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I. Introduction

Wolf Häfele and Alan S. Manne [1] present a model optimizing strategies on a transition from fossil to nuclear fuels: substitution of LWR and FBR for coal for the use of electricity, and of hydrogen from HTGR process heat for petroleum-and-gas for the use of non-electrical energy.

This paper treats another transition from fossil to nuclear fuels, i.e. that from coal to the molten-salt reactor (MSR) for electrical use, and from petroleum-and-gas to MSR process heat for non-electrical use.

MSR technology offers important advantages for power generation: avoidance of fuel element fabrication, rapid and inexpensive reprocessing, on-line refueling, high specific power, good neutron economy and high-temperature operation at low pressure. A review of the status and future of the MSR program, [2] suggests that the MSR technology should still be considered as one of the possible nuclear options for energy supply. Therefore, it is worth while to study the MSR strategy as well as the FBR and HTGR strategies.

The aim of this paper is to compare the MSR strategy with the Häfele-Manne strategy via an example of the optimal transitions based on MSR technology, as opposed to today's situation where virtually all electrical and non-electrical energy demands are met by coal and petroleum-and-gas, respectively.

II. Analytical Method and Input Data

The energy supply system considered here is shown in Figure 1. There are four MSR's: MSRF, MSR3, MSR5, and MSR9, classified into two types;

1) MSRF: This has been under consideration in France [3] (and the reference design has been made so that the reactor system might be developed as soon as possible) to prove the technological and economic feasibility. First, the fuel circulation system--to keep criticality for the neutron chain reaction--is not designed so as to operate continuously during the entire plant life.

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The reactor must be shut down every 6 years to exchange the core fuel, so that, for a 30-year plant life, five refueling stages are required. Second, while the reactor uses Th-Pu (fissile) in the first stage and Th-U^{233} in the following four stages, the breeding ratio of U^{233} is nearly 1.0; the reactor is therefore, not actually a breeder but merely self-sustaining.

2) MSR3, MSR5, and MSR9[1]: These reactor systems are in the R/D stage at Oak Ridge National Laboratory, USA, [4]. The reference design indicates that they have the closed-loop fuel circulation system which makes on-line fuel reprocessing possible, hence, eliminating the need to stop operation for refueling. In addition, the breeding gain of U^{233} is such that the reactor can be called a breeder.

Now, the question is which compound structure of the energy supply alternatives minimizes the total energy costs over the given planning horizon to meet exogenous energy demand, subject to the following constraints:

- the limited reserves of petroleum-and-gas,
- the limited reserves of low-cost uranium,
- the limited industrial capacity for construction of MSR´s, and
- the limited financial resources available to the energy supply sector.

The general framework of the analytical method to solve the problem is based on the Häfele-Manne model. So that linear programming optimization techniques can be used, Häfele-Manne make the following assumptions:

a) time-differential equations are to be approximated by two-point difference equations, and

b) all the coefficients of those equations, such as annual discount rate and relevant reactor data, are independent of the activity level of each variable.

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[1] MSR3, MSR5 or MSR9 indentify the kind of fuel used at the beginning of operation. MSR3 is started with U^{233} which cannot be introduced until enough U^{233} for initial inventory requirement has been produced by other reactors; MSR5 and MSR9 are started with U^{235} and Pu (fissile), respectively, and are considered to be of use when MSR3 cannot be produced.

The mathematical description of the method for our problem is shown in the Appendix.

While the required input data for fossil fuel and LWR technologies are fixed in accordance with the data used in the Häfele-Manne model, the data for MSR technology are additionally given. They take into consideration both the reactor specifications in the conceptual design studies [3,4] and the corresponding data for the FBR and the HTGR employed in the Häfele-Manne model. Tables 1 to 3 give these input data for MSR´s, comparing them with the Häfele-Manne data for the FBR and the HTGR. The upper bounds on reactor construction rates are fixed in such a way that the MSR´s, with the closed-loop fuel circulation system, have the same bounds as the HTGR or the advanced FBR in the Häfele-Manne model: MSRF has bounds permitting earlier introduction.

The MSRF data are taken from [3] and the data for the other MSR´s are taken, in principle, from [4]. Note that the inventory requirements of the MSR case are less than those of all the other nuclear reactor cases.

The cost estimates for the MSR´s are based on the following considerations:

1) There is no reason why the current annual costs for the MSR´s are greater than for the FBR; hence costs for the MSR´s with the closed-loop fuel circulation system are assumed to be equal to those for the FBR in Häfele-Manne model.

2) It is stated in [2] that the capital costs for the MSR´s with the closed-loop system are comparable to those for the LWR. Thus for a more conservative estimate on MSR technology, we assume that the capital costs are equal to those for the HTGR of the Häfele-Manne model, which are assessed to be 10% greater than the cost for the LWR.

3) It is clear that both the current and the capital costs for the MSRF are lower than those for the other MSR´s--we assume by 10-20%.

III. An Illustrated Example

The Häfele-Manne model considers for final demand projections three kinds of model societies[1]. Here, model society 1 will be taken as an illustration:

between the years 1970 and 2015, the population increases from $250 \cdot 10^6$ to $360 \cdot 10^6$ and the per capita consumption doubles from 10 to 20 kW_{th}.

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[1] For details, see W. Häfele and A.S. Manne [1], pp. 20-27.

Furthermore, numerical results are given for three cases. depending on the assumed petroleum-and-gas resource availabilities for 40, 60 and 80 years of resources, in terms of the annual consumption rate which is equivalent to 35% of the world's 1970 production of petroleum-and-gas, as 1.875TW = .0560.[2] We will take the case of 80 years as an example, and will call it case 1.80 after Häfele-Manne.

Figure 2 and 3 display the calculation results that express two optimal transition strategies for the case 1.80; one for the MSR fueled with U-233, and the other for the FRB fueled with Pu. Several features of these results are striking:

a) The coal consumptions are exactly the same and yet the petroleum-and-gas consumptions are remarkably different. With the MSR strategy, the petroleum-and-gas resources consumed are approximately 50 years of the 80-year availability, whereas with the FBR strategy, they are approximately 70 years.

b) Despite the lesser consumption of fossil fuels, the MSR strategy requires nearly the same total natural uranium consumption as the FBR strategy, as the integrated LWR installed capacities are the same for both. (Figures 4, 5 and 6). [3]

c) Because of a) and b), the total natural resource consumption over the planning horizon is less for the MSR strategy than for the FBR strategy.

d) Macroscopically speaking, the MSRF is introduced in about 1990; and the MSR3 comes into use 30 years later, since the initial inventory requirements for U-233 are supplied mainly by the retired core of the MSRF.

e) The solution for the MSR strategy shows that in the distant future both electrical and non-electrical energy demands can be met by one type of MSR, i.e. MSR3; with the FBR strategy, the FBR supplies the entire electrical energy demand and the HTGR supplies the entire non-electrical energy demand.

Table 4 summarizes the results on natural energy resource consumption over the planning horizon.

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[2] For details, see W. Häfele and A.S. Manne [1], pp. 27-32.

[3] Figures 4, 5 and 6 also illustrate an extreme strategy, i.e., LWR (for electricity) and HTGR with U-235 (for non-electrical energy) without FBR.

IV. Concluding Remarks

As far as the calculation results demonstrated here are concerned, the MSR strategy is more efficient than the FBR strategy if we define efficiency in terms of the total natural resource (petroleum-and-gas and uranium) consumption over the whole planning horizon.

It goes without saying that this conclusion depends on the input data used not only in assessing the MSR technology (Tables 1 to 3) but also in projecting future energy demands. The fuel breeding gain for MSR is less than for FBR; therefore, if future energy demands are projected to be continuously increasing (model societies 2 and 3 of the Häfele-Manne study), FBR technology will be the more effective. For model society 1, where energy demands are to be stationary from the year 2015 on, the MSR strategy seems to be the more effective.

Table 1. Upper bounds on reactor construction rates, MCR_i^t.

Calendar Year	Nuclear Plant Type i / Period t	LWR[1]	HTGR[1]	FBR[1]		MSR			
						open-loop	closed-loop		
				not-advanced	advanced	MSRF	MSR3	MSR5	MSR9
1970	0	0	0	0	0	0	0	0	0
73	3	20	0	0	0	0	0	0	0
76	6	40	0	0	0	0	0	0	0
79	9	60	0	0	0	0	0	0	0
82	12	80	0	0	0	0	0	0	0
85	15	100	0	0	0	0	0	0	0
88	18	∞	0	30	0	30	0	0	0
91	21	∞	20	60	20	60	20	20	20
94	24	∞	40	90	40	90	40	40	40
97	27	∞	60	∞	60	∞	60	60	60
2000	30	∞	∞	∞	∞	∞	∞	∞	∞
and thereafter		∞	∞	∞	∞	∞	∞	∞	∞

[1] after W. Häfele and A.S. Manne [1], p. 21.

Table 2. Relevant reactor data.

NUCLEAR PLANT TYPE i			LWR1)	HTGR1)	FBR1) (advanced)	MSR			
						MSRF2)	MSR33)	MSR54)	MSR94)
Annual Requirements for Natural Uranium,	$\frac{10^6\,\text{ton}}{\text{TWe}\cdot\text{Y}}$	a_i	.18						
Inventory Requirements for Natural Uranium,	$\frac{10^6\,\text{ton}}{\text{TWe}}$	b_i	.50		.54			.035)	
Annual Requirements for Separative Work,	$\frac{10^6\,\text{ton}}{\text{TWe}\cdot\text{Y}}$	c_i	.11						
Inventory Requirements for Separative Work,	$\frac{10^6\,\text{ton}}{\text{TWe}}$	d_i	.23		.44			.025)	
U-233 or Pu(fissile) Net Production,	$\frac{10^3\,\text{ton}}{\text{TWe}\cdot\text{Y}}$	e_i	.17 (Pu)	.166) (Pu)			.057) (U-233)	.057) (U-233)	.057) (U-233)
U-233 or Pu(fissile) Inventory Demand,	$\frac{10^3\,\text{ton}}{\text{TWe}}$	f_i		2.00 (Pu)		1.14 (Pu)	1.50 (U-233)		1.508) (Pu)
Thermal Efficiency	-	η_i	.33	.40	.40	.40	.40		.40

1) after W. Häfele and A.S. Manne [1], p. A-3.

2) after

3) after R.C. Robertson, ed. [4], p. 31.

4) the data are made from an analogy of the data for MSR5.

5) corresponding to 1.5 ton/TWe of highly enriched uranium.

6) the corresponding annual yield is 8% (.08 x 2.00 = .16).

7) the corresponding annual yield is 3.2% (.032 x 1.50 = .05).

8) the same amount as for U-233 of MSR3 is taken for simplification and hence the difference of the demand between MSR9 and MSRF implies mainly the requirement for out-of-case inventory.

Table 3. Cost coefficients.

Energy Costs / Energy Supply Alternatives, i	Current, $(\frac{\$10^9}{\text{TWrh}\cdot\text{Y}})$	Capital, $(\frac{\$10^9}{\text{TWrh}})$	Total Annual Energy Costs2)
for Electricity			
Coal-fired1)	30.0	192	46
LWR1)	4.4	200	32
FBR1)	3.5	264	31
MSRF	3.0	200	24
MSR3	3.5	220	27
MSR5	3.5	220	27
MSR9	3.5	220	27
for Non-electrical Energy			
PETG (petroleum and gas)1)	50.0	-	50
ELHY (electrolytic hydrogen)1)	-	20	84
HTGR1)	7.0	220	35
MSRF	3.0	200	29
MSR3	3.5	220	32
MSR5	3.5	220	32
MSR9	3.5	220	32
Intermediate Item			
Separative Work Units1)	20.0	2003)	-
High Cost Natural Uranium1)	77.0	-	-

1) after W. Häfele and A.S. Manne [1], pp. B-2 to B-4.

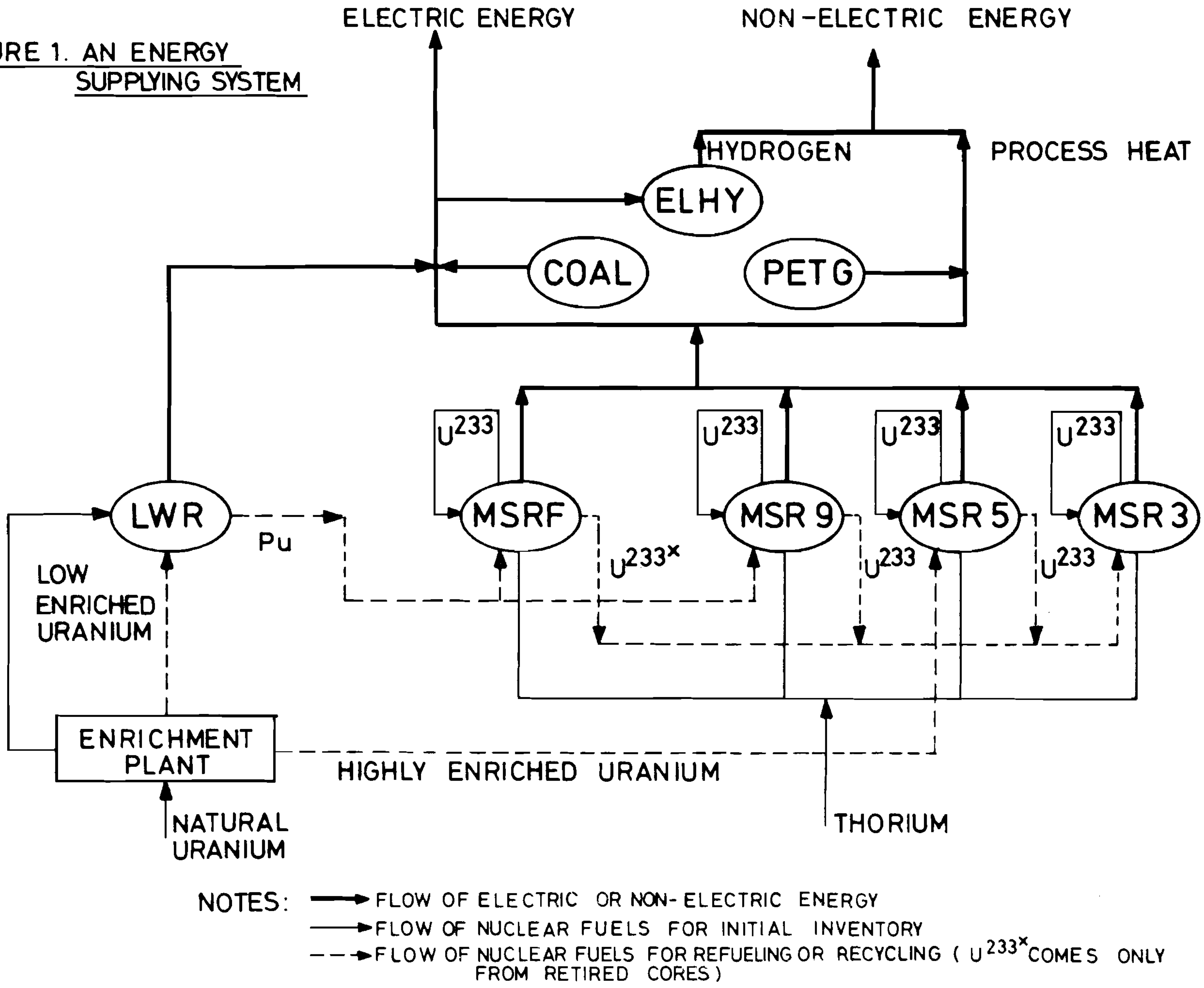
2) Units: for electricity, $\$10^9$/TWrh equivalent for LWR·Year
for non-elec. e., $\$10^9$/TWrh equivalent for P.&G.·Year, net capital recovery factor = 0.13/year (10% discount rate, and 30. year plant life),

3) Unit: $\$10^9/10^6$ tons/year.

Table 4. Natural energy resource consumption over the planning horizon (1970-2045).

	Strategies		
	MSR-for-all	FBR-HTGR	LWR-HTGR
coal ($Q = 10^{18}$BTU)	.67	.67	.67
petroleum-and-gas (Q)	2.84		4.5
Uranium (million tons)	3.15	3.06	20.50 ton

FIGURE 1. AN ENERGY SUPPLYING SYSTEM



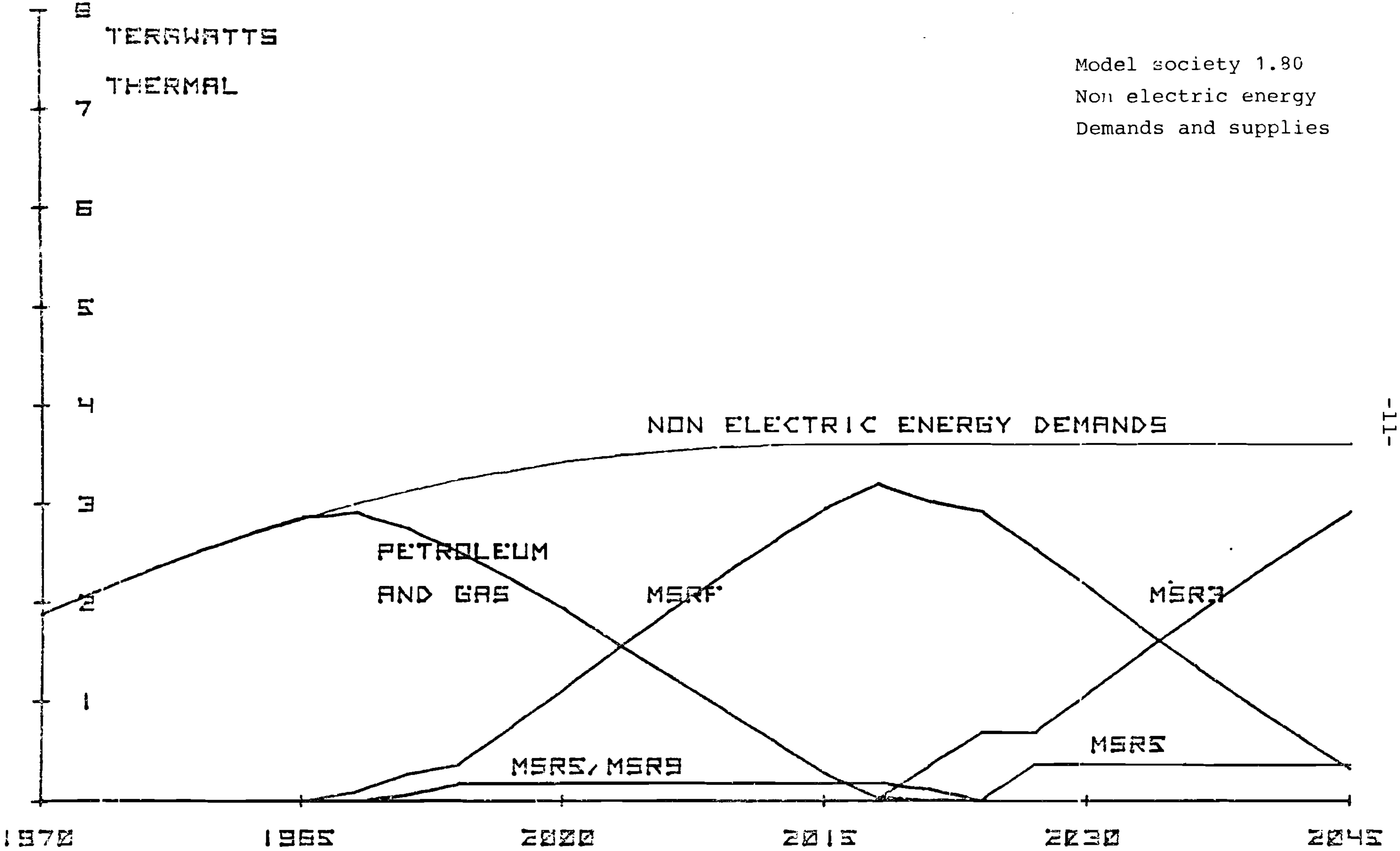


Figure 2a. MSR fueled with U-233

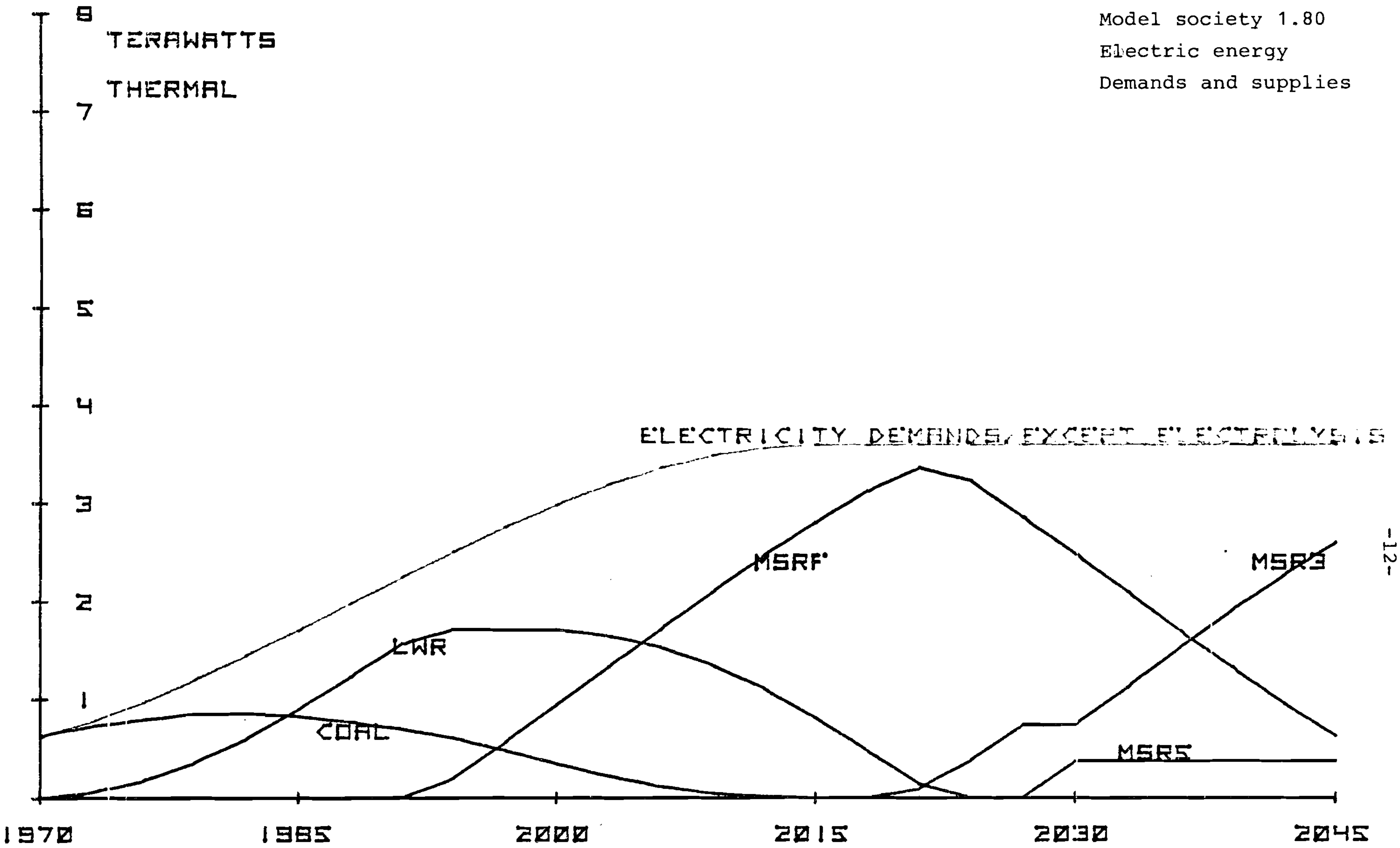


Figure 2b. MSR fueled with U-233

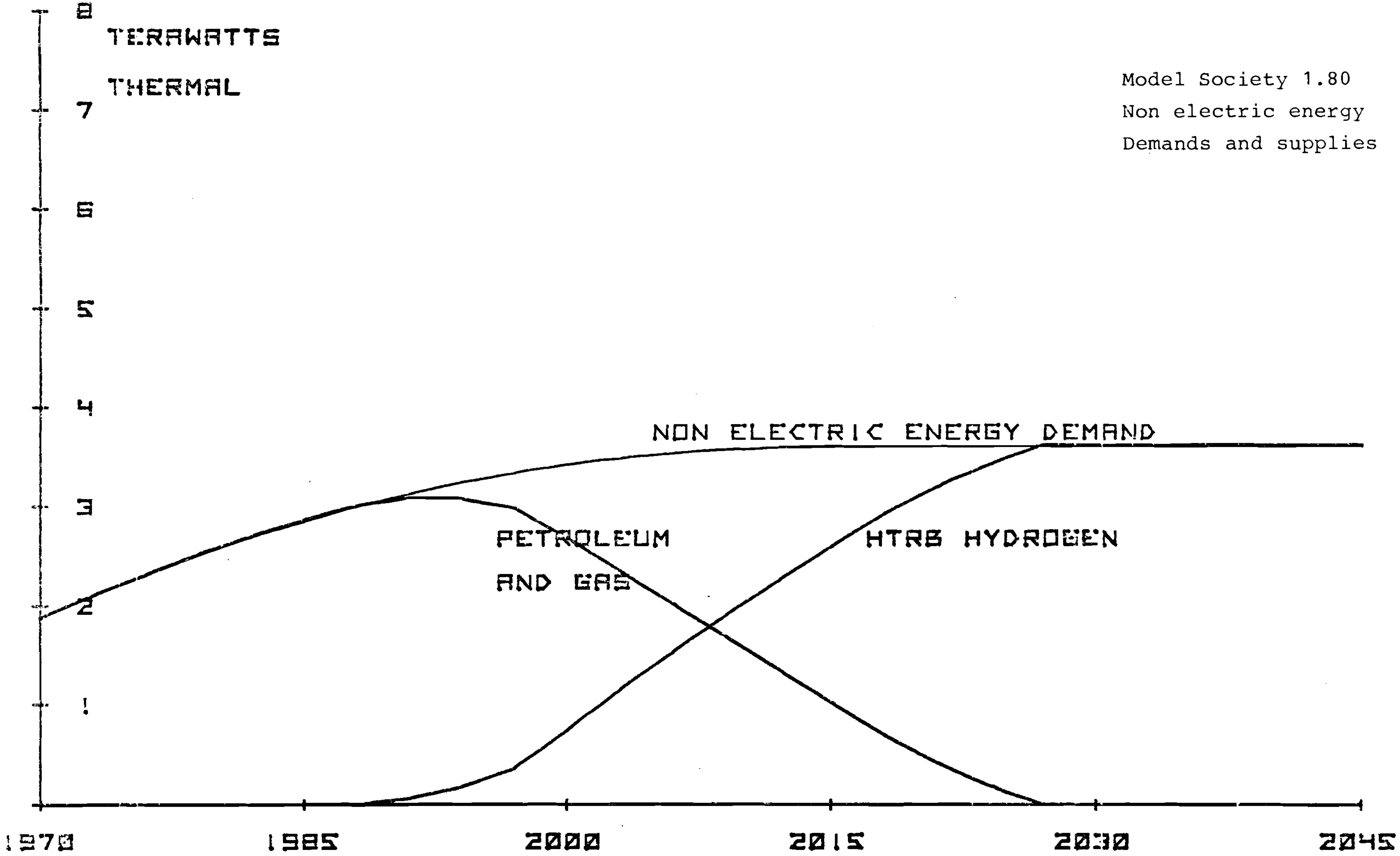


Figure 3a. FBR fueled with Pu

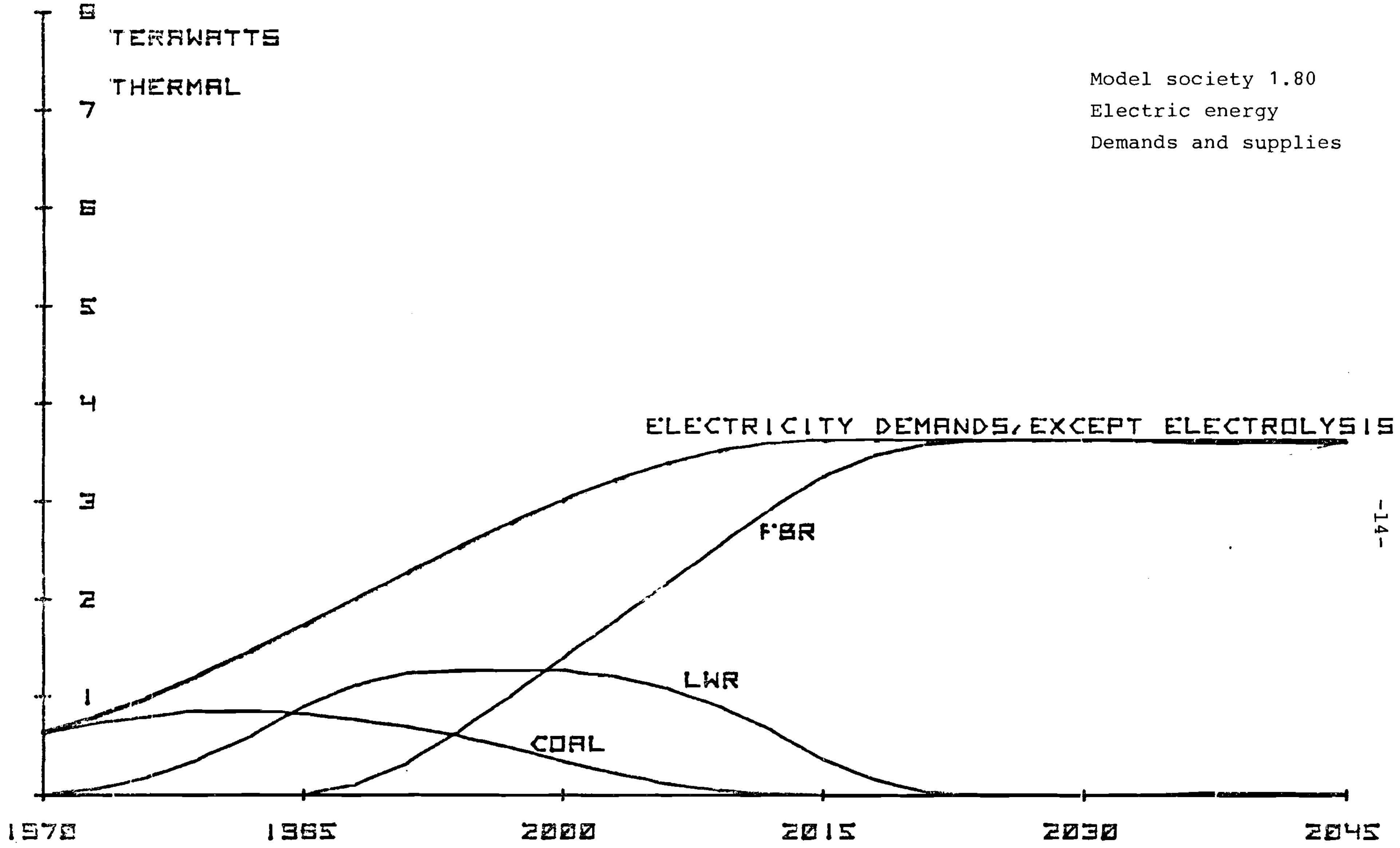


Figure 3b. FBR fueled with Pu

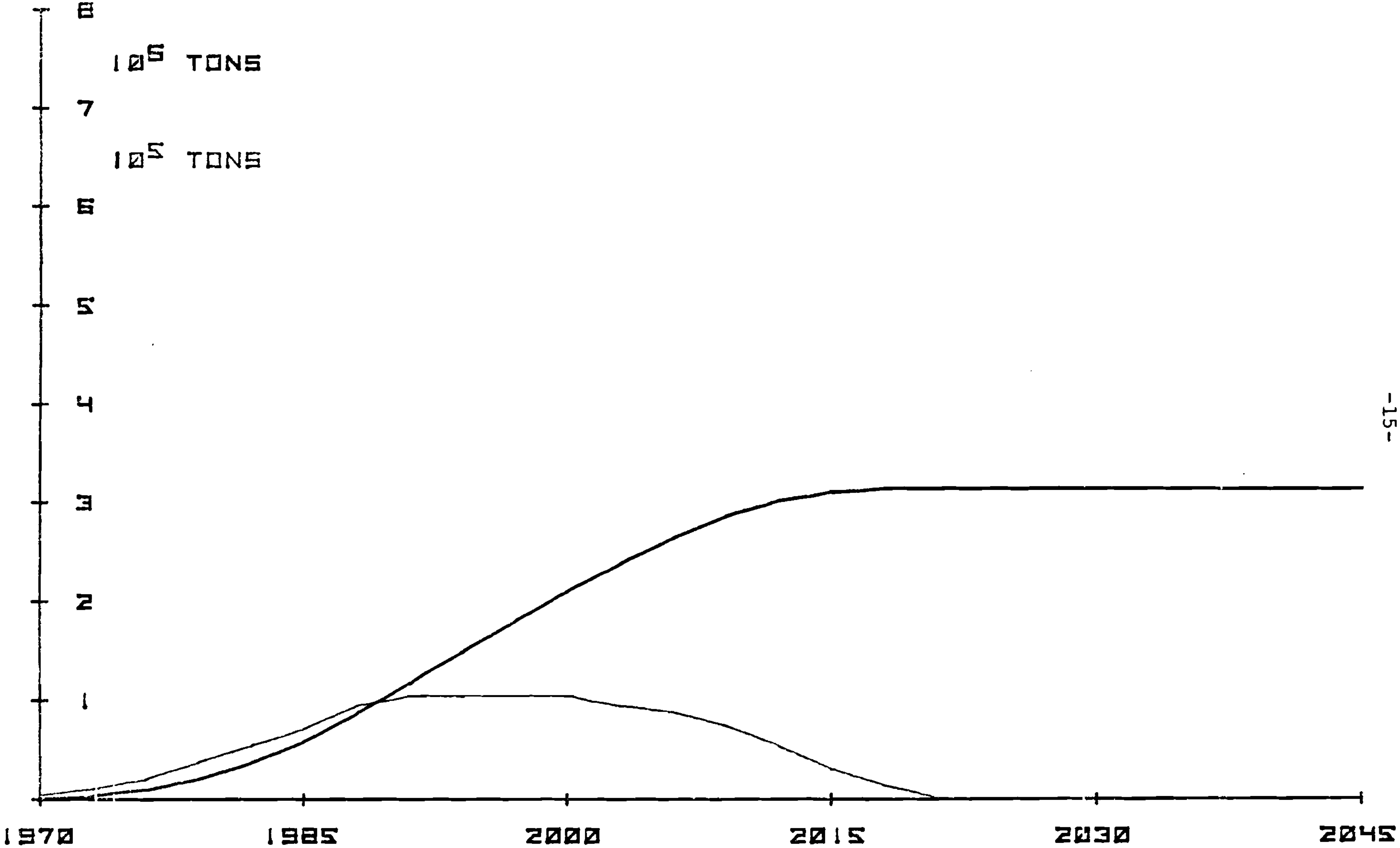


Figure 4. Natural uranium requirement, annual and cumulative, for MSR fueled with U-233 (Model Society 1.80).

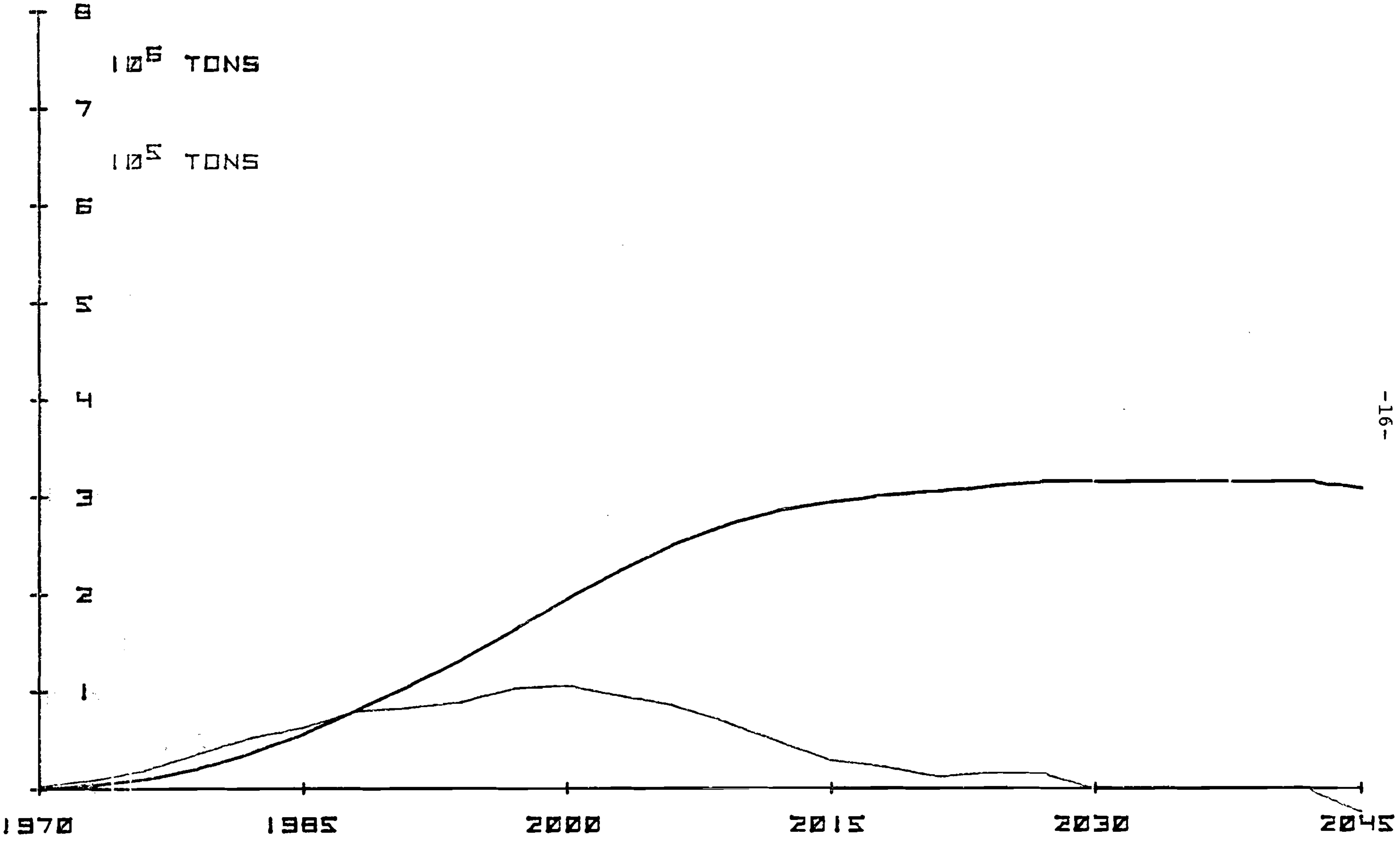


Figure 5. Natural uranium requirement, annual and cumulative, for FBR fueled with Pu (Model Society 1.80).

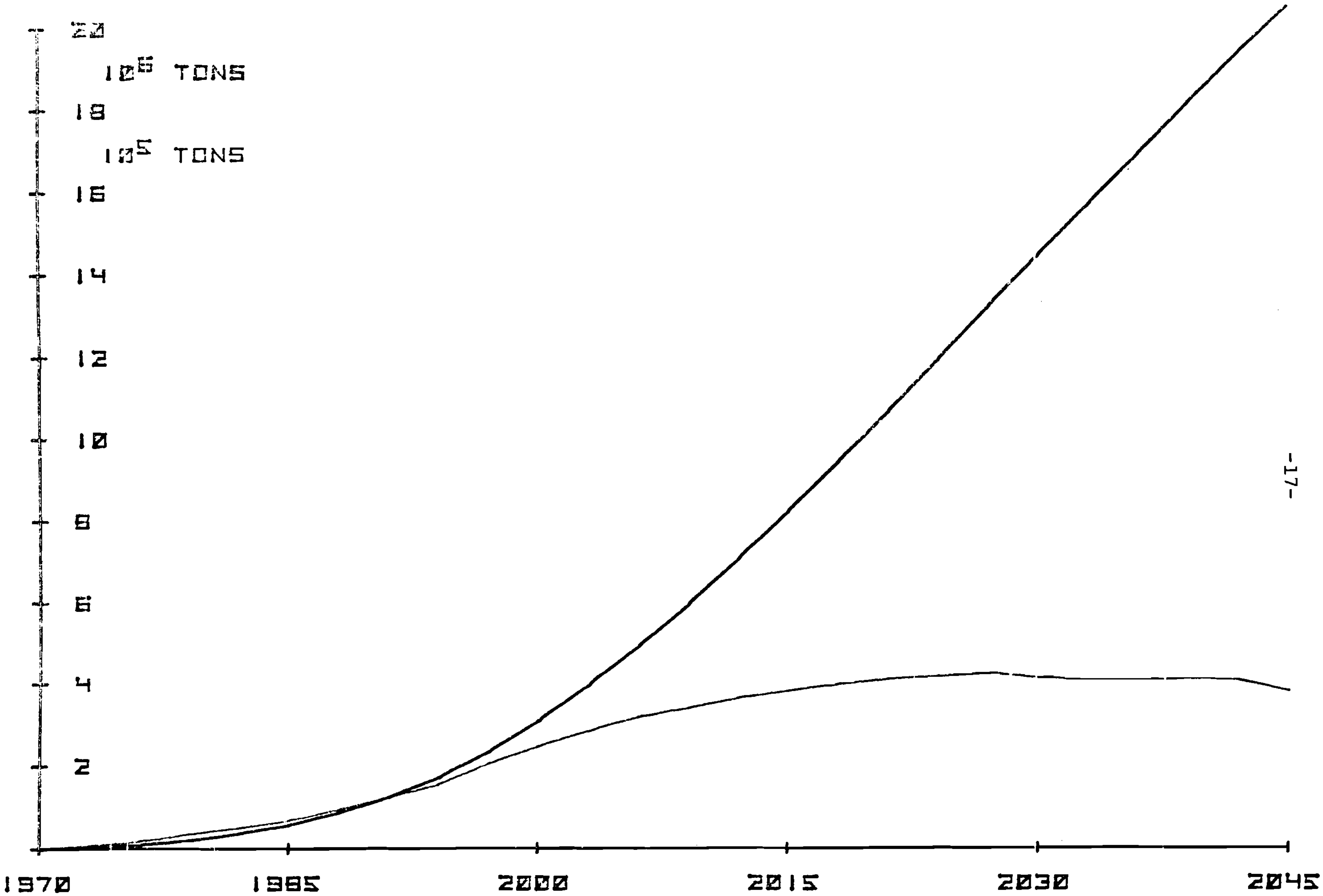


Figure 6. Natural uranium requirement, annual and cumulative, where FBR cannot be introduced and only LWR and HTGR fueled with U-235 are used for electricity and non-electrical energy, respectively (Model Society 1.80).

Appendix

The Mathematical Description of Constraints

1. Installed capacity of energy supply sector i, defined by 3-year time step difference equation:

   a) For electricity (unit: TWth of primary energy input),

$$PCE_i^t = PCE_i^{t-3} + [DPE_i^t - DPE_i^{t-30}],$$

$$i = COAL, LWR, MSRF, MSR3, MSR5, MSR9,$$

where the initial condition,

$$PCE_{COAL}^o = \overline{FDE}^o$$

$$PCE_i^o = o \ , \quad i \neq COAL$$

   b) For non-electrical energy (unit: TWth of primary energy input),

$$PCN_i^t = PCN_i^{t-3} + 3[DPN_i^t - DPE_i^{t-30}] ;$$

$$i = PETG, ELHY, MSRF, MSR3, MSR5, MSR9.$$

initial condition,

$$PCN_{PETG}^o = \overline{FDN}^o$$

$$PCN_i^o = 0 \ , \quad i \neq PETG.$$

2. Upper bounds on reactor construction rates (i = LWR, MSRF, MSR3, MSR5, MSR9):

a) For LWR,

$$DPE^{t}_{LWR} \leq 10^{-3} * MCR^{t}_{LWR} .$$

b) For the others,

$$DPE^{t}_{i} + DPN^{t}_{i} \leq 10^{-3} * MCR^{t}_{i} .$$

MCR^{t}_{i} is given in Table 1.

3. Cumulative sum of energy resource j:

a) For Coal (unit: 10^{18}BTU),

$$CS^{*}_{COAL} = CS^{t-3}_{COAL} + 3^{*} .03(PCE^{*}_{COAL} + \overline{RI}^{t}_{COAL} .$$

b) For PETG (unit: 10^{18}BTU),

$$CS^{*}_{PETG} = CS^{t-3}_{PETG} + 3^{*} .03(PCE^{t}_{PETG} + \overline{RI}^{t}_{PETG}) .$$

c) For NULC (unit: 10^{6} tons),

$$\begin{aligned} CS^{t}_{NULC} = CS^{t-3}_{NULC} + 3[&a_{L} \cdot \eta_{L} \cdot PCE^{t}_{LWR} - PC^{t}_{NUHC} \\ &+ b_{L} \cdot \eta_{L}(DPE^{t+3}_{LWR} - DPE^{t-30}_{LWR}) \\ &+ b_{5} \cdot \eta_{5}(DPE^{t+3}_{MSR5} + DPN^{t+3}_{MSR5})] . \end{aligned}$$

d) For PLUT (unit: 10^{3} tons),

$$\begin{aligned} CS^{t}_{PLUT} = CS^{t-3}_{PLUT} + 3[&e_{L} \cdot \eta_{L} \cdot PCE^{t-3}_{LWR} \\ &- f_{F} \cdot \eta_{F}(DPE^{t}_{MSRF} + DPN^{t}_{MSRF}) \\ &- f_{9} \cdot \eta_{9}(DPE^{t}_{MSR9} + DPN^{t}_{MSR9})] . \end{aligned}$$

e) For U233 (unit: 10^3 tons),

$$\begin{aligned} CS^{t}_{U233} = CS^{t-3}_{U233} + 3[&e_3 \cdot \eta_3 (PCE^{t-3}_{MSR3} + PCN^{t-3}_{MSR3}) \\ &+ e_5 \cdot \eta_5 (PCE^{t-3}_{MSR5} + PCN^{t-3}_{MSR5}) \\ &+ e_9 \cdot \eta_9 (PCE^{t-3}_{MSR9} + PCN^{t-3}_{MSR9}) \\ &+ f_3 \cdot \eta_3 (DPE^{t-30}_{MSR3} - DPE^{t}_{MSR3}) \\ &+ f_3 \cdot \eta_3 (DPN^{t-30}_{MSR3} - DPN^{t}_{MSR3}) \\ &+ f_3 \cdot \eta_5 (DPE^{t-30}_{MSR5} + DPN^{t-30}_{MSR5}) \\ &+ f_3 \cdot \eta_9 (DPE^{t-30}_{MSR9} + DPN^{t-30}_{MSR9}) \\ &+ f_3 \cdot \eta_F (DPE^{t-30}_{MSRF} + DPN^{t-30}_{MSRF})] \end{aligned}$$

4. Upper bounds on cumulative resource extraction:

a) For COAL, no-limit.

b) For PETG,

$$CS^{t}_{PETG} \leq \frac{.03(10^{18}BTU)}{(TWth \cdot year)} \times PCN^{o}_{PETG}\ (TWth) \times A_{PETG}(year).$$

c) In model society 1.80,

$$PCN^{o}_{PETG} = 1.875(TWth)$$

$$A_{PETG} = 80(year).$$

d) For NULC,

$$CS^{t}_{NULC} \leq 2.0\ (10^6\ tons)\ .$$

e) For NUHC, no-limit.

5. Demand for intermediate item:

a) For SWU (unit: 10^6 tons/year),

$$PC^t_{SWU} \geq C_L \cdot \eta_L \; PCE^t_{LWR} + d_L \cdot \eta_L (DPE^{t+3}_{LWR} - DPE^{t-30}_{LWR})$$
$$+ d_5 \cdot \eta_5 (DPE^{t+3}_{MSR5} + DPN^{t+3}_{MSR5})$$

6. Final demand:

a) For electricity (unit: TWth, LWR equivalent),

$$\overline{RI}^t_{COAL} + (\frac{\eta_c}{\eta_L}) \; PCE^t_{COAL} + PCE^t_{LWR} + (\frac{\eta_F}{\eta_L}) \; PCE^t_{MSRF}$$
$$+ (\frac{\eta_3}{\eta_L}) \; PCE^t_{MSR3} + (\frac{\eta_5}{\eta_L}) \; PCE^t_{MSR5} + (\frac{\eta_9}{\eta_L}) \; PCE^t_{MSR9}$$
$$\geq \overline{FDE}^t + PCN^t_{ELHY} \quad ,$$

where

η_c = .40 thermal efficiency of coal steam generating plant.

b) For non-electrical energy (unit: TWth, PETG equivalent),

$$\overline{RI}^t_{PETG} + PCN^t_{PETG} + \eta_U \cdot \eta_L \cdot \eta_E \cdot PCN^t_{ELHY}$$
$$+ \zeta_P (PCN^t_{MSRF} + PCN^t_{MSR3} + PCN^t_{MSR5} + PCN^t_{MSR9})$$
$$\geq \overline{FDN}^t \quad ,$$

where

η_U = 1.5 hydrogen utilization factor,

η_E = .80 hydrogen production efficiency by electrolysis,

ζ_P = 1.0 BTU of PETG replaceable for 1 BTU of process heat produced by MSR's.

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