 826 672
60			38 413			1 612	2 828 284
61	↓		39 117				

Table 3  
Thorium Consumption

Time (years)	FBR		THTR		Cumulative
	Annual	Initial	Annual	Initial	
15		1 037			1 037
16	12				1 049
17	12				1 061
18	12	2 073		891	4 037
19	36		21		4 094
20	36		21		4 151
21	36	2 073	21	1 781	8 062
22	60		62		8 184
23	60		62		8 306
24	60	2 073	62	1 781	12 282
25	84		103		12 469
26	84		103		12 656
27	84	2 073	103	1 781	16 697
28	107		144		16 948
29	107		144		17 199
30	107	2 073	144	1 781	21 304
31	131		185		21 620
32	131		185		21 936
33	131	2 073	185	1 781	26 106
34	155		226		26 487
35	155		226		26 868
36	155	2 073	226	1 781	31 103
37	179		267		31 549
38	179		267		31 935
39	179	2 073	267	1 781	36 295
40	203		309		36 807
41	203		309		37 319
42	203	2 073	309	1 781	41 685

Table 3 Continued

43	227		350		42 262
44	227		350		42 839
45	227	2 073	350	1 781	47 270
6	251		391		47 912
47	251		391		48 554
48	251	2 073	391	1 781	53 050
49	274		432		53 756
50	274		432		54 462
51	274	2 073	432	1 781	59 022
52	298		473		59 793
53	298		473		60 564
54	298	1 613	473	1 781	64 729
55	317		514		65 560
56	317		514		66 391
57	317	115	514	1 385	68 722
58	318		546		69 586
59	318		546		70 450
60	318		546	99	71 314
61	318		549		72 280
62	318		549		73 147
63					
64					
65	↓		↓		
66					

Table 4

Separative work

Time (years)	LWR		THTR	Cumulative
	Annual	Initial	Initial	
- 3		6 507		6 507
- 2	3 105			9 612
- 1	3 105			12 717
0	3 105	13 014		28 836
1	9 315			38 151
2	9 315			47 466
3	9 315	13 014		69 795
4	15 525			85 320
5	15 525			100 845
6	15 525	13 014		129 384
7	21 735			151 119
8	21 735			172 854
9	21 735	13 014		207 603
10	27 945			235 548
11	27 945			263 493
12	27 945	13 014		304 452
13	34 155			338 607
14	34 155			372 762
15	34 155	6 507		413 424
16	37 260			450 684
17				487 944
18			11 826	537 030
19				574 290
20				611 550
21			23 652	672 462
22				709 722
23				746 982
24			23 652	807 894
25				845 154
26				882 414
27		6 507	23 652	949 833
28				987 093
29				1 024 353
30	▽	13 014	23 652	1 000 279

Table 4 continued

31	37 260			1 135 539
32	↓			1 172 799
33		13 014	23 652	1 246 725
34	↓			1 283 985
35	▽			1 321 245
36	35 880	10 122	23 652	1 390 899
37	35 880			1 426 779
38	35 880			1 462 659
39	30 015	723	23 652	1 517 049
40	30 615			1 547 064
41	30 615			1 577 679
42	23 805		23 652	1 624 536
43	23 805			1 648 341
44	23 805			1 672 146
45	17 595		23 652	1 713 393
46	17 595			1 730 988
47	17 595			1 748 583
48	11 385		23 652	1 783 620
49	11 385			1 795 005
50	11 385			1 806 390
51	5 175		23 652	1 835 217
52	5 175			1 840 392
53	5 175			1 845 567
54	345		23 652	1 869 564
55	345			1 869 909
56	345			1 870 254
57			18 396	1 888 650
58				1 888 650
59				1 111 650
60			1 314	1 889 964
61				↓
62				
63				
64				
65				
66				▽

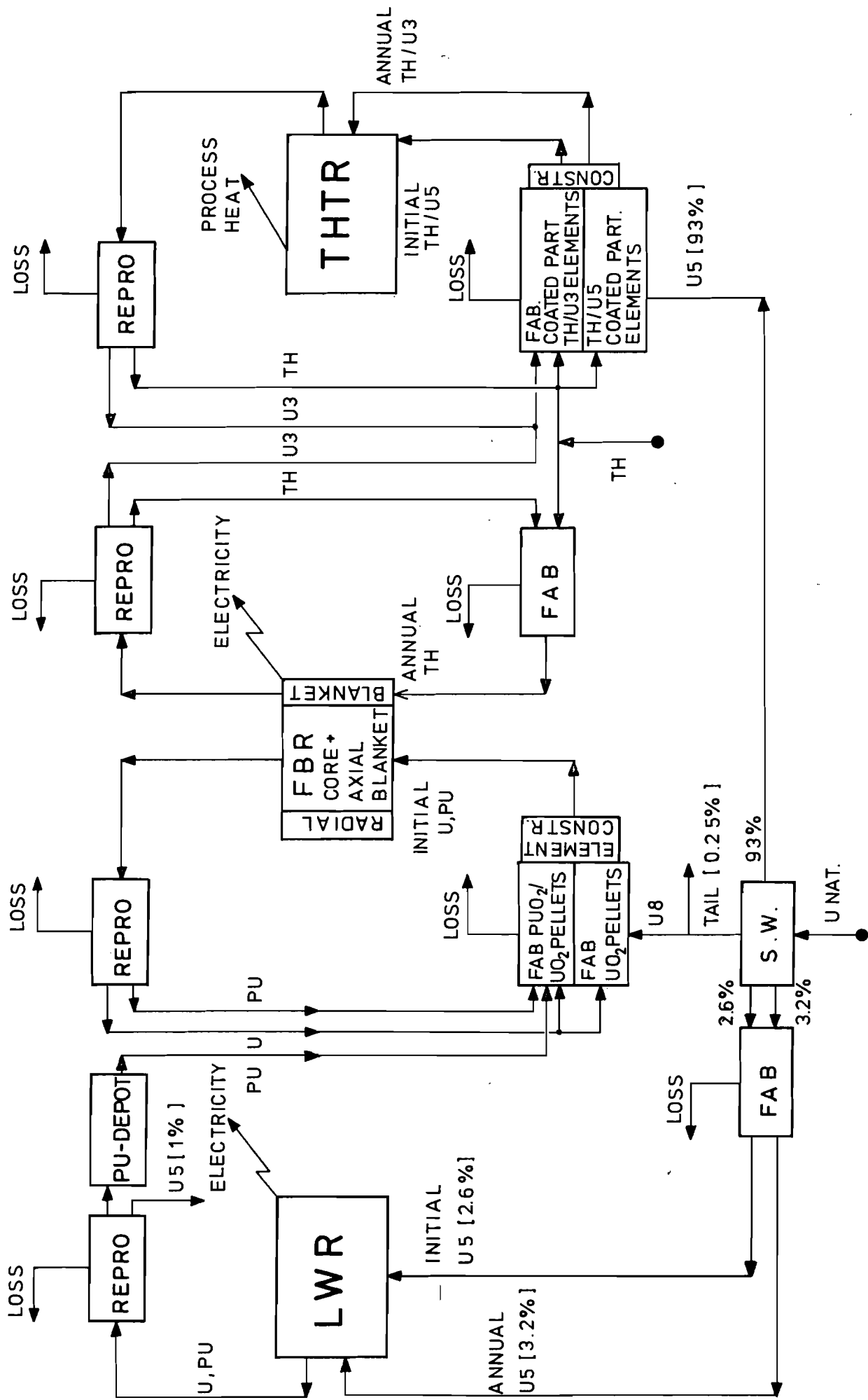


FIGURE 1. TRANSIENT REACTOR SYSTEM

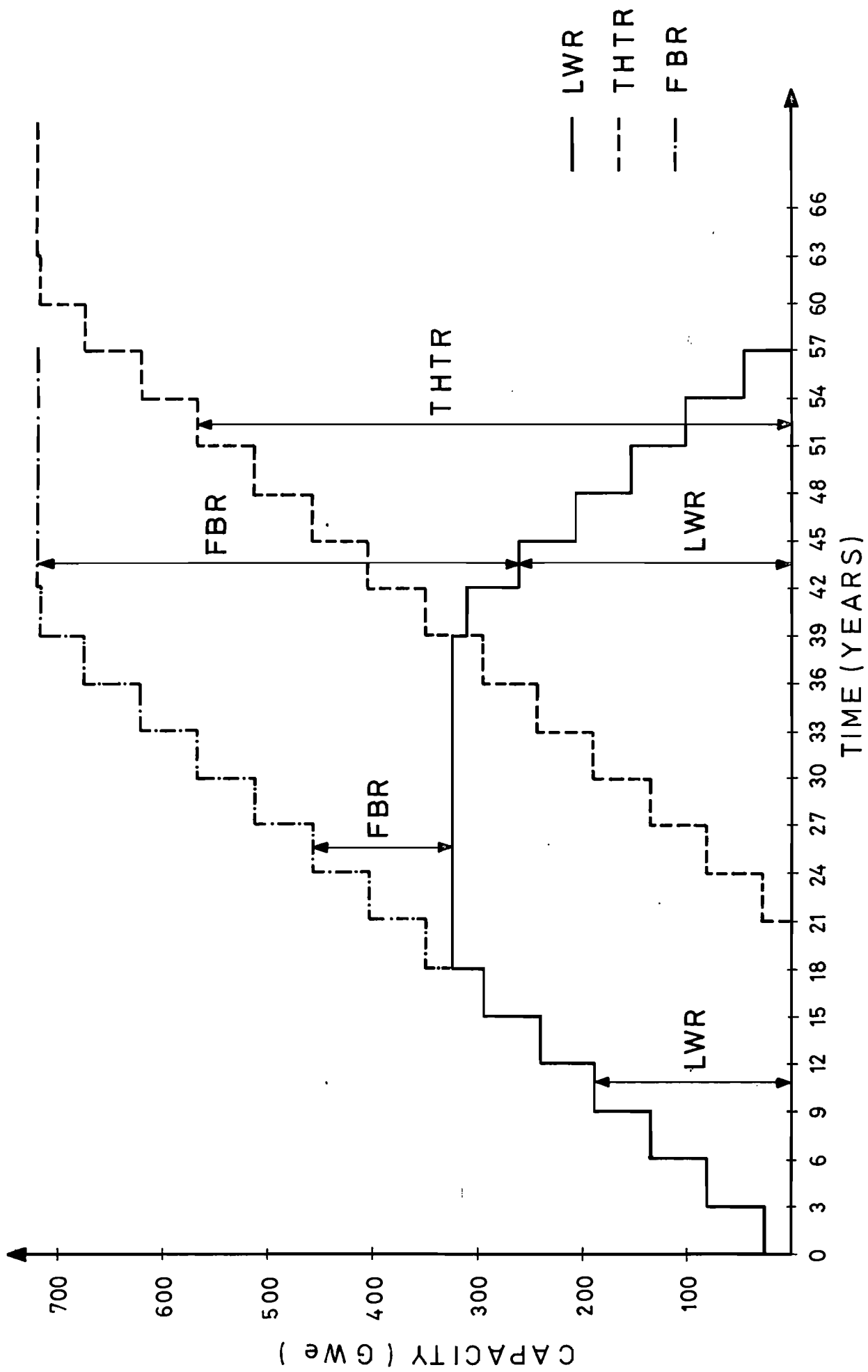


FIGURE 2. INSTALLATION SCHEDULE FOR LWR, FBR AND THTR

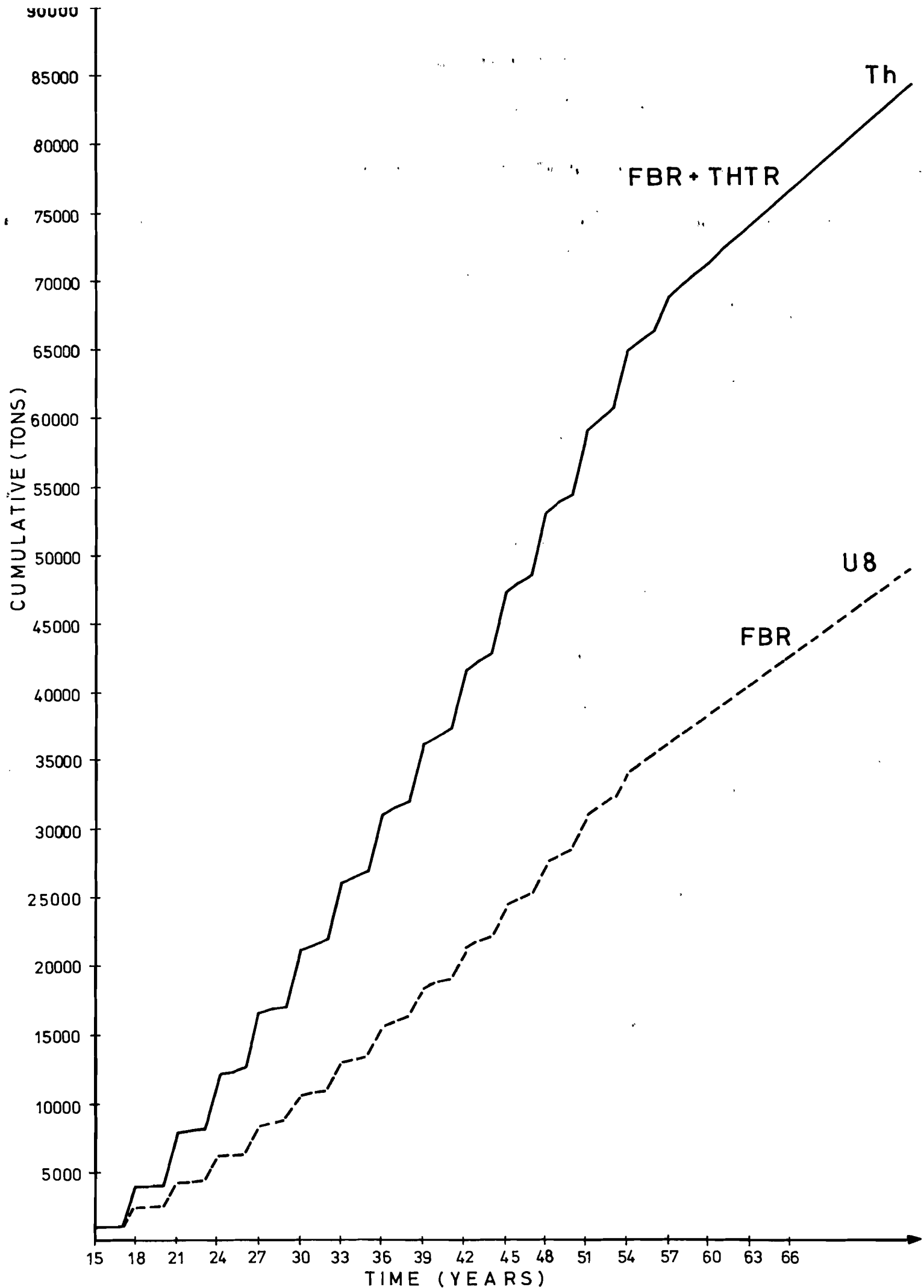


FIGURE 3. Th AND U8 CONSUMPTION



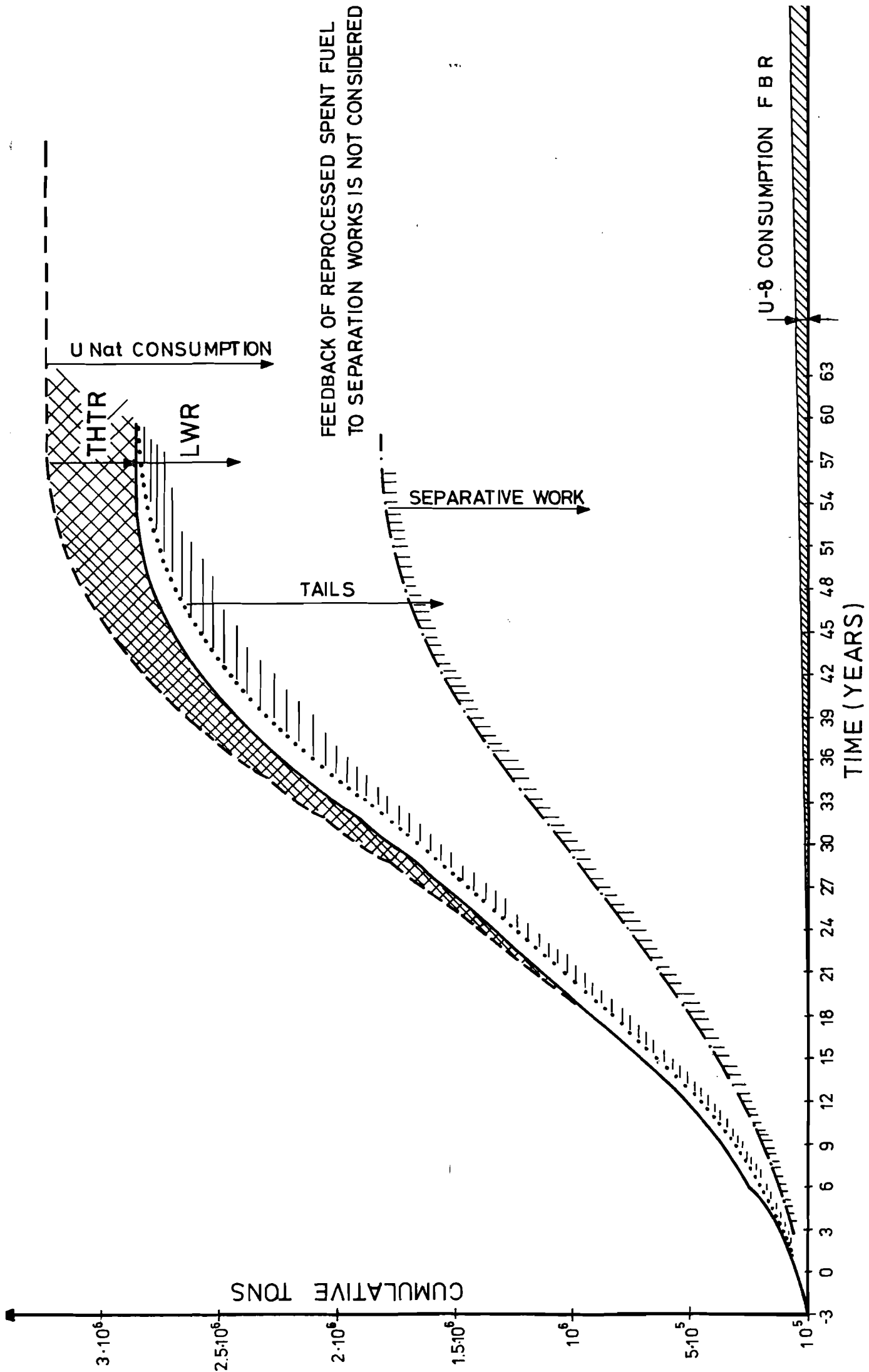


FIGURE 4. CONSUMPTION OF U Nat, PRODUCTION OF TAILS, SEPARATIVE WORK