THE DYNAMICS OF GROWTH AND ECONOMIC ANALYSIS OF NUCLEAR POWER GENERATING INDUSTRIES BASED ON PLUTONIUM CONVERTER AND BREEDER REACTORS

by

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ABSTRACT

This thesis research deals with the growth of nuclear power generating industries in United States during years 1965-2040. It discusses mainly the problem of nuclear fuels and their efficient utilization and analyses the importance of Advanced Converter [ACR] and fast breeder reactors in the nuclear power complex. With certain suggestions regarding better nuclear fuel utilization, a mathematical model of the growth of nuclear power is formulated and analysed with the help of a computer.

Comparing the anticipated growth in nuclear power, the U utilization in present Light Water Reactors [LWR], and available economic U resources, it is concluded that for the nuclear power to remain competitive in coming decades, it is essential to develop ACRs and fast Breeders.

For better fuel utilization, a scheme of Balanced Nuclear Economy[BNE] is suggested. In BNE, the rate of new breeder installations is determined by the net Pu production rate in converters and breeders themselves, three years earlier. It has the following advantages: (1) it provides a commercial market for Pu and eliminates the unintended investments in it, (2) it requires less external fuel and thus extends the economic fuel base, (3) it utilizes fuel more efficiently and thus reduces the fuel cycle costs, (4) it stabilises the fuel prices, and (5) it creates a demand for Pu produced in converters, thus reducing the uncertainty in its production or recycling.

Following BNE, another suggested scheme of nuclear fuel utilization is called Integrated Balanced Nuclear Economy[IBNE]. In IBNE, the excess of Pu left over after fulfilling new breeder inventory requirements is fed into new ACR installations to meet their fissile makeup requirements. This scheme, maintaining the advantages of BNE, assures the further economic advantage of including less capital intensive ACRs in the complex with decreasing load factors and an added degree of freedom on local conditions.

With exponential growth in established nuclear power, the growths of ACRs and of Breeders in BNE largely depend on the Pu production rates in each of them [a and b kgm/MWeyr, respectively], the nuclear power growth rate constant [λ] , the specific Pu inventory requirement of Breeders [I_b kgm/MWe] and the load factor [l] and the delay [δ] between plutonium production and its availability for use.

In BNE, if $(b\ 1)/I_b < \lambda e^{\lambda\delta}$, both ACR and Breeder capacities grow with time, indefinitely. If $(b\ 1)/I_b > \lambda e^{\lambda\delta}$, the ACR capacity decreases with time until it goes to zero, although if $(a\ 1)/I_b < \lambda e^{\lambda\delta}$ then it increases initially before decreasing. If $(b-a)1/I_b > \lambda e^{\lambda\delta}$, ACR capacity decreases with time until it goes to zero. The time span (i.e. the time at which ACR capacity goes to zero) of BNE is almost forty years with HWOCR(U) type of ACRs and reduces to thirty years if Fast U-235 fueled reactors are substituted for them. It is also seen that if Fast U-235 reactors are substituted for HWOCR(U) in BNE, they are required in smaller proportion and thus would require less cumulative uranium.

This scheme of BNE offers a new method of determining Pu price. The Pu price in BNE increases with time and is directly proportional to the difference in unit cost of power generation in ACRs and Breeders, Pu transactions excluded. The expression for Pu price in BNE asymptotically reaches the value obtained by equating the total cost of power generation in ACRs and fast Breeders, Pu transactions included.

In the mathematical model of the growth of nuclear power, three basic assumptions are made regarding : (1) the revised nuclear power growth as postulated in the report to the President [USAEC, 1963], (2) reactor performance characteristics and (3) reactor industry development trends. Then a number of nuclear power complex systems are compared for their U requirements and Pu production, with the help of a new computer code DYNUCLEAR specially developed for this purpose. It is quantitatively concluded that, (1) with the introduction of ACRs and Breeders and schemes of BNE and IBNE, the total U requirements and net Pu stockpile are considerably reduced, (2) if fast Breeders are not commercially feasible, HTGR-Th type of ACRs will require less U in the long run than HWOCR-U reactors, bred fuel recycled, (3) Fast U-235 fueled reactors show a higher promise as a substitute for ACRs in BNE, because they will (a) require less cumulative U, (b) produce more Pu prior to and during BNE, (c) develop the art of fast reactor technology and (d) eliminate the investments needed for research and development in ACRs altogether; and (4) the uranium price will not exceed \$ 10/lb of U_3O_8 by year 2000 and will remain stable around that value thereafter, if fast breeders are developed by late eighties.

Contrary to general belief, it is concluded that with a properly designed nuclear power complex consisting of LWRs, ACR or Fast U-235 fueled reactors, fast breeder reactors and the schemes of BNE and IBNE, even if the commercial fast reactors are not available by year 2000, there does not seem to be an acute problem of nuclear fuel scarcity.

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LIST OF PRINCIPAL SYMBOLS

A(t)	Established Advanced Converter Reactor capacity (MWe) at t
ACR	Advanced Converter Reactor
B(t)	Established total Breeder reactor capacity (MWe) at time t
C(t)	Established light water reactor capacity (MWe) at time t
FTNCX	Fraction of total nuclear capacity in X type of reactor (GRX/GRP)
GRX(t)	Annual growth of nuclear capacity in X type of reactor (MWe/yr)
LWR	Light Water Reactor
MPuV	Marginal Plutonium Value (\$ /kgm)
P(t)	Total established nuclear power capacity (MWe) at time t
STPCX	Share of total power capacity in X type of reactor (X(t)/P(t))

a	Plutonium production rate in ACRs (kgm/MWeyr)
b	Net plutonium production rate in Breeders (kgm/MWeyr)
c	Plutonium production rate in LWRs (kgm/MWeyr)
l	load factor
I_b	Specific Pu inventory of fast breeders (kgm/MWe)

$\alpha = l\, a/I_b$, $\beta = l\, b/I_b$, $\gamma = l\, c/I_b$

δ	delay of three years
λ	growth rate constant (fraction/yr)
μ	solution of transcendental equation : $\mu e^{\mu\delta} = (\beta - \alpha)$

$\xi = (\alpha)/[\alpha - \beta + \lambda e^{\lambda\delta}]$

INTRODUCTION

The history of energy consumption has been always a dynamic one characterised by substantial growth of overall energy requirements and shifting markets between various fuels. Nuclear power, already at the threshold of economic competition in some parts of the world, is coming into predominant use at present and will be a major source of energy by the end of this century. Introduction of low cost nuclear power will (1) conserve the conventional energy resources, (2) stabilise the energy prices, (3) increase the economic savings, (4) introduce an economic stimulus in power generating industries, (5) increase the growth opportunities in energy-intensive industries, and (6) make it possible to use it in industrial processes, water desalinasation and naval propulsion.

This thesis research deals with the growth of nuclear power generating industries in U.S. during 1965-2040 with the perspective of nuclear fuel availability and their efficient utilization.

Although today's light water reactors produce nuclear power economically, because of their very poor nuclear fuel utilization characteristic they pose a serious problem of nuclear fuel scarcity in the long run. Advanced converter reactors have higher capaital costs but utilise the nuclear fuel more efficiently. Fast breeder reactors will be the most capital intensive but will be self-sufficient in their fuel requirements within few decades.

Chapter I of this thesis discusses the problem of efficient nuclear fuel utilization and recommends that for nuclear power to remain competitive in the coming decades, it is essential to incorporate the advanced converter and breeder reactors in the nuclear power complex. Based on this recommendation, Chapter II is a formulation of a general mathematical model of growth of nuclear power industries, consisting of converter and breeder reactors, which will meet the total demand for nuclear power. Chapter III analyses further, mathematically, the growth of converter and breeder reactor industries based on the suggested scheme of Balanced Nuclear Economy. Following the assumed growth of converter and breeder reactor industries, Chapter IV extends the mathematical model to compute the total uranium and plutonium requirements of the system.

The mathematical model of Chapters II, III, and IV makes it possible to formulate a new method to determine the plutonium value in a case of Balanced Nuclear Economy and is presented in Chapter V.

On the basis of the mathematical model and reactor performance characteristics, Chapter VI analyses a number of nuclear power complex systems for their uranium requirements and plutonium production. A new computer code, called DYNUCLEAR is used to project the analysis quantitatively. Chapter VII is the extension of the previous chapter and focusses its attention on uranium value analysis.

In the end, the conclusions and the suggestions for further advanced study of this subject are presented.

CHAPTER I

NUCLEAR FUEL UTILIZATION

I. A INTRODUCTION :

The growth of nuclear power as postulated in the AEC's report to the President [Ref. 1] and recent revisions of it has focussed attention on U.S. nuclear fuel resources and their efficient utilization. By nuclear fuel utilization is meant the amount of uranium and/or thorium which must be mined to make possible generation of a given quantity of electric energy. This is largest for today's light water reactors, smaller for advanced converter reactors and least for breeder reactors.

The demand for nuclear fuels depends on the rate of growth of nuclear power generation and the installed nuclear power generating capability. The former one corresponds to the inventory requirements of reactors per megawatt of electrical capacity installed and the latter to the net consumption rate of fuel. With a slow rate of growth of nuclear power the fuel problem can be solved by the leisurely development of Pu fueled fast breeder reactors. However, if the rate of growth is higher and if the current estimates of uranim resources are correct in order of magnitude, the solution to the nuclear fuel problem requires both the rapid development of breeder reactors and improvement in fuel utilization by converter reactors. A pessimistic assumption about the rate of growth of nuclear power or an optimistic assumption about the discovery of new uranium resources will be a costly gamble.

Table I. 1 shows the anticipated growth of nuclear power generating capability and the cumulative generated electrical power.

Table I. 1

Anticipated Growth of Nuclear Power in U.S. [Ref. 2]

Year	Installed nuclear power capacity in thousands (M· We)	Cumulative Generated Elec. Power since '65 in billion(M·We·Yrs.)
1965	1.5	0.0
1970	6.5	0.017
1980	75.0	0.298
1990	295.0	1.269
2000	730.0	5.357
2010	1380.0	12.921
2020	2200.0	25.590
2030	3216.0 *	44.825
2040	4611.0 *	72.488

* assumed

The recent AEC's estimates of domestic natural uranium and thorium resources are given in Table I. 2 and Table I. 3 and thus form the basic data of this problem.

Table I.2

U.S. Uranium Resources [Ref. 2] *

Price Range $ per lb of U_3O_8	Reasonably assured	Estimated additional	Total Resources (Rounded)
5-10	470	325	800
10-30	400	500	900
30-50	5,000	3,000	8,000
50-100	6,000	9,000	15,000
100-500	500,000	1,500,000	2,000,000

*All figures in thousand Short Tons of U_3O_8

Table I.3

U.S. Thorium Resources [Ref. 1] *

Price Range $/lb of ThO_2	Reasonably assured	Estimated additional	Total Resources (rounded)
5-10	100	300	400
10-30	100	100	200
30-50	3,000	7,000	10,000
50-100	8,000	17,000	25,000
100-500	1,000,000	2,000,000	3,000,000

* all figures in thousand short tons of ThO_2

A study of these tables of the size of nuclear resources and their energy content suggests that the proper utilization of nuclear resources, if technically possible and available on massive scale, is economically reasonable. Here, however the discussion is limited to the utilization of uranium and bred fissile fuels, although thorium is a potential nuclear fuel.

I. B URANIUM UTILIZATION :

Uranium is required in nuclear reactors for (1) inventory and (2) make-up. The inventory requirements depend on : (a) the specific power of the reactor [MWth/ton of fuel], (b) the thermal efficiency of the reactor, (c) the enrichment of fuel, (d) the ratio of out-of-core inventory to in-core inventory requirements, and (e) the mode of fuel cycle operation. Net make-up requirements depend on (a) thermal efficiency, (b) fuel enrichment, (c) conversion ratio and (d) whether the bred fissile fuel is recycled. It is customary to express the inventory requirements as short tons of natural U_3O_8 per megawatt of electrical capacity installed and specific make-up requirements as short tons of natural U_3O_8 per megawattyear of electricity produced.

(a) Uranium Utilization of Light Water Reactors :

In light water reactors [LWR] such as pressurised water reactors [PWR] and boiling water reactors [BWR], only about one percent of natural uranium mined is utilised i.e. converted to fission products-if bred fissile plutonium is not recycled. If the bred Pu is recycled the utilization increases upto 1.3 percent of mined U. The fuel utilization in LWR is poor mainly because of : (1) low conversion ratio, (2) low value of η for Pu^{239} in thermal reactors and (3) the loss of fissile isotope in diffusion plant tailings. Factors (2) and (3) can not be improved simultaneously because to increase average η one has to increase the enrichment of feed fuel and thus reduce the burnup of Pu in the reactor, but with increased enrichment diffusion plant losses also increase. On the other hand, to decrease the diffusion plant losses by increasing burnup value would decrease η .

It is possible to conclude here that if only LWR were to be installed, the growth of nuclear power forcast in U.S. would require that more than two million short tons of natural uranium be mined by year 2000 [see Fig VII. 2]. As this amount exceeds the present low-cost uranium reserves, improvements in LWR fuel utilization are essential if LWR are to play an important role.

(b) Uranium Utilization & Pu Recycling in LWR :

Although there have been many different conclusions and views regarding the economics and the applications of fissile plutonium, depending on different assumptions regarding (1) the availability of natural resources, (2) the degree of completeness of nuclear industries considered, (3) the objectives of the specific fuel considered, (4) the economics of the system involved, they range from (1) storing the irradiated uranium fuels and not salvaging the plutonium contained for years, (2) recycle Pu in thermal reactors as it becomes available, to (3) accelerating Pu fast breeder development with the available Pu stockpile, to (4) immediate development of Th fueling system as a logical alternative to the uranium fueling systems on the economic basis. Although such views differ very much, Pu is an important nuclear fuel.

Plutonium recycling increases the fuel utilization in U-Pu fueled reactors, although the extension of utilization achievable in this way in LWR has the disadvantages of low value of η of Pu in thermal specturm and also the production of parasitic absorbers U-236 and Pu-242 by radiative capture.

Plutonium recyclihg in LWR will reduce the pressure of great demands for U in long-run, but whether it will be a wise decision is debatable.

Although Pu is a valuable fuel in fast breeder reactors, the incentives for its recycling in thermal reactors are because of :

(a) short term economic considerations
(b) development of recycle technology in both the thermal and fast breeder reactors
(c) need to establish an immediate value for Pu to preserve a favourable economic environment for the development of nuclear power industry.

The determination of Pu value does involve its ancestry and time factor, however the value in successive recycling in LWR is indicated to be in the range of \$10-12/gm of fissile Pu. [Ref 3]

(c) Uranium utilization of Advanced Converter Reactors :

Advanced Converter Reactors [ACR] of the type mainly considered are: Heavy water Organic Cooled[HWOCR] , High Temperature Gas Cooled [HTGR] and Seed Blanket [SBR]. They are of major interest because they make more efficient utilization of natural uranium than do LWR. Although, Fast U-235 fueled reactors are not advanced converter reactors, they are very good substitutes for ACR in a nuclear power complex because they perform the similar functions, and hence will be treated in this catagory.

Table I.4 on next page compares the nuclear fuel utilization in light water reactors and advanced converter reactors.It shows that the inventory and make-up requirements of these advanced converter reactors are less than that of light water reactors. The inventory requiremments, with bred fuel recycled, is about one-fifth in advanced converts of HWOCR-U type, that of the LWR's and that burnup requirements, with bred fuel recycled, in HTGR-Th is one-fifth that of LWR's.

The fuel utilization in these advanced converters is better because of better neutron economy and higher thermal efficiency. The percentage fuel utilization in SBR is as high as fifty times as that of LWR's, and in HTGR-Th as high as five times that of LWR. The product of fuel utilization and thermal efficincy given in last row of Table I.4 is an overall figure of merit.

Table I.5 compares the plutonium production rate for three types of reactors using U-238 as fertile material,without recycling.

Table I.5

Plutonium Production Rate

Reactor Type	Pu Production Rate
LWR	0.32 kgm/MWeYr
HWOCR-U	0.35 "
FAST U-235	0.83 "

It can be seen that ACR of HWOCR-U type are somewhat better to LWR in their plutonium production rate where as FAST

Comparison of Fuel Utilization in LWR and ACR [Ref 2]

Reactor concept	LWR	Advanced converter reactors			
Reactor type [fertile material]	BWR/PWR [U-238]	HWOCR [U-238]	HTGR [Th]	SBR [Th]	FAST U-235 [U-238]
Nat U Inventory Req. (ST U_3O_8/MWe) Bred fuel recycled	0.7-1.0 (ILWRC)*	0.20 (IHWRC)	0.6-0.9 (IHTRC)	0.7-1.0	-
Nat U Inventory Req. (ST U_3O_8/MWe) Bred fuel not rec	1.0 (ILWWR)	0.33 (IHWWR)	-	-	1.44 (INFUR)
Nat U Burnup Req. (ST U_3O_8/MWeYr) Bred fuel recycled	0.13-0.16 (BLWRC)	0.09 (BHWRC)	0.025-.04 (BHTRC)	0.09#	-
Nat U Burnup Req. (ST U_3O_8/MWeYr) Bred fuel not rec.	0.25 (BLWWR)	0.15 (BHWWR)	-	-	0.23 (BNFUR)
Thermal efficiency (percentage)	31	33	44	31	?
Fuel Utilization (percentage)	1-1.3	2	3-5	50-55	
Eff. x Utilization (percentage)	$\frac{30-40}{100}$	$\frac{66}{100}$	$\frac{130-200}{100}$	$\frac{1600-1700}{100}$	

* Abbrevations used in this thesis

\# For first five years, zero thereafter.

Table I.4

U-235 fueled reactors are almost two and half times better than LWR's. In the ACR of HTGR-Th type, it is more economical to recycle the bred fissile U-233. The HWOCR-U type ACR may thus prove to be of more importance, because of their flexibility in the use of their bred fissile plutonium, than HTGR-Th type of advanced converter reactors.

I. C THE IMPACT OF ACR IN NUCLEAR POWER COMPLEX :

The importance of ACR's in nuclear power complex is for the following reasons :

[1] The introduction of ACR's will mark as an important step in the development of nuclear technology and the power programme. ACR will stand as an intermediate step between the development of fast breeders and LWR's.

[2] The ACR's show a fuel cost advantage with respect to LWR's. This cost differential will be substantial in long-run and will counterbalance the higher capital costs of ACR's. At higher U prices the economic advantage of ACR over LWR will be still greater.

[3] The more efficient utilization of U in ACR's will lower the absolute fuel requirements as compared with that of LWR's.

The development of ACR's will thus :

[a] achieve the timely introduction of advanced technology into the growing nuclear complex with reduced costs

[b] reduce the absolute requirements for fissile material mined from the ground, thus extending the availability of nuclear

mined from the ground, thus extending the availability of nuclear fuels.

[c] permit the use of higher cost nuclear fuel resources while still producing the low cost energy and thus expanding the energy resource base.

[e] lengthen the time during which low-cost natural U could be made available for use in the present reactors until the fast bredders are commercially available.

[f] be able to supply the high initial plutonium inventory requirements of large fast breeders to be developed at later stage, because of their higher conversion ratio.

[g] ACR's will not only supply the initial high Pu inventory requirements of breeders but will also supply a major part of Pu needed for the later installations of breeders and will continue to do so till the breeders become self-sustaining for their inventory requirements i.e. till the doubling time of breeders becomes equal to the doubling time of nuclear power growth.

[h] also have a brddding gain (in SBR's) sufficient to compensate for recycle losses or atleast attain high conversion ratios. This has the advantage over LWR because, with increasing uranium prices, the optimum conversion ratio for the minimized fuel cost can be gradually made to approach the breeding.

[i] be less sensitive to variations in U prices. ACR's are only about half as sensitive to U prices as LWR's i.e. a given

increase in the cost of natural uranium increases the cost of energy from current types of LWR's twice as much as it increases that of the ACR's.

I. D PLUTONIUM UTILIZATION :

Although it was suggested previously that plutonium recycling in LWR will reduce the total uranium requirements, the fuel characterstics of Pu make it more suitable for use in fast reactor spectrum than in thermal reactors.

The important Pu isotopes produced are : Pu-239, Pu-240, Pu-241 and Pu-242 whose percentage compositions largely depend on the reactor concept and the maximum burnup achieved, but for illustration purpose, they are in the order of 70-80%, 15-20 %, 3-5%, and 1-3%, of total plutonium produced, respectively.

In summary, following are their characterstics:

Pu-239 is a satisfactory fissile material in thermal reactors and is an outstanding fuel in fast reactors.

Pu-240 is a valuable fertile material in thermal reactors although a strong absorber, and is a fissile material in most fast reactors. Fissile Pu-240 is superior to U-238 in fast reactors.

Pu-241 is an excellent fissile material in thermal and fast reactors, except for its relatively short half life of 13 years.

Pu-242 is a parasitic neutron absorber in thermal reactors (although the resulting Am-243 leads to a possible valuable decay heat source- Curium-244) and is likely a useful fissile fuel in fast reactors.

Plutonium has a considerably higher conversion ratio in fast spectrum and hence is more valuable in fast reactors than in thermal reactors. Increasing the overall conversion ratio of reactor complex system (as in BNE) leads to :

[a] reduction in fuel burnup cost due to the increase in energy fraction produced by converted fertile material.

[b] reduction in required initial fuel inventory cost for a given reactivity life time because of improved burnup value.

[c] reduction in fabrication and reprocessing cost per MWth of heat produced because of higher reactivity lifetime achieved.

[d] improved fuel utilization.

It is thus possible to infer that, when uranium utilization is improved because of its use in ACR's the plutonium produced is of especially high value in fast reactors. Better utilization of uranium in ACR's is thus synonymous with the better plutonium utilization in fast breeders.

An especially attractive feature of Pu fueled fast breeders is that they have very high fuel utilization efficiency, as high as 80 %. The utilization does not reach 100% because of losses in fabrication, reprocessing and because of conversion of Pu-242 to Am-243. The breeding ratio in breeders, itself is not important to utilization as long as it exceeds a threshold level such that the breeding gain somewhat exceeds the recycling losses; however, it is important from the point of view of:

[1] the breeder inventory requirements, since a short fissile inventory doubling time reduces the dependence of plutonium fueled breeders on an external supply of Pu.

[2] sensitivity of fuel costs to the cost of natural U, since the shorter the doubling time of breeders the lower will be the sensitivity of breeder fuel costs to the costs of U, and

[3] self-sufficiency in fuel requirements , since a higher breeding gain will make the system self-sufficient much earlier.

[4] utilization of already built stockpile of depleted U.

I. E FUEL UTILIZATION IN BALANCED NUCLEAR ECONOMY :

Since advanced converters make better use of natural U and also are better plutonium produceds than light water reactors, and since fast breeders make much better use of plutonium than either, it is much desirable to use advanced converters and fast breeders together in such a way, that the plutonium produced by advanced converters is used to provide the plutonium inventory needed in starting up an increasing amount of fast breeder capacity. We will call an arrangement in which the rate of growth of breeders is determined by the rate at which plutonium becomes available from operating light water, advanced converter and breeder type of reactors, a "Balanced Nuclear Economy", (Ref 4). Fig I.1 shows schematically the flow of uranium and Pu in such a Balanced Nuclear Economy (BNE). It shows that the plutonium inventory requirements of a rapidly increasing number of fast breeders are satisfied by using reactor grade plutonium produced in the LWR's and ACR's, together with the net plutonium produced in the breeders. A delay of three years

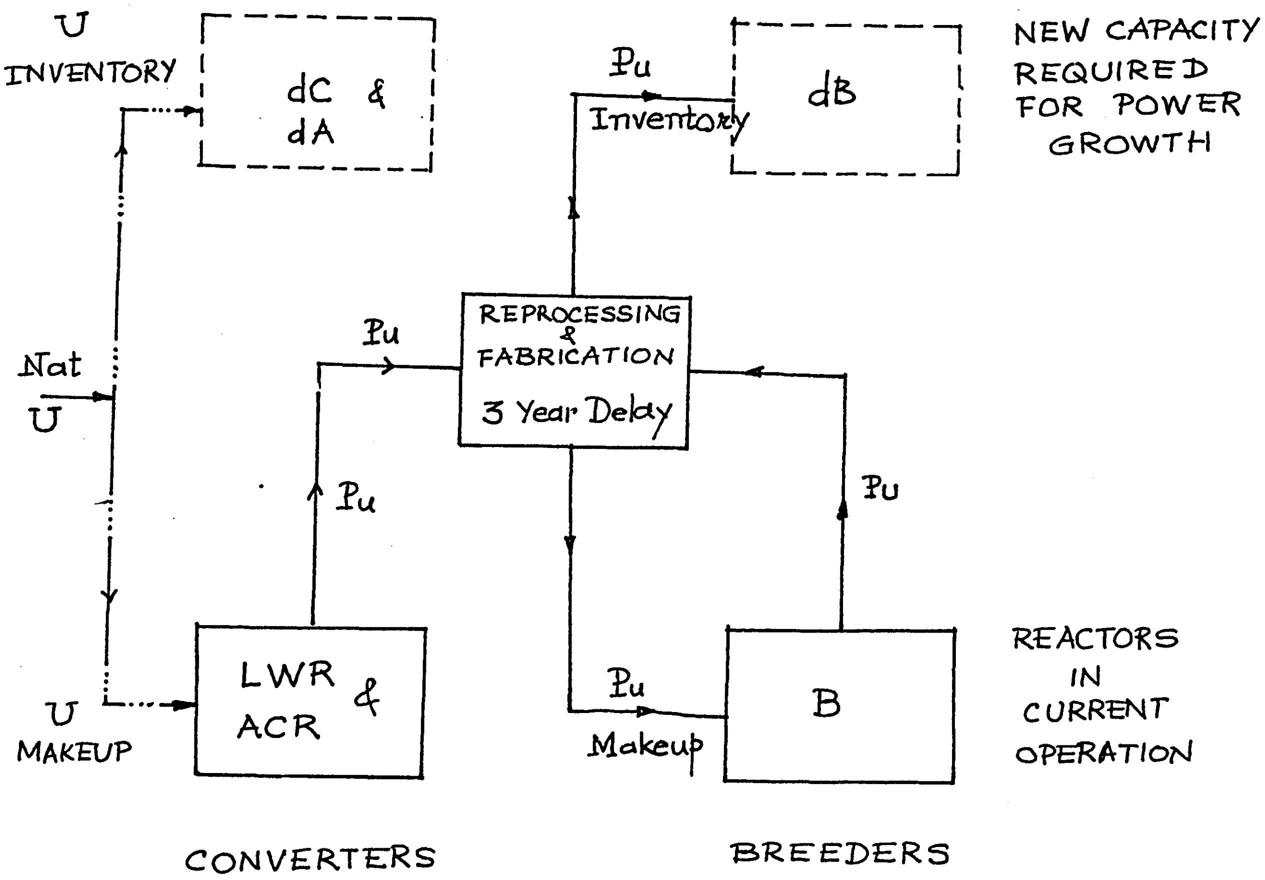


Fig I.1 : Fuel utilization in BNE

because of cooling, reprocessing and fabricating time is assumed between the actual production of plutonium and its reuse in the breeder inventory.

The condition of BNE is thus :

Demand for plutonium in the inventory requirement of new breeder installations every year	=	supply of plutonium produced in LWR, ACR and breeder reactors, three years earlier.

or alternatively,

$$I_b \frac{d}{dt}[B(t+\delta)] = c\,C(t) + a\,A(t) + b\,B(t) \qquad \text{Kgm/yr} \qquad \ldots\ldots\ldots\ldots\text{Eq I.1}$$

where,

I_b : specific plutonium inventory requirement in breeder reactors kgms/MWe

a, b, c : net fissile plutonium production rate in ACR's, Breeders and LWR's respectively kgms/MWeYr

A(t), B(t), C(t) : total installed nuclear MWe capacity in ACR's, Breeders and LWR's respectively

δ : delay in production of Pu and its reuse in breeders as inventory, yrs

This scheme of BNE has following advantages :

[1] It will provide an economic interaction between Pu producers (LWR and ACR) and users (breeders) since, producers will find it more profitable to sell their byproduct Pu to its more efficient users than to recycle it themselves in lieu of U-235. More efficient users of Pu will also demand it and would be able to pay higher prices for it.

[2] With a free market for byproduct Pu between its suppliers and demanders the plutonium stockpile will remain at zero and thus unintended investments in Pu will be eliminated.

[3) Market clearing mechanism will determine price for plutonium thus reducing the uncertainty in its production and/or consumption in stockpiling or recycling.

[4] With efficient fuel utilization and reduced fuel costs

the cost of power generation will be substantially reduced-in both ACR's as well as in Breeders. Hence, the share of nuclear power will be higher than in a non-BNE case.

[5] With BNE, the fast reactors will be fed by depleted uranium from the diffusion plant tailings which otherwise would be rapidly stockpiled and wasted. No natural uranium will be required for fast reactors since an adequate supply of depleted uranium will exist as a result of enriched uranium required in non-fast reactors. This ability of fast reactors to utilise completely the uranium tailings without any economic costs results in best utilization of uranium in BNE.

[6] In these respects, BNE promises major conservation of natural energy resources after the turn of the century without increasing energy costs.

[7] The fast breeder power generating costs are themselves insensitive to changes in uranium price because it uses very little uranium and with BNE, it literally burns the zero value tailings produced in the diffusion plant enrichment process.

This scheme of BNE however may not continue indefinitely, because it is expected that the relative growth rate of nuclear power will decrease as time goes on and the time may come when the rate at which plutonium is needed as inventory for breeder installations becomes too low to consume all of the net plutonium produced in light water reactors, ACR's and existing Breeders. In other words, time may come when the doubling time of breeders will be the higher than the doubling time of growth rate of nuclear power. When this happens, a plutonium surplus will begin to develope, as soon as all the ACR's are completely retired, not needed anymore.

I. F FUEL UTILIZATION IN INTEGRATED BALANCED NUCLEAR ECONOMY :

When, in a Balanced Nuclear Economy, the rate at which Pu is required as inventory for new breeders becomes too low to consume the net Pu production rate in converters and existing breeders, a stockpile of unused Pu starts developing. Rather than allowing this unintended investment in Pu to rise, it will be desirable to use this excess Pu as enriched feed in newly installed ACR's in order to reduce their fissile makeup requirements. In fact, it will be possible, to reduce the fissile makeup requirements tof the ACR's to zero, if the rate at which they are introduced is limited by the rate at which excess Pu becomes available from the breeders. A flowsheet representing this situation is shown in FigI. 2. If it is economically desirable to generate a larger fraction of the total power required in ACR's, this can be done by using enriched uranium to supplement the excess Pu from breeders. A nuclear power complex in which the plutonium stockpile is kept from increasing further by this kind of balance between the rate at which advanced converters and breeders are added to the system will be called an " Integrated Balanced Nuclear Economy [IBNE] ".

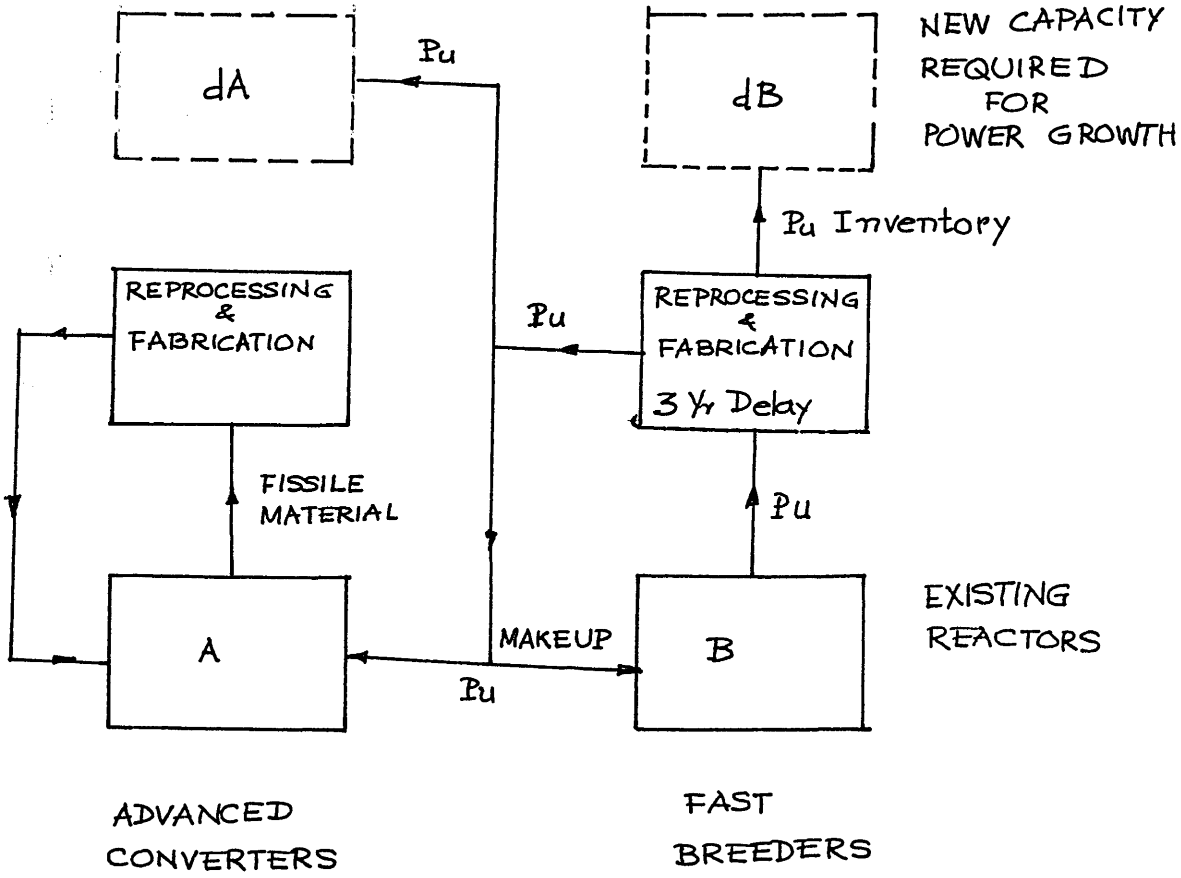


Fig I. 2: Fuel utilization in IBNE

The extent to which enriched uranium will be used as supplementary feed and the relative rates at which advanced converters and breeders will be built depends on many technical and economic factors, included are the unit capital costs of the two types of reactor (more favourable for ACR's), their specific power ratings(more favorable for ACR's), their fuel cycle costs (more favorable for breeders), uranium prices and load factors. High U prices favor breeders whereas low load factors favor converters.

This scheme has following advantages in addition to that of earlier BNE :

[1] Plutonium stockpile is still kept at zero, reducing the unintended investments.

[2] A competitive market for plutonium will be still maintained thus avoiding a heavy disruptive depreciation in plutonium value.

[3] With IBNE and ACR's in the nuclear power complex the penalty on highly capital intensive breeders because of decreasing load factors will be lesser than without it.

[4] Through optimisation between load factor effects, specific fissile fuel ratings, breeding and conversion ratios, the IBNE will offer an added degree of freedom on the choice of the local conditions and various parameters, provided enriched uranium is available for use in variable amount to supplement plutonium as fissile feed.

CHAPTER II

DYNAMICS OF GROWTH OF NUCLEAR POWER

II. A TERMINOLOGY

A_i (t), B_i (t) & C_i (t)	Established total Advanced-converter-thermal reactor, Breeder-reactor and light-water Converter reactor power capacity, at time t during ith phase of growth. (MWe).
a, b, c	Net reactor grade fissile plutonium production rate in A, B & C reactors, respectively (Kgms/MWeyr).
λ_i	Nuclear power growth rate constant during phase i (fraction/yr)
i	subscript for i th phase of growth
GRX_i (t)	Growth rate in X type of reactors during i th phase of growth (dX_i/dt) (MWe/yr).
$FTNCX_i$	Fraction of total new nuclear capacity in new X type of reactors = GRX_i / GRP_i (fraction).
P_i (t)	Total established nuclear power generating capacity at time t, during i th phase (MWe).
$STPCX_i$	The share of total established power capacity in X type of reactor = X_i (t)/P(t).

II. B THE MATHEMATICAL MODEL

It is assumed that the total established nuclear power generating capacity is given by an exponential function like

$$P(t) = P_o e^{\lambda t} \quad \text{MWe} \qquad (\text{II}.1)$$

The complete time interval is then broken in a number of different phases, followed in sequence, depending upon different assumptions. λ remains constant in one particular phase but changes with different phases, and thus looks like a step-down function of time. Although different assumptions are made regarding the installed capacities of different types of reactors in different phases, there is a gradual transition from LWR to ACR to Breeder reactor installations. For simplicity only one type of ACR is assumed although in actual case it need not be so. The time interval of different phases is not necessarily the same and for simplicity the reactor plant life is assumed to be infinite. This implies that all retiring reactors will be re-installed. This is not a realistic assumption but serves the purpose of illustration of the growth of nuclear power in a simple mathematical model like this.

Figure II.1 and Table II.1 summarise the assumptions of this model.

II.C FIRST PHASE OF GROWTH

Total installed nuclear power capacity, all of LWR's is given by:

$$P_1(t) = P_o e^{\lambda_1(t - t_o)} = C_1(t) \quad \text{MWe} \qquad \text{(II. 2)}$$

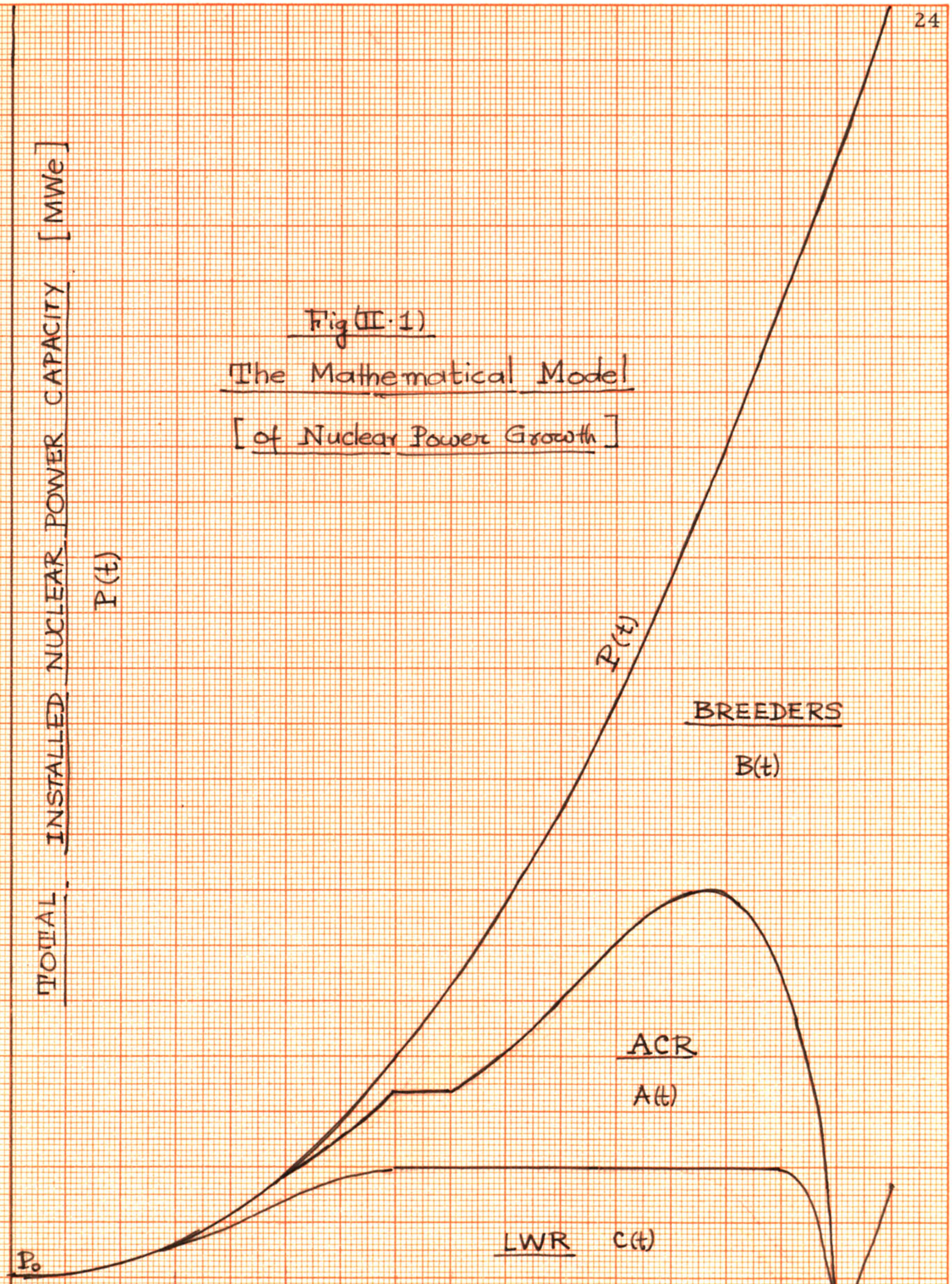


Fig (II·1)

The Mathematical Model

[of Nuclear Power Growth]

Summary of Assumptions of the Mathematical Model

Phase no.	Time int.	Growth const.	Condition on the growth of LWRs	ACRs	Breeders	Use of Plutonium stockpile
I	$t_0 - t_1$	λ_1	Provide all power	None built	None built	None, Pu stockpile accumulated.
II	$t_1 - t_2$	λ_2	Provide balance of power	Built to the extent of f fraction of new capacity in first yr, 2f in second year and so on	None built	"
III	$t_2 - t_3$	λ_3	"	$(t - t_1 + 1)f$ fraction of new nonbreeder capacity in first yr, and so on	Example, new breeder capacity $= 2x(t-t_2)$	Pu begins to go in breeders.
IV	$t_3 - t_4$	λ_4	No new LWRs	No new ACRs	All new capacity of Breeders	Pu stockpile goes to zero at t_4.
V	$t_4 - t_5$	λ_5	"	ACRs and Breeders built to keep Pu stockpile at zero as in BNE		Pu stockpile kept zero in BNE.
VI	$t_5 - t_6$	λ_6	"	New capacity is mainly of Breeders rest are ACRs to keep Pu stockpile zero.		Excess Pu fed to ACRs, no stockpile.

Table II.1

Summary of Assumptions of the Mathematical Model

and at time t_1,

$$P_1(t_1) = P_{11} = C_{11} = P_o e^{\lambda_1(t_1 - t_o)} \text{ MWe} \qquad \text{(II. 3)}$$

The new established total nuclear capacity every year is the growth rate, and is :

$$GRP_1(t) = GRC_1(t) = dP_1/dt = \lambda_1 P_1(t) \text{ MWe/yr} \qquad \text{(II. 4)}$$

The fraction of growth in LWRs is

$$GRC_1(t)/GRP_1(t) = 1 \qquad \text{(II. 5)}$$

The share of LWR capacity in total established nuclear power is :

$$STPCC_1 = C_1(t)/P_1(t) = 1 \qquad \text{(II. 6)}$$

II. D SECOND PHASE OF GROWTH :

Total established power is

$$P_2(t) = P_{11} e^{\lambda_2(t - t_1)} \qquad \text{MWe} \qquad \text{(II. 7)}$$

and at t_2, $P_2(t_2) = P_{22} = P_{11} e^{\lambda_2(t_2 - t_1)}$ MWe (II. 8)

The growth rate is, $GRP_2(t) = dP_2/dt = \lambda_2 P_2(t)$ MWe/yr (II. 9)

The growth rate of advanced converters is assumed to increase linearly such that - during first year it is ten percent of total growth rate, during second year it becomes twenty percent and so on until time t_2.

Hence,

$$GRA_2(t) = dA_2/dt = [(t - t_1) f] [\lambda_2 P_2(t)] \text{ MWe/yr} \qquad \text{(II. 10)}$$

where f is fraction/yr = 0.1 in this study.

Hence,

$$A_2(t) = \int_{t_1}^{t} [dA_2/dt] \, dt$$

$$= \int_{t_1}^{t} f \lambda_2 P_{11} (t - t_1) e^{\lambda_2(t - t_1)} dt$$

$$= [f P_{11}/\lambda_2] \left\{ 1 + [\lambda_2(t - t_1) - 1] e^{\lambda_2(t - t_1)} \right\} \qquad \text{(II. 11)}$$

Balance being LWRs, $C_2(t) = P_2(t) - A_2(t)$ MWe (II.12)

The share of total established power of A_2 reactors is

$$STPCA_2(t) = A_2(t)/P_2(t)$$

$$= [\,f/\lambda_2\,]\;[\,\lambda_2(t-t_1) + e^{-\lambda_2(t-t\ )} - 1\,] \qquad (II.13)$$

and of C_2 reactors is, $1 - STPCA_2(t)$

The fraction of growth in A_2 reactors is

$$FTNCA_2(t) = GRA_2(t)/\,GRP_2(t) = f\,(t-t_1) \qquad (II.14)$$

and in C_2 reactors is

$$FTNCC_2(t) = 1 - f\,(t-t_1) \qquad (II.15)$$

II. E THIRD PHASE OF GROWTH :

Total nuclear power is $P_3(t) = P_{22}\, e^{\lambda_3(t-t_2)}$ MWe (II.16)

and at time t_3 is , $P_{33} = P_{22}\, e^{\lambda_3(t_3-t_2)}$ (II.17)

Total growth rate is $GRP_3(t) = \lambda_3 P_3(t)$ MWe/yr (II.18)

It is envisaged at this stage that- (1) commercial breeders will be available by this time and (2) a huge plutonium stockpile could be utilised to install breeders more rapidly at later stage. Depending on the economic attractiveness of breeders, the risk in installing them, and the plutonium stockpile available at that time, new breeders will be installed initially at a much smaller growth rate but will increase later. The growth of breeders could be represented by a linear law or an arithmatic progression or geometric progression or some other combination, depending upon the particular situation.

For illustration purpose a linear growth rate has been assumed, and thus,

$$GRB_3(t) = dB_3/dt = 2x(t - t_2) \quad \text{MWe/yr} \qquad (\text{II.}19)$$

where x is the unit size constant of breeder reactors in yr^{-2}.

Integrating the above equation,

$$B_3(t) = \int_{t_2}^{t} 2x(t - t_2)\,dt$$

$$= x(t - t_2)^2 \qquad \text{MWe} \qquad (\text{II.}20)$$

Of the remaining growth, a fraction is of advanced converter installations, such that - the fraction f continues to grow with the same law as in the previous case, thus , if second and third phases are each of five years, during the first year of third phase the new advanced converter installation will be sixty percent of total growth left after breeder installations; during the second year it will rise to seventy perceent and so on.

or,
$$GRA_3(t) = f(t - t_1)[\lambda_3 P_3(t) - 2x(t - t_2)] \qquad (\text{II.}21)$$

Hence,
$$A_3(t) = A_{22} + \int_{t_2}^{t} f(t - t_1)[\lambda_3 P_3(t) - 2x(t - t_2)]\,dt$$

or
$$= A_{22} + [f P_{22}/\lambda_3][\lambda_3(t - t_1) - 1]\, e^{\lambda_3(t - t_2)}$$
$$- 2fx\left\{[(t^3 - t_2^3)/3] - [(t_1 + t_2)/2][t^2 - t_2^2] + t_1 t_2 (t - t_2)\right\} \qquad (\text{II.}22)$$

Balance being LWRs,

$$C_3(t) = P_3(t) - B_3(t) - A_3(t) \qquad (\text{II.}23)$$

similarly,
$$GRC_3(t) = GRP_3(t) - GRB_3(t) - GRA_3(t) \qquad (\text{II.}24)$$

From these equations it is possible to compute the share and the fractional growth in each individual reactor type.

II. F FOURTH PHASE OF GROWTH :

If some unused plutonium remains in stockpile after third phase, in the fourth phase it will be used to install all new reactor capacity of breeders. The fourth phase thus becomes applicable only if there exists a huge plutonium stockpile after the third phase. Fourth phase will continue until the Pu stockpile has been reduced to zero or to some limiting practical value.

Total installed nuclear power is $P_4(t) = P_{33}e^{\lambda_4(t-t_3)}$ MWe (II. 25)

and the growth rate is, $GRP_4(t) = \lambda_4 P_4(t)$ MWe/yr (II. 26)

Since all new installed capacity is of breeders,

$$GRB_4(t) = GRP_4(t)$$

Hence, $$B_4(t) = B_{33} + \int_{t_3}^{t} P_{33}e^{\lambda_4(t-t_3)}$$

or, $$= B_{33} + P_{33}[e^{\lambda_4(t-t_3)} - 1] \qquad \text{(II. 27)}$$

Also,

$$GRA_4(t) = GRC_4(t) = 0 \qquad \text{(II. 28)}$$

and, $$A_4(t) = A_{33} \quad , \quad C_4(t) = C_{33} \qquad \text{(II. 29)}$$

The time t_4 upto which this phase will take place will be determined by the balance between breeder inventory requirements and existing plutonium stockpile. If the stockpile is say $PuSP(t_4)$ by the time t_4, then,

$$PuSP(t_4) = \int_{t_3}^{t_4} I_b[dB_4/dt]\, dt$$
$$= \lambda_4 I_b \int_{t_3}^{t_4} P_4(t)\, dt$$

from which,

$$t_4 = t_3 + (1/\lambda_4)[\ \ln \frac{PuSP(t_4) + I_b P_{33}}{I_b\ P_{33}}\ ] \qquad \text{(II. 30)}$$

II. G FIFTH PHASE OF GROWTH :

This is the case of Balanced Nuclear Economy, balancing the plutonium production rate and consumption rate δ years later, i.e.

$$I_b \frac{d}{dt}[\,B_5(t+\delta)] = 1\,[\,a\ A_5(t) + b\ B_5(t) + c\ C_5(t)\,] \qquad \text{(II. 31)}$$

Assuming $C_5(t)$ constant for convenience, this equation can be solved for $B_5(t)$ and $A_5(t)$. The detailed discussion is given in the next chapter on BNE. For the assumed value of λ in this study, the number of ACR capacity will eventually drop down to zero, and after that time a plutonium surplus will start to develop. This phase operates until ACR capacity goes to zero, holding the net plutonium stockpile constant.

II. H SIXTH PHASE OF GROWTH :

This is the case of Integrated Balanced Nuclear Economy [IBNE] where the excess of plutonium is fed to newly established advanced converter reactors. In this phase, a major fraction of new installations will be of breeders, the rest being of ACRs. The extent to which new ACRs are installed would depend on : the excess fissile plutonium, the capital costs of breeders and ACRs, their fuel cycle costs and the load factor.

CHAPTER III

BALANCED NUCLEAR ECONOMY

[I]

We have defined a Balanced Nuclear Economy (BNE) as one in which the rate at which plutonium is produced in converter and breeder reactors just equals the rate at which it is consumed in providing inventory to fuel new breeder reactors, three years later. The purpose of this chapter is to derive explicit expressions for the variation with time of the amounts of power generated in converter and breeder reactors in a balanced nuclear economy and to determine the conditions under which it is possible to maintain a balanced nuclear economy. The effect of reactor performance characteristics on the condition of BNE is also studied.

The total nuclear power generating capacity is assumed to be,

$$P(t) = P_o e^{\lambda t} \qquad \text{(III.1)}$$

where t is the time in years after the BNE starts and P_o is the total generating capacity at t = 0.

The condition of BNE is expressed in terms of the plutonium material balance

$$I_b \frac{d}{dt}[B(t+\delta)] = 1[a A(t) + b B(t) + c C(t)] \qquad \text{(III.2)}$$

where

$B(t)$ = generating capacity of breeders at t

$A(t)$ = generating capacity of ACR's at t

$C(t)$ = generating capacity of LWR's at t

b, a and c = net kgm of plutonium produced per MWeyr of electricity generated in these respective types of reactors

l = load factor

I_b = breeder specific plutonium inventory in kgm/MWe

δ = delay in years between production of plutonium and its availability for use as inventory in breeders

We shall assume that LWR capacity C is constant at its value C_o at $t = 0$ and that the total generating capacity P(t) is

$$P(t) = A(t) + B(t) + C_o \tag{III. 3}$$

Further, we define

$$\alpha = l\,a/I_b \tag{III. 4}$$

$$\beta = l\,b/I_b \tag{III. 5}$$

and

$$\gamma = l\,c/I_b \tag{III. 6}$$

Note that β is the reciprocal of the doubling time for the breeders. Thus, rewriting Eq. (III. 2),

$$\frac{d}{dt}[B(t+\delta)] = \alpha A(t) + \beta B(t) + \gamma C_o \tag{III. 7}$$

$$= \alpha P(t) + (\beta - \alpha)B(t) + (\gamma - \alpha)C_o \tag{III. 8}$$

This equation can be solved for B(t) by either of the three methods: (1) step-by - step solution, (2) Asymptotic solution and (3) Laplace transforms. The former two will be discussed here.

Step-by-step Solution:

Equation (III. 8) can be solved by integrating it successively through the time intervals between 0 and δ, between δ and 2δ, etc. For example, if B(t) between $-\delta$ and 0 is denoted by $B^{(0)}(t')$ and B(t) during the interval between 0 and δ is denoted by $B^{(1)}(t)$, Eq. (III, 8) may be integrated to give:

$$B^{(1)}(t) = B^{(0)}(0) + \int_{-\delta}^{-\delta+t} [\alpha P(t') + (\beta - \alpha) B^{(0)}(t')]\, dt' + (\gamma - \alpha) C_0\, t \qquad 0 < t < \delta \qquad \text{(III. 9)}$$

With $B^{(1)}(t)$ obtained in this way between 0 and δ, $B^{(2)}(t)$ in the next interval between δ and 2δ can be calculated by another integration:

$$B^{(2)}(t) = B^{(1)}(\delta) + \int_{0}^{t} [\alpha P(t') + (\beta - \alpha) B^{(1)}(t')]\, dt' + (\gamma - \alpha) C_0\, (t) - \text{[illegible]}\,) \qquad \delta < t < 2\delta \qquad \text{(III. 10)}$$

Similarly $B^{(3)}(t)$ in the interval between 2δ and 3δ can be obtained by integrating $B^{(2)}(t)$ etc.

This sequence of solutions gives rather little insight into the general way in which the breeder capacity B(t) or ACR capacity $A(t) = P(t) - B(t) - C_0$ changes with time, because of the discontinuity in the functional form for their dependence on time which occurs at δ, 2δ, 3δ, etc. Better insight into the variation of B(t) and A(t) can be had from an asymptotic solution of Eq. (III. 8).

Asymptotic Solution:

An asymptotic solution of Eq. (III. 8) is valid for $t \gg \delta$ and holds for all $t > \delta$ for a particular set of values of B in the interval $-\delta < t < 0$. When P(t) is given by Eq. (III. 1) this asymptotic solution is of the form

$$B(t) = k_1 + k_2 e^{\lambda t} + k_3 e^{\mu t} \qquad \text{(III. 11)}$$

It will be shown that Eq. (III. 11) is a solution of Eq. (III. 8) by substituting Eq. (III. 1) and Eq. (III. 11) into Eq. (III. 8) and finding values for the constants k_1, k_2, k_3 and μ which satisfy the resulting equation identically.

The result of making these substitutions is

$$\begin{aligned} & [\, k_2 \lambda e^{\lambda\delta} - \alpha P_o - (\beta - \alpha) k_2 \,]\, e^{\lambda t} \\ + & [\, k_3 \mu e^{\mu\delta} - (\beta - \alpha) k_3 \,]\, e^{\mu t} \\ + & [\, (\alpha - \beta) k_1 + (-\gamma + \alpha) C_o \,] \end{aligned} = 0 \qquad \text{(III. 12)}$$

For this equation to be valid at all t, it is necessary and sufficient that each term in brackets vanish separately. Thus, k_2 is given by

$$k_2 = \frac{\alpha P_0}{\alpha - \beta + \lambda e^{\lambda\delta}} \qquad (\text{III}\cdot 13)$$

μ is the solution of transcendental equation :

$$\mu e^{\mu\delta} = (\beta - \alpha) \qquad (\text{III}\cdot 14)$$

and k_1 is given by

$$k_1 = \frac{(\alpha - \gamma)\, C_0}{\beta - \alpha} \qquad (\text{III}\cdot 15)$$

k_3 is determined from the initial condition, that

$$B(0) = B_0 \ , \qquad (\text{III}.16)$$

$$\begin{aligned} k_3 &= B_0 - k_1 - k_2 \\ &= B_0 - \frac{(\alpha - \gamma)\, C_0}{\beta - \alpha} - \frac{\alpha P_0}{\alpha - \beta + \lambda e^{\lambda\delta}} \qquad (\text{III}.17) \end{aligned}$$

Hence

$$\begin{aligned} B(t) = {} & \frac{(\alpha - \gamma)\, C_0}{\beta - \alpha} + \frac{\alpha P_0 e^{\lambda t}}{\alpha - \beta + \lambda e^{\lambda\delta}} \\ & + \left[B_0 - \frac{(\alpha - \gamma)\, C_0}{(\beta - \alpha)} - \frac{\alpha P_0}{\alpha - \beta + \lambda e^{\lambda\delta}} \right] e^{\mu t} \qquad (\text{III}\cdot 18) \end{aligned}$$

This asymptotic solution will hold for all $t > 0$, provided $B(t)$ has this dependence on t for the interval $-\delta < t < 0$.

The corresponding solution for A(t) is obtained from

$$A(t) = P_0 \ e^{\lambda t} - B(t) - C_0 \qquad (\text{III}.19)$$

$$\begin{aligned} = {} & \frac{(\gamma - \beta)\, C_0}{(\beta - \alpha)} + \left[1 - \frac{\alpha}{\alpha - \beta + \lambda e^{\lambda\delta}} \right] P_0 \, e^{\lambda t} \\ & - \left[B_0 + \frac{(\gamma - \alpha)\, C_0}{(\beta - \alpha)} - \frac{\alpha P_0}{\alpha - \beta + \lambda e^{\lambda\delta}} \right] e^{\mu t} \end{aligned}$$

$$(\text{III}\cdot 20)$$

The behaviour of Eqs (III.18) and (III.20) for the breeder capacity B(t) and ACR capacity A(t) depends principally on the magnitudes of μ and $\frac{\alpha}{\alpha-\beta+\lambda e^{\lambda\delta}}$, because for the cases we are interested in C_0 is so small as to be negligible.

Let us define,

$$\xi \equiv \frac{\alpha}{\alpha-\beta+\lambda e^{\lambda\delta}} \qquad \text{(III. 21)}$$

It is clear from this equation that,

Case I : when $\lambda e^{\lambda\delta} < (\beta-\alpha)$, $\xi < 0$ (III. 22)

Case II : when $(\beta-\alpha) < \lambda e^{\lambda\delta} < \beta$, $1 < \xi$ (III. 23)

Case III : when $\beta < \lambda e^{\lambda\delta}$, $0 < \xi < 1$ (III. 24)

Further, from equation

$$\mu e^{\mu\delta} = (\beta-\alpha)$$

it is evident that,

when $\alpha < \beta$, $\mu > 0$ (III. 25)

when $\beta < \alpha$, $\mu < 0$ (III. 26)

when $\beta-\alpha < \lambda e^{\lambda\delta}$, $\mu < \lambda$ (III. 27)

and when, $\lambda e^{\lambda\delta} < \beta-\alpha$, $\mu > \lambda$ (III. 28)

Thus, in conclusion, the relative magnitudes of α, β and $\lambda e^{\lambda\delta}$ determine the character of the time dependence of B(t) and A(t).

Table (III.1) distinguishes these three different cases:

Table (III.1)

Case		
I	$\lambda e^{\lambda\delta} < \beta-\alpha$,	$\mu > \lambda$ & $\xi < 0$
II	$\beta-\alpha < \lambda e^{\lambda\delta} < \beta$,	$\mu < \lambda$ and $1 < \xi$
III	$\beta < \lambda e^{\lambda\delta}$,	$0 < \xi < 1$ and $\mu < \lambda$

Note that since λ and $\lambda e^{\lambda\delta} > 0$, Case I can occur only when $\beta-\alpha > 0$, i.e. plutonium production rate in breeders is higher than that in advanced converters.

[II]

To examine the way A(t) and B(t) vary with time, for differnt values of ξ , we will simplify Eqs(III.18) and (III.20) by setting $C_0 = 0$. Thus,

$$B(t) = \xi P_0 e^{\lambda t} + P_0 \left[\left(\frac{B_0}{P_0}\right) - \xi \right] e^{\mu t} \qquad \text{(III.29)}$$

$$A(t) = (1-\xi) P_0 e^{\lambda t} - P_0 \left[\left(\frac{B_0}{P_0}\right) - \xi \right] e^{\mu t} \qquad \text{(III.30)}$$

The new breeder installations every year is the growth rate and is :

$$GRB(t) = dB/dt = \xi \lambda P_0 e^{\lambda t} + \mu P_0 \left[\left(\frac{B_0}{P_0}\right) - \xi \right] e^{\mu t} \qquad \text{(III.31)}$$

The new ACR installations every year will be the remaining growth rate, and is :

$$GRA(t) = dA/dt = \lambda(1-\xi)P_0 e^{\mu t} - \mu P_0 \left[\left(\frac{B_0}{P_0}\right)-\xi\right] e^{\mu t} \qquad \text{(III. 32)}$$

The share of total established nuclear power capacity in breeders is :

$$STPCB(t) = B(t)/P(t) = \xi + \left[\left(\frac{B_0}{P_0}\right)-\xi\right] e^{(\mu-\lambda)t} \qquad \text{(III. 33)}$$

and similarly in ACRs is :

$$STPCA(t) = A(t)/P(t) = 1 - [B(t)/P(t)]$$

$$= 1 - \xi - \left[\left(\frac{B_0}{P_0}\right)-\xi\right] e^{(\mu-\lambda)t} \qquad \text{(III. 34)}$$

Now, consider the above mentioned three cases :

[A] Case III : In this case, $\beta < \lambda e^{\lambda\delta}$, ξ is a positive fraction and $\mu < \lambda$. The share of total established nuclear capacity in ACRs [STPCA(t)] changes monotonically from $1 - (B_0/P_0)$ at $t = 0$ to $1 - \xi$ at $t \to \infty$. The share of total nuclear capacity in breeders [STPCB(t)] changes correspondingly from B_0/P_0 at $t = 0$ to ξ as $t \to \infty$. Since these limiting values fall between 0 and 1, advanced converters and breeders are used together at all times so long as $\beta < \lambda e^{\lambda\delta}$. The BNE condition in this case persists indefinitely.

[B] Case II : In this case $(\beta-\alpha) < \lambda e^{\lambda\delta} < \beta$; $\xi > 1$ and $\mu < \lambda$. The fraction of power generated in breeders [STPCB(t)] starts at (B_0/P_0) at $t = 0$ and eventually reaches the maximum permissible value of one. The fraction of power generated in advanced converters starts at $1 - (B_0/P_0)$ at $t = 0$ and eventually drops to zero, because the limiting value of STPCA(t) as $t \rightarrow \infty$ is $1 - \xi$, which is negative since $\xi > 1$. The time t_3 at which $A(t) = 0$ is obtained from equation (III. 34) as:

$$t_3 = \frac{1}{(\lambda - \mu)} \ln \left[\frac{\xi - (B_0/P_0)}{\xi - 1} \right] \qquad \text{(III. 35)}$$

This value of t_3 is positive because $(B_0/P_0) < 1$ and $\mu < \lambda$. It is thus clear that a condition of BNE exists when $0 < t < t_3$, but is not possible after t_3, when a plutonium surplus starts to develop. At the start of the period of BNE, A(t) may increase with time under some circumstances but eventually starts to decrease. This can be seen from the expression for GRA(t), eq. (III. 32), as follows,

$$\mathrm{GRA}(t) = (1 - \xi)\lambda P_0 e^{\lambda t} - \mu P_0 \left[(B_0/P_0) - \xi \right] e^{\mu t}$$

After long time, the first term in this expression dominates, which is negative because $\xi > 1$. Also initially at $t = 0$,

$$\mathrm{GRA}(0) = (1 - \xi)\lambda P_0 - \mu P_0 \left[(B_0/P_0) - \xi \right] \qquad \text{(III. 36)}$$

and for $\mu > 0$, this has its highest value when $(B_0/P_0) = 0$. This maximum value is:

$$\mathrm{GRA}(0)_{\max} = (1 - \xi)\lambda P_0 + \mu \xi P_0 \qquad \text{(III. 37)}$$

It is possible to show that this value may be positive under some circumstances, as follows :

Since, $$\mu = (\beta - \alpha)\, e^{-\mu\delta} \qquad \text{(III.14)}$$

so that, $$\begin{aligned} \text{GRA}(0)_{\max} &= \lambda P_0 - \xi\left[\lambda + (\alpha-\beta)\, e^{-\mu\delta}\right] P_0 \\ &> \lambda P_0 - \xi\left[\lambda + (\alpha-\beta)\, e^{-\lambda\delta}\right] P_0 \\ &= \lambda\left[1 - \alpha\, e^{-\lambda\delta}\right] P_0 \qquad \text{(III.38)} \end{aligned}$$

Thus, if $\alpha < \lambda e^{\lambda\delta}$ and $(B_0/P_0) = 0$, A(t) increases initially after t = 0. The time t_2 at which the growth in advanced converters becomes zero, i.e. GRA(t) = 0 is obtained from Eq. (III. 32),

$$t_2 = \frac{1}{(\lambda-\mu)} \ln\left[\frac{(\xi - (B_0/P_0))\,\mu}{(\xi - 1)\,\lambda}\right] \qquad \text{(III. 39)}$$

If $(B_0/P_0) < 0.5$, there is a time t_1 greater than zero at which the fraction of power generated by converters drops to half, i.e. at which A(t) = B(t). This is obtained by setting STPCA(t) of equation (III. 34) equal to 0.5,

$$t_1 = \frac{1}{(\lambda-\mu)} \ln\left[\frac{\xi - (B_0/P_0)}{\xi - 0{\cdot}5}\right] \qquad \text{(III. 40)}$$

<u>[C] Case I :</u> In this case we have, $\lambda e^{\lambda\delta} < \beta - \alpha$, $\xi < 0$, and $\lambda < \mu$. The fraction of power generated in advanced converters starts at $1 - (B_0/P_0)$ at t = 0 and eventually drops to zero, because $e^{(\mu-\lambda)t}$ increases without limit and its coefficient is negative. The time t_3 at which A(t) drops to zero is given by :

$$t_3 = \frac{1}{(\mu-\lambda)} \ln\left[\frac{1-\xi}{(B_0/P_0) - \xi}\right] \qquad \text{(III. 41)}$$

After t_3, BNE is impossible and plutonium surplus develops.

Since, $\xi < 0$ and $\mu > \lambda$, the growth in advanced converter reactors GRA(t) of equation (III. 32) becomes negative as time increases. The initial value of growth in ACRs, GRA(0) of equation (III. 36) can be positive when $(B_o/P_o) \to 0$ and $|\xi| \to 0$. The time t_2 at which GRA(t) = 0 is given by a variant of equation (III. 39) :

$$t_2 = \frac{1}{(\mu-\lambda)} \ln \left[\frac{(1-\xi)\lambda}{[(B_o/P_o)-\xi]\mu} \right] \qquad \text{(III. 42)}$$

The time t_1 at which the fraction of power generated in converters and breeders become equal, (i. e. at which A(t) = B(t)) is now, assuming $(B_o/P_o) < 0.5$,

$$t_1 = \frac{1}{(\mu-\lambda)} \ln \left[\frac{0.5-\xi}{(B_o/P_o)-\xi} \right] \qquad \text{(III. 43)}$$

In conclusion, it is possible to say that, the condition of BNE largely depends on the value of ξ . If ξ is a positive fraction and $\beta < \lambda e^{\lambda\delta}$, the condition of BNE will exist indefinitely, where converters and breeders will be needed together to meet the total power demands. The value of ξ depends on the plutonium production rate in converters as well as breeders, the growth rate constant λ and the value of delay δ .

Table III. 2 lists the values of α , β , δ , μ and ξ

for two combinations of reactors of special interest in this study. These two combinations are very instructive in the study of the characteristics of BNE because in the first case [using HWOCRs] the plutonium production rate is smaller than that of breeders, and in the second case it is higher than that of breeders. Table III. 3 shows how the value of ξ is influenced by the growth rate constant λ and the value of delay δ, for these two combinations. Note that in Table III. 3, for the growth rate constant equal to 0.07 [i.e. doubling time of 10 years] the value of ξ changes from 0.94 with delay of three years to 1.22 when the delay is reduced to zero. The former value of ξ corresponds to previously described case III, where as the latter value corresponds to case II. This changeover has an important bearing on the condition of BNE and the growth of advanced converters during BNE. Notice also that, the value of ξ can never become negative in the combination of Fast U-235 reactors with breeders, and hence previously described case I will never be observed. Case III corresponds to the case of indefinite BNE so long as $\beta < \lambda e^{\lambda\delta}$ and becomes applicable when the value of λ is equal to or higher than 0.07, and is independant of the converter reactors is used during the BNE.

Fig III.1 shows the behaviour of HWOCR capacity in BNE with different values of λ. At $\lambda = 0.02$, the value of ξ is 11.65 and the analysis of Case II applies. Since, α is smaller than $\lambda e^{\lambda\delta}$, A(t) decreases continuously until it reaches zero in about 18 years.

Table III.2

Characteristics of BNE (I)

Reactor combination in BNE	HWOCR + Breeders			FAST U-235 + Breeders		
a kgm/MWyr	0.35			0.83		
b kgm/MWyr	0.43			0.43		
I_b kgm/MWe	4.20			4.20		
l load factor	0.80			0.80		
δ years	3.0			3,0		
α yr^{-1}	0.0666			0.1580		
β yr^{-1}	0.0820			0.0820		
μ yr^{-1}	0.0150			- 0.1040		
λ yr^{-1}	0.01	0.06	0.1	0.01	0.06	0.1
$\lambda e^{\lambda\delta}$ yr^{-1}	0.01304	.0718	.1350	.013	.0718	.1350
$\xi = \frac{\alpha}{\alpha-\beta+\lambda e^{\lambda\delta}}$	- 12.80	1.85	0.558	1.78	1.07	0.75
Case	I	II	III	II	II	III

Table III. 3

Characteristics of BNE (II)

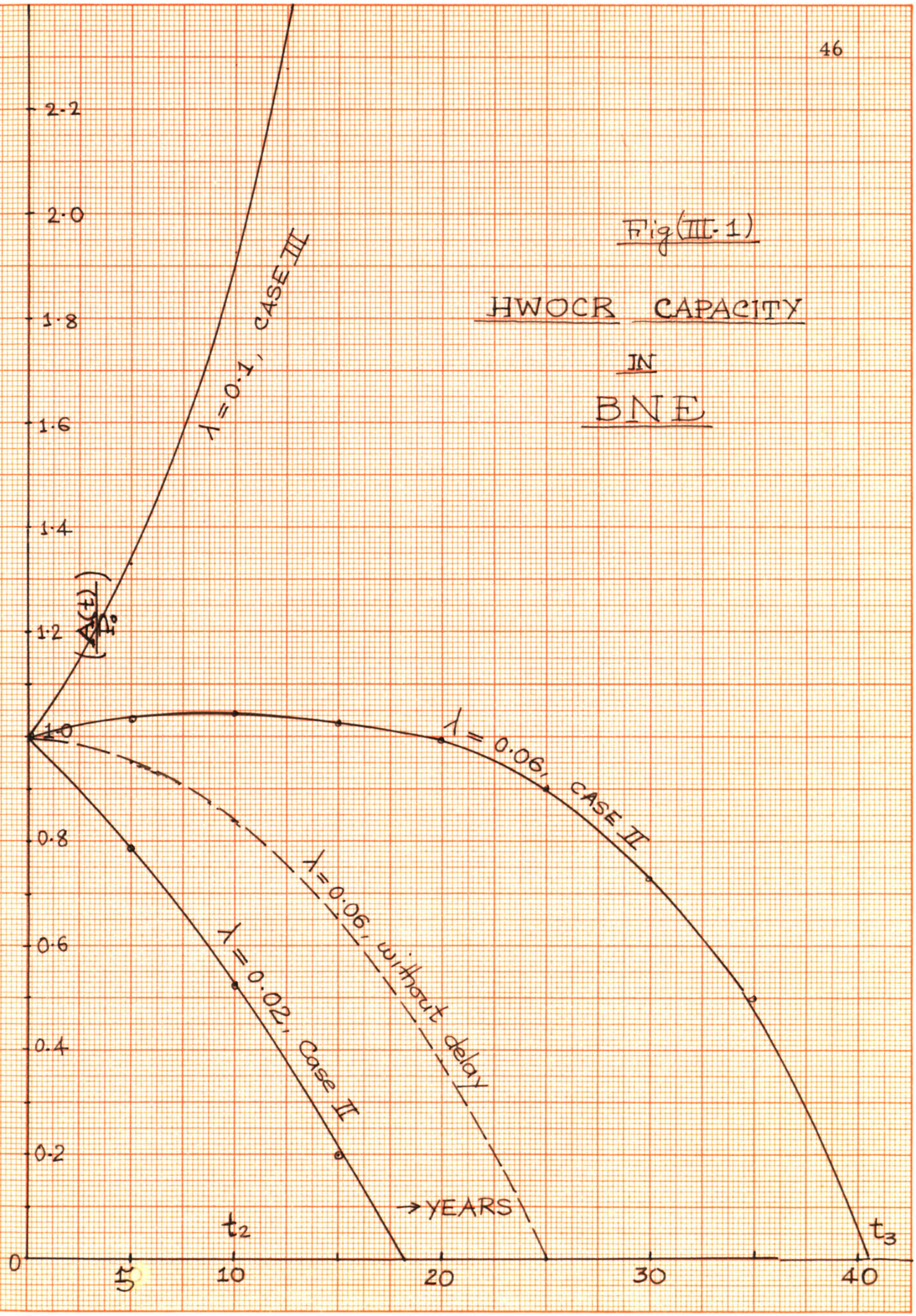
Lambda λ	HWOCR + Breeders				FAST U-235 + Breeders			
	ξ				ξ			
	δ = 3 yrs	Case	δ = 0	Case	δ = 3 yrs	Case	δ =0	Case
0.01	-12.800	I	-12.1	I	1.78	II	1.84	II
0.02	11. 65	II	14.7	II	1.630	II	1.65	II
0.03	3.84	II	4.60	II	1.455	II	1.50	II
0.04	1.97	II	2.72	II	1.25	II	1.36	II
0.05	1.56	II	1.93	II	1.18	II	1.26	II
0.06	1.185	II	1.50	II	1.07	II	1.165	II
0.07 *	0.94	III	1.22	II	0.975	III	1.081	II
0.08	0.77	III	1.03	II	0.89	III	1.01	II
0.09	0.65	III	0.895	III	0.82	III	0.96	III
0.10	0.56	III	0.79	III	0.75	III	0.90	III
0.14 #	0.34	III	0.54	III	0.55	III	0.70	III

* 10 year doubling time

\# 5 year doubling time

At $\lambda = 0.06$, the value of $\xi = 1.85$ and still the case II applies, however, because now $\lambda e^{\lambda\delta} = 0.0718$, is higher than the value of $\alpha = 0.0666$, A(t) increases initially and then decreases. A(t) goes to zero in about 41 years. The effect of neglecting the value of delay can be observed from the curve shown in dashed lines in Fig III.1, and it is obvious that the advanced converter reactor capacity will always decrease when delay is neglected, at $\lambda = 0.06$. At $\lambda = 0.1$ the value of ξ is 0.56 and hence Case III applies. This is well demonstrated by the curve corresponding to $\lambda = 0.1$. The advanced converter and breeder reactor capacity will always increase in this case so long as $\beta < \lambda e^{\lambda\delta}$.

Figure III.2 shows the behaviour of Fast U-235 reactor capacity in BNE for different values of λ. These curves are also plotted for the same values of λ, and show very interesting behaviour. Even with $\lambda = 0.06$, the advanced converter capacity always decreases because $\alpha > \lambda e^{\lambda\delta}$. Notice that these curves are concave from below as compared to the similar curves in the previous case of HWOCR installations, which are convex from below. What this means is that the rate of decrease in A(t) is much higher when Fast U-235 reactors are installed during BNE, rather than HWOCR reactors. The time at which A(t) is reduced to zero is almost one half of that required when HWOCRs are installed. Notice further that even with $\lambda = 0.1$, and $\xi = 0.75$, [Case III] the Fast U-235 reactor capacity decreases initially and then rises with time, making it a situation of indefinite BNE. This initial decrease in A(t) is because :



Fig(III·1)

HWOCR CAPACITY IN BNE

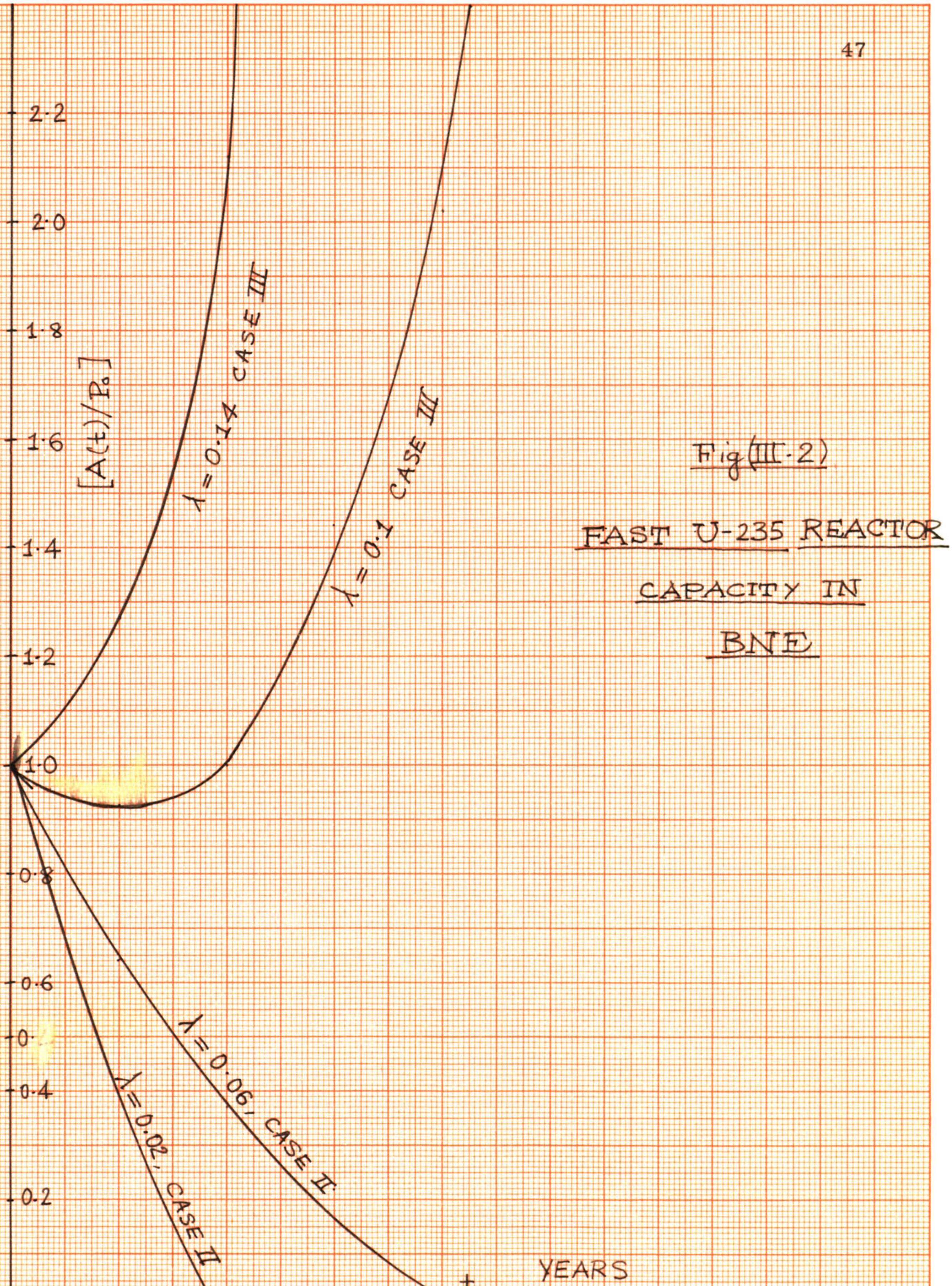


Fig (III·2)

FAST U-235 REACTOR CAPACITY IN BNE

$\alpha > \lambda e^{\lambda\delta}$. It is further evident from these graphs, that for the same value of λ [i.e. new installations] less amounts of Fast U-235 reactors will be required, than HWOCRs, to fulfill the requirements of total growth in nuclear power and at the same time keep the plutonium stockpile constant. This could have been expected also because Fast U-235 reactors produce much higher plutonium than HWOCRs for the same amount of electricity generated. This fact, that Fast U-235 reactors are required in lesser proportion, will be important in the cumulative uranium requirements of the nuclear power complex.

The breeder reactor capacity in a BNE, although not plotted here, will always increase as compared to advanced converter reactor capacity. This is because of positive feedback of, more breeder installations will produce more plutonium and with more available plutonium more new breeders will be installed.

With $\lambda = 0.14$, and $\xi = 0.547$ [Case III], the Fast U-235 reactor capacity increases with time in accordance to a case of indefinite BNE so long as $\beta < \lambda e^{\lambda\delta}$. It is interesting to notice that, a case of initial growth in A(t) and then decrease eventually, can not be observed with Fast U-235 reactors. This is because in all the cases of this reactor combination in BNE, which belong to Case II, the value of α is always greater than $\lambda e^{\lambda\delta}$ which makes the initial growth in advanced converters [GRA(0)] to decrease.

[III]

The condition of BNE depends on the values of α, β, γ, δ, μ, and ξ. In this section the influence of variation in these parameters on ξ is examined, since ξ is the limiting value of share of breeders in the nuclear power complex.

(1) Effect of λ : With increase in time, the rate of growth of nuclear power decreases, decreasing the value of λ. In the present study, the value of λ decreases from about 0.3 fraction per year in 1965 to about 0.036 in year 2025. Lamda is thus by far the most influencing factor in setting the BNE condition.

Since $\xi = \dfrac{\alpha}{\alpha - \beta + \lambda e^{\lambda\delta}}$ (III. 21)

differentiating with respect to λ and rearranging,

$$\frac{d\xi}{d\lambda} = -\xi^2 \frac{(1 + \lambda\delta)\, e^{\lambda\delta}}{\alpha} \qquad \text{(III. 44)}$$

Hence, a small decrease in λ [i.e. $d\lambda$, a negative fraction] the value of ξ will increase , by $d\xi$, proportional to its own square. The effect of change in λ on breeder growth can be observed by differentiating equation (III. 31) :

$$\frac{d}{d\lambda}[\, \mathrm{GRB}(t) \,] = [\, \xi + \xi\lambda^2 + \lambda(\tfrac{d\xi}{d\lambda}) \,]\, P_o\, e^{\lambda t} \qquad \text{(III. 45)}$$

A small decrease in λ will thus decrease the growth in breeders, however, the fraction of power generated in breeders may be higher than in advanced converters as discussed in the last section.

(2) Effect of δ : The total delay δ is because of time spent in irradiated fuel cooling, reprocessing and refabrication. Decrease of time spent in each process (or combined) will make Pu available earlier for its use in breeder inventory; increasing the growth rate of breeders. More breeders in turn will breed more plutonium and so on. Hence, because of this positive feedback characterstic the effect of delay will be of higher importance.

The analysis developed before shows that the existance of delay causes the condition that a BNE persist for all time to change from

$$\frac{b\,l}{I_b} < \lambda$$

to
$$\frac{b\,l}{I_b} < \lambda e^{\lambda\delta}$$

That is, breeders will never become capable of carrying the full load unless the relative power growth rate is reduced by the factor $e^{-\lambda\delta}$ when the delay is taken into account.

The value of ξ without delay is

$$\xi = \frac{\alpha}{\beta - \alpha}$$

and is higher than that with delay, meaning that the proportion of breeder installation will be higher in the absence of delay.

Also since,
$$\frac{d\xi}{d\delta} = -\xi^2 \frac{\lambda^2 e^{\lambda\delta}}{\alpha} \qquad \text{(III. 46)}$$

a small decrease in delay will increase the value of ξ by a fraction. Comparing equations (III. 44) and (III. 46) it is obvious that :
$$\frac{d\xi}{d\lambda} > \frac{d\xi}{d\delta} \qquad \text{(III. 47)}$$

which implies that for the same fractional change in the values of λ and δ , the change in the value of ξ will be higher in the former case and lower in the latter.

(3) Effect of α :

$$\text{Since,} \quad \frac{d\xi}{d\alpha} = \left(\frac{\xi^2}{\alpha^2}\right)\left[\lambda e^{\lambda\delta} - \beta\right] \tag{III.48}$$

a decrease in α will decrease ξ , the limiting fraction of breeder capacity in the nuclear power complex, by a fraction, since ξ is a positive fraction since, $\lambda e^{\lambda\delta} > \beta$.

(4) Effect of β:

$$\text{Since,} \quad \frac{d\xi}{d\beta} = \frac{\xi^2}{\alpha} \tag{III.49}$$

hence, a small decrease in β will decrease ξ by a fraction.

It is important to note that changing α and β changes ξ in the same direction, whereas, changing λ and δ changes ξ in the opposite direction.

In summary, the limiting fraction of breeder generating capacity [ξ] will increase if the plutonium production rate in converter reactors [a] and breeders [b] were improved or if the power growth rate constant [λ] and/or the delay [δ] were reduced. The fractional changes in λ affect the limiting fraction of breeder generating capacity more than in δ and the extent to which it will be affected by fractional changes in α and β will depend on their relative magnitudes.

CHAPTER IV

POWER GENERATION, URANIUM REQUIREMENTS & PLUTONIUM STÖCKPILE

IV.A POWER GENERATION

The power generated during a time interval dt (years) by a reactor operating at R(t) MWe capacity with a load factor of l is equal to $l\,R(t)\,dt$ MWeyrs. The total generated electrical power between t_0 and t, is the total sum of $l\,R\,dt$ during that time. Thus,

$$\text{Total power generated upto } t = \int_{t_0}^{t} l\,R(t)\,dt \quad \text{MWeyr} \qquad (IV.1)$$

Hence, total power generated upto t in the nuclear power complex is

$$\begin{aligned} TPGP(t) &= \int_{t_0}^{t} l\,P(t)\,dt = \int_{t_0}^{t} l\,P_o\,e^{\lambda t}\,dt \\ &= [\,l\,P_o/\lambda\,]\,[\,e^{\lambda t} - e^{\lambda t_0}\,] \end{aligned} \qquad (IV.2)$$

when l and λ are assumed to be constant during that time interval.

Similarly, total power generated in LWR, ACR & Breeders, upto t are:

$$TPGC(t) = \int_{t_0}^{t} l\,C(t)\,dt \qquad (IV.3)$$

$$TPGA(t) = \int_{t_0}^{t} l\,A(t)\,dt \qquad (IV.4)$$

$$TPGB(t) = \int_{t_0}^{t} l\,B(t)\,dt \qquad (IV.5)$$

and at any time, $TPGP(t) = TPGC(t) + TPGA(t) + TPGB(t)$ (IV.6)

Using the various expressions for C(t), A(t) and B(t) of the previously described mathematical model and corresponding values of load factor and lamda during those time intervals, the electrical power generated by each individual reactor can be obtained.

The share of total power generated by each of these reactors is

$$\mathrm{STPGA}(t) = \mathrm{PGA}(t)/\mathrm{PGP}(t) \qquad \text{(IV. 7)}$$

$$\mathrm{STPGB}(t) = \mathrm{PGB}(t)/\mathrm{PGP}(t) \qquad \text{(IV. 8)}$$

and

$$\mathrm{STPGC}(t) = \mathrm{PGC}(t)/\mathrm{PGP}(t) \qquad \text{(IV. 9)}$$

IV. B URANIUM REQUIREMENTS

The rate at which uranium will be required in a particular nuclear power complex is determined by the fuel inventory required for new installations and fuel makeup (or burnup) required to produce the required electrical power.

Thus, uranium required during a time interval dt is

$$\begin{array}{l} \text{Rate of U} \\ \text{requirement} \\ \text{during } dt \end{array} = \begin{array}{l} [\text{ specific inventory}]\ [\text{ Growth of reactor installation during } dt]\ dt \\ +\,[\text{ specific burnup}]\ [\text{ Power generated in } dt]\ dt \end{array} \qquad \text{(IV.10)}$$

The specific inventory (ST of U_3O_8 /MWe) depends on the type of reactor installation, the mode of fuel cycle (whether bred fuel recycled) and for some reactors, the time factor if the reactor is built during year 1965-2000. The appropriate values were listed in Table I. 4. The specific burnup (ST of U_3O_8 /MWeyr) similarly depends on the type of reactors already installed, the mode of fuel cycle and the time.

Thus, for X type of reactor installations, the rate of uranium requirements during dt [ST of U_3O_8 / yr] is

$$\text{URANX}(t) = [\text{ SPINXt}]\ [\text{ GRX}(t)]\ dt + [\text{ SPBUX}(t)]\ [\text{ RPGX}(t)]\ dt \qquad (\text{IV}.11)$$

The total uranium requirements during t_0 and t will be the integral of this ——

$$\text{TURNX}(t) = \int_{t_0}^{t} \Big\{ [\text{ SPINX}(t)]\ [\text{ GRX}(t)] + [\text{ SPBUX}(t)[\text{ RPGX}(t)] \Big\}\ dt \qquad (\text{IV}.12)$$

Using the proper values for specific inventory requirements [SPINX(t)] and specific burnup requirements [SPBUX(t)] from Table IV. 4, the equation for growth rates GRX(t) from the mathematical model described in Chapter II and the rate of power generation RPGX(t) from the previous section, these integrals in each individual cases can be evaluated.

Assuming a delay of one year between uranium production and its use in reactor, the above values of uranium required will be those which must be mined at least one year in advance.

The price of uranium paid in each individual case is discussed in chapter on uranium value analysis, (Chapter VII)

IV. C PLUTONIUM STOCKPILE

The plutonium stockpile at any time is the net amount of plutonium in reserve. The actual plutonium production rate in converter and breeder reactors is proportional to their installed capacities at that time.

$$\text{Actual Pu production rate} = 1\,a\,A(t)+1\,b\,B(t)+1\,c\,C(t) \quad \text{kgm/yr} \qquad \text{(IV. 13)}$$

but the rate at which it becomes available is after δ years of delay: i. e.

$$\text{Pu availability rate} = \text{actual Pu production rate } \delta \text{ years earlier} \qquad \text{(IV. 14)}$$

Pu consumption rate is proportional to the breeder inventory requirement rate, $I_b\,[\,dB/dt]$ (IV. 15)

Hence, net plutonium available every year is the difference between these two and the total plutonium stockpile will be the integral of this, during the time interval considered

$$\text{Net Pu stockpile} = \int_{t_0+\delta}^{t+\delta} 1\,a\,A(t)+1\,b\,B(t)+1\,c\,C(t) \;-\; \int_{t_0}^{t} I_b\,[\,dB(t)/dt] \quad \text{kgms} \qquad \text{(IV. 16)}$$

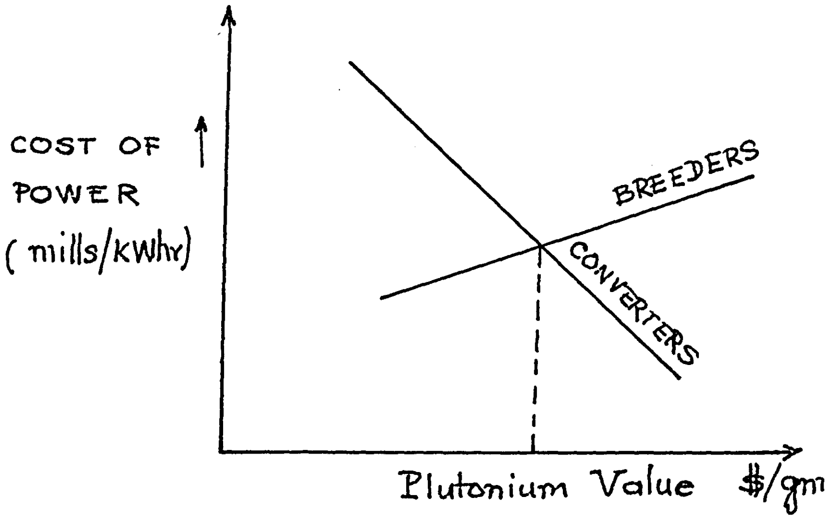
The plutonium stockpile in a balanced nuclear economy, will thus remain constant at the level prior to which BNE starts. The plutonium stockpile in an integrated-balanced-nuclear- economy will also be constant, because all the excess plutonium will be fed into advanced converter reactors.

CHAPTER V

PLUTONIUM VALUE ANALYSIS

V. A: INTRODUCTION

One of the objectives of present study is to estimate the value of plutonium at a time in the development of nuclear power when the supply of plutonium from converter reactors and demand for plutonium to provide inventory for fast breeder reactors has come into balance. When both converter reactors and breeder reactors are in operation the cost of power will depend on the value of plutonium roughly as shown in the adjoining figure:



The value of plutonium, is at point where the cost of power from each type of reactor is same, where the two curves intersect. The cost of power from converter reactors decreases substantially as the value of plutonium increases, because these reactors produce from 0.3 to 0.35 kilograms of plutonium (0.83 in case of FAST U-235 fueled reactors) per megawatt year of electricity generated. The cost of power from fast breeders, on the other hand, decreses less rapidly with plutonium value, or may even increase actuallv, because of the substantial charge for the inventory of plutonium in these reactors.

In the following two sections expressions for plutonium value are derived for two different cases of static equilibrium and dynamic equilibrium, respectively.

V. B: PLUTONIUM VALUE - EQUAL COST OF POWER BASIS :

Consider a case of a nuclear power complex having only advanced converter reactors of A type and breeder reactors of B type, producing a and b kilograms of net fissile plutonium per megawattyear of electricity generated, respectively. In advanced converters no plutonium is recycled and in breeders b kgms/mweyr are after allowing for its own fissile makeup requirements and losses. Assume no delay in plutonium production and its consumption as inventory in breeders.

Define :

PLV	:	Plutonium value	$/kgm
FCC	:	Fixed Capital Charges	$/MWeyr
OM	:	Operation and Maintainance costs	$/MWeyr
F, R, & D	:	Fabrication, Reprocessing and Depletion costs respectively	$/MWeyr
i	:	interest rate	fraction/year
UIV	:	Uranium Inventory Value	$/MWe

FIV : Fuel Fabrication Investment value $/MWe

a : Pu production rate in ACRs kgms/MWeyr

b : Pu production rate in Breeders "

I_b : Specific Pu inventory requirement kgm/MWe

CPG : Cost of power generation excluding plutonium transactions $/MWeyr

TCPG : Total cost of power generation including Pu transactions $/MWeyr

With suffix A for converters and B for breeders, we have,

$$CPGA = FCCA + OMA + (FA + RA + DA) + i\,(FIVA + UIVA) \qquad (V.1)$$

$$CPGB = FCCB + OMB + (FB + RB) + i\,(FIVB) \qquad (V.2)$$

and with plutonium transactions included--

$$TCPGA = CPGA - l\,a\,PLV \quad \$/MWeyr \qquad (V.3)$$

$$TCPGB = CPGB + (i\,I_b - l\,b)\,PLV \quad \$/MWeyr \qquad (V.4)$$

where l is the load factor.

For equal power costs in A and B reactors,

$$TCPGA = TCPGB \quad \$/MWeyr \qquad (V.5)$$

and hence,

$$\text{Plutonium Value } PLV = \frac{CPGA - CPGB}{a - b + i\,I_b/l} \quad \$/kgm \qquad (V.6)$$

Illustrative value :

Assume $l = 0.8$, $CPGA = 4.85$ mills/kwhr, $CPGB = 4$ mills/kwhr
$a = 0.35$ kgms/mweyr, $b = 0.43$ kgms/mweyr ,
$I_b = 4.20$ kgms/mwe $i = 0.10$

then,

$$PLV = \frac{(4.85-4)\text{mills/kwhr} \times 10^{-3}\ \$/\text{mill} \times 365 \times 24\ \text{hr/yr} \times 10^{3}\ \text{kw/mw}}{[\,0.35 + (4.2 \times 0.1/0.8) - 0.43\,]\ \text{kgms/mweyr} \times 10^{3}\ \text{gm/kgm}}$$

$$= 16.8\ \$/gm$$

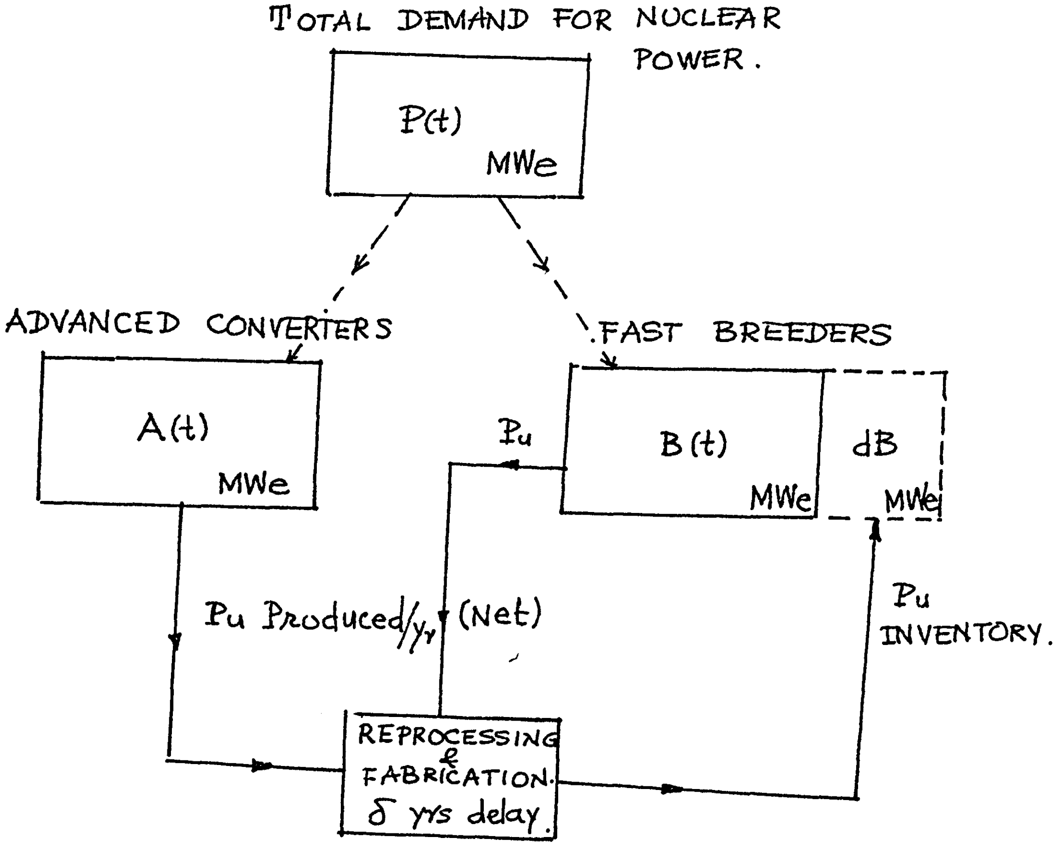
The value of plutonium given by Eq. (V.6) is the free market price at which it would be a matter of indifference whether a converter or breeder reactor were built ; the cost of power from each would be the same. If the plutonium price were higher, more converters and fewer breeders would be built, leading to an increased supply of plutonium and consquently lower prices; if the plutonium price were lower, fewer converters would be built and more breeders, leading to a reduced supply of plutonium and higher prices.

V. C: PLUTONIUM VALUE IN BALANCED NUCLEAR ECONOMY:

In a dynamic situation such as the Balanced Nuclear Economy, in which the power generation is changing with time, the marginal cost of plutonium is a more appropriate measure of its value than the equal-cost of power basis treated above.

The marginal value of plutonium to the power generating system will depend on the extent to which its use affects the cost of power production from the system as a whole. If initially there is a balance of plutonium flow between the fissile plutonium producers (converters and breeders) and consumers (breeders) with a net zero plutonium stockpile as in the case of BNE, and if now there is an incentive or commitment to export some plutonium out of the system, there will be a perturbation in the system. The impact of this perturbation will depend on the quantity of plutonium extracted from the system. With this imbalance, the cost of power generation will tend to be higher in general, because more U feed-plutonium producer reactors will have to be installed than plutonium feed-plutonium producer reactors, and the cost of power generation in the former is higher than in the latter, excluding the plutonium transactions. This increased cost will be directly proportional to the cost of extracted plutonium, if the cost of power to the consumer has to remain the same. This price of plutonium is thus its " export price ".

The follwing model is proposed to determine the plutonium value in balanced nuclear economy.



In the initial system :

(a) Total nuclear power $P(t) = A(t) + B(t)$ MWe (V. 7)

(b) Plutonium material balance in BNE

$$I_b \frac{d}{dt}[\, B(t+\delta)] = l\,[\, a\,A(t) + b\,B(t)\,] \qquad (V.8)$$

(c) Total cost of power generation, including Pu transactions, is

$$TCPG(t) = l\,[\, CPGA\;A(t) + CPGB\;B(t)\,] + i\, I_b\, PLV \cdot B(t) \quad \$/yr \qquad (V.9)$$

After extracting q kgms/yr of plutonium from the system, above set of equations are modified to :

(a')
$$P(t) = A'(t) + B'(t) \quad MWe \qquad (V.10)$$

(b')
$$q + I_b \frac{d}{dt}[\, B'(t+\delta)] = l\,[\, a\,A'(t) + b\,B'(t)\,] \qquad (V.11)$$

(c')
$$TCPG'(t) = l\,[\, CPGA\;A'(t) + CPGB\;B'(t)] + i\, I_b PLV'\; B'(t) \qquad (V.12)$$

From equations(V. 7) and (V. 10),

$$A'(t) - A(t) = B(t) - B'(t) = X(t) \qquad (V.13)$$

and,
$$\frac{dA'}{dt} - \frac{dA}{dt} = \frac{dB}{dt} - \frac{dB'}{dt} = \frac{dX}{dt} \qquad (V.14)$$

From equations (V. 8) and (V. 11), after subtractions,

$$q + I_b \left[\frac{dB'(t+\delta)}{dt} - \frac{dB(t+\delta)}{dt} \right] = l\,[\, a\;A'(t) + b\;B'(t)] - l\,[\, a\;A(t) + b\;B(t)\,]$$

or alternatively,

$$q - I_b \left[\frac{dX(t+\delta)}{dt} \right] = l\,a\;X(t) - l\,b\;X(t)$$

or,
$$\frac{dX(t+\delta)}{dt} + \frac{l\,(a-b)}{I_b}\, X(t) + q = 0 \qquad (V.15)$$

The solution of this equation may be obtained in the same manner as for Eq. (III. 11) for the breeder capacity in BNE. With the initial condition $X = 0$ at $t = 0$, the asymptotic solution is :

$$X(t) = \frac{q}{1(a - b)} [1 - e^{u t}] \qquad \text{MWe} \qquad (V.16)$$

Where u is the solution of

$$\mu e^{u\delta} = (b - a)/ I_b \qquad (V.17)$$

The cost of extracting q kilograms of plutonium every year from the system is obtained subtracting equation (V.12) from (V.9) : TCPG' — TCPG dollars/year

$$= 1 \, \text{CPGA} [A'(t) - A(t)] + 1 \, \text{CPGB} [B'(t) - B(t)]$$

$$+ \, i \, I_b [\text{PLV}' \, B'(t) - \text{PLV} \, B(t)] \ \$/\text{yr} \qquad (V.18)$$

Defining, the marginal cost of plutonium as :

$$\text{MPuV}(t) = \lim_{q \to 0} \left[\frac{\text{TCPG}' - \text{TCPG}}{q} \right] \quad \$/\text{kgm} \qquad (V.19)$$

But the marginal cost of plutonium is also given by :

$$\text{MPuV}(t) = \lim_{q \to 0} \left[\frac{(B'(t) \, \text{PLV}' - B(t) \, \text{PLV})}{(B'(t) - B(t))} \right] \quad \$/\text{kgm} \qquad (V.20)$$

Solving these last three equations and substituting for X(t) from equation (V.16),

$$\text{MPuV}(t) = \frac{1 (\text{CPGA} - \text{CPGB}) [1 - e^{u t}]}{1 (a - b) + i \, I_b [1 - e^{u t}]} \quad \$/\text{kgm} \qquad (V.21)$$

It is possible to infer from this equation :

1. that MPuV is zero at the start of BNE
2. that MPuV is directly proportional to the cost difference in power generation in advanced converters and breeders-Pu transactions excluded- and increases with higher difference.
3. that the marginal cost of plutonium increases with time to the following limiting expressions :

Case I: $a > b,\ \mu < 0$ [when ACRs are FAST U-235]

$$\lim_{t \to \infty} [\ \mathrm{MPuV}(t)\ ] = \frac{1\,[\ \mathrm{CPGA} - \mathrm{CPGB}\ ]}{1\,(a - b) + i\, I_b} \qquad (\mathrm{V.}\,22)$$

Note that this is equation (V. 6) for plutonium value on equal cost of power basis.

Case II : $a = b,\ \mu \neq 0$ or ∞

$$\lim_{t \to \infty} [\ \mathrm{MPuV}(t)\ ] = 1\,[\ \mathrm{CPGA} - \mathrm{CPGB}]\ /\ i\, I_b \qquad (\mathrm{V.}\,23)$$

Case III : $b > a,\ \mu > 0$ [when ACRs are HWOCR or other]

$$\lim_{t \to \infty} [\ \mathrm{MPuV}(t)\ ] = 1\,[\ \mathrm{CPGA} - \mathrm{CPGB}]\ /\ i\, I_b \qquad (\mathrm{V.}\,24)$$

4. that the total power growth constant lambda does not occur in the equation for MPuV(t).
5. that, if in the nuclear power complex there were more than one type of converter reactors, the expression for MPuV(t) will change. The expression will, however, remain the same if the capacity of additional type of converter is held constant.

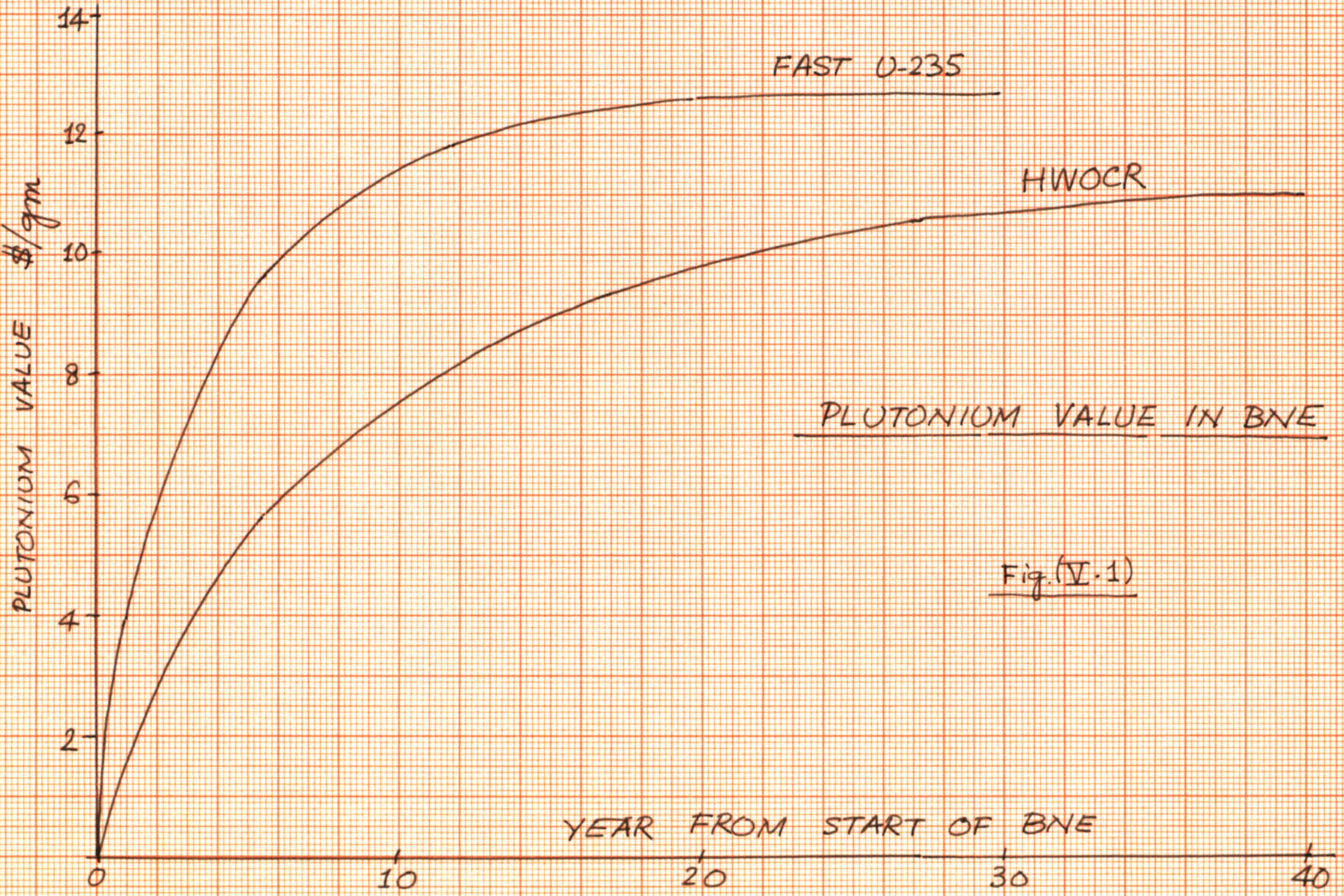
This can be checked by putting the constant terms in the equations for the model, which are cancelled out later by subtraction of perturbed and non-perturbed system equations.

6. Fast breeders of more favourable breeding characteristics show a higher exporting price for plutonium while the more favourable plutonium producing converters show a lower one. When the plutonium production rate becomes in surplus to its requirements, the plutonium price is negligible for small amounts exported but increases very rapidly as soon as the amount exported is sufficient to eliminate the surplus. Fast breeders of good breeding potential will thus introduce more fluctuations in the plutonium value with the amount exported.

Following equation (V.21) a computer programme [please see the Appendix] was written to compute the marginal plutonium values in two different cases of plutonium producers : (a) HWOCRs and (b) FAST U-235 fueled reactors. The following data was used in the computation :

$a = 0.35$ kgms/MWeyr for HWOCR
& $= 0.83$ " for FAST U-235 reactors
$b = 0.43$ " for fast Breeders
$I_b = 4.20$ kgms/MWe "
$l = 0.80$
$i = 0.10$ fraction/year
CPGA – CPGB $\doteq$ 0.85 mills/kwhr with HWOCRs, and
= 12,826 \$/MWeyear with FAST U-235 reactors.
(please see the appendix)
to this chapter

The results for plutonium values are shown in the Fig V.1 and are tabulated in the accompanying table.



PLUTONIUM VALUE IN BNE

Fig.(V.1)

```
resume dyn plutm madtrn
W 1303.1
```

Table V.1

```
PAGE 1      PLUTM      PLUTONIUM VALUE IN BNE           03/01/66   1303.1

  TIME                     PLVHW                   PLVFU
  E+00                     E+00                    E+00
   .000                    -.000                    .000
  1.000                    1.523                   3.684
  2.000                    2.740                   5.970
  3.000                    3.733                   7.512
  4.000                    4.560                   8.612
  5.000                    5.258                   9.428
  6.000                    5.856                  10.051
  7.000                    6.373                  10.538
  8.000                    6.826                  10.925
  9.000                    7.224                  11.237
 10.000                    7.578                  11.490
 11.000                    7.894                  11.699
 12.000                    8.178                  11.872
 13.000                    8.434                  12.016
 14.000                    8.667                  12.136
 15.000                    8.880                  12.237
 16.000                    9.074                  12.322
 17.000                    9.253                  12.395
 18.000                    9.417                  12.456
 19.000                    9.570                  12.508
 20.000                    9.711                  12.553
 21.000                    9.842                  12.590
 22.000                    9.964                  12.623
 23.000                   10.078                  12.651
 24.000                   10.185                  12.674
 25.000                   10.285                  12.695
 26.000                   10.379                  12.712
 27.000                   10.468                  12.727
 28.000                   10.551                  12.740
 29.000                   10.630                  12.751
 30.000                   10.704                  12.760
 31.000                   10.775                  12.768
 32.000                   10.842                  12.775
 33.000                   10.905                  12.781
 34.000                   10.965                  12.786
 35.000                   11.023                  12.791
 36.000                   11.077                  12.795
 37.000                   11.129                  12.798
 38.000                   11.179                  12.801
 39.000                   11.226                  12.803
 40.000                   11.272                  12.805


TYPE CHANGES IF RERUN DESIRED
```

From Fig V.1, it is obvious that the plutonium value is zero at the start of BNE in either case but increases with time. The duration of BNE is almost forty years when HWOCR type of ACRs are put in the power complex but reduces to about thirty years if FAST U-235 reactors are substituted for HWOCRs. Because of higher cost differential the plutonium value is higher in the complex using FAST U-235 reactors. The Pu value rises gradually to a maximum level of 11 $/gm when HWOCRs are used but rises very fast when FAST U-235 reactors are used, reaching a maximum level of 13 $/gm.

V. D : FACTORS INFLUENCING PLUTONIUM VALUE :

Following factors will influence the market price of plutonium :

(1) Uranium requirements and its price.

(2) Plutonium stockpile and demand for it.

(3) conversion and breeding ratios of reactors.

(4) Mode of plutonium use (whether recycled or not).

(5) Established international market for plutonium.

Appendix to Chapter V

Estimation of CPGA – CPGB

CPGA - CPGB for a combination of Fast U-235 reactors and fast Pu breeders can be estimated more reliably than for a combination of HWOCRs and fast breeders because the unit capital cost of the two types of fast reactors are practically the same. The following development illustrates how the difference in the fuel cycle costs for these two types of fast reactors can be estimated.

Assuming same fixed capital charges, operation and maintainance costs and reprocessing costs for both reactors, FCCA = FCCB, OMA = OMB, and RA = RB.

If FA-FB = -\$40/kgm of fuel, then with a burnup of 100,000 MWthD/T and $\eta = 0.40$, we have

$$\text{FA} - \text{FB} = \frac{-40\ \$/\text{kg} \times 10\ \text{kg/T} \times 365\ \text{d/yr}}{100{,}000\ \text{MWthd/T} \times 0.4\ \text{e/th}} = -365\ \$/\text{MWeyr}$$

Fast U-235 reactors require say 20 % enriched U, and hence fissile makeup requirements will be :

$$\text{Kgm of U} = \frac{0.23\ \text{ST of}\ U_3O_8 \times 238/270\ U/U_3O_8 \times 907.18\ \text{kg/ST}}{(20 - 0.2531)}$$

$$\times (0.711 - 0.2531)\ [\ 20\%\ \text{U-235/nat U}]$$

$$= 4.26\ \text{kgms/MWeyr}$$

This costs 2252 \$/kgm or alternatively, 9610 \$/MWeyr. = DA.

Similarly the inventory requirements are :

$$\text{Kgm of U} = 1.44\ \text{ST of}\ U_3O_8 \times 238/270\ U/U_3O_8 \times 907.18\ \text{kg/ST}$$

$$\times (0.711 - 0.2531)/(20 - 0.2531)\ [\ 20\%\text{U-235/nat U}]$$

$$= 27.2\ \text{kgm of U-235/MWe}$$

Hence, FCA - FCB = - 40 \$/kgm x 27.2 kgm/MWe = - 1088 \$/MWe

Uranium inventory value can be taken as :

= 0.6 x value of specific inventory
= 0.6 x 27.2 x 2252 $/MWe
= 36900 $/MWe

Finally,

FCCA - FCCB = 0
OMA - OMB = 0
FA - FB = - 365
RA - RB = 0
DA = 9610
i(FCA-FCB) = -0.1(1088)
i UCA = 0.1(36900)

Hence, CPGA – CPGB = 12,826 $/MWeyr

CHAPTER VI

NUCLEAR POWER COMPLEX SYSTEMS

VI A INTRODUCTION :

A nuclear power complex system means a particular combination of light water reactors, advanced converter reactors and breeder reactors set up on the basis of developing nuclear technology, efficient fuel utilization and total demand for power.

The purpose of this chapter is to derive the quantitative conclusions with a given set of data on reactor performance, growing nuclear technology and assumptions regarding the nuclear power complex systems.

A computer code was developed (see the Appendix) for this purpose and is to be called "DYNUCLEAR". This code, written in a computer language called DYNAMO [Ref.(5)], calculates for every quarter of year from 1965 to 2040, the total installed nuclear power capacity, the growth of nuclear power, the share of total power capacity by individual reactor types, the total electrical power generated by each of them, the cumulative uranium requirements of the complex, net plutonium stockpile and the price of uranium and plutonium.(for the case of BNE).

VI B DATA AND ASSUMPTIONS :

Most of the data used in this computer code is derived from USAEC's report, "Analysis of advanced converter and self-sustaining breeders (March 1965).

[1] Installed Capacity & Growth of Nuclear Power :

It is assumed that the total installed nuclear power generating capacity is an exponential function of time, given by :

$$P(t) = P_o e^{\lambda t} \quad \text{MWe} \quad \text{.....Eq. VI.1}$$

where,

$P(t)$: Total installed nuclear MWe capacity at time t
P_o : Nuclear capacity at $t = 0$
λ : Fractional growth rate constant (fraction/yr)

Lambda (λ) is assumed to be constant over a five year period and is different for every five year periods. Lambda is computed first to fit AEC's data (Table I.1) upto year 2020 and is assumed to be 0.040 between year 2020-2025 and 0.0360 per year between 2025 to 2040 for the lack of good data. The computed value of Lambda, drawn as a histogram, is shown in Fig VI.1 and is tabulated in Table DATA. Based on these values of λ and equation VI.1, the total installed nuclear megawatt-electrical capacity [TMWE] is computed and is as shown in Fig. VI.2 and Table DATA. The difference between two successive values of installed nuclear megawatt-electrical capacity is growth rate of nuclear power [GROTH] , i.e.

$$\text{GROTH}(t) = \text{TMWE}(t+1) - \text{TMWE}(t) \quad \text{.....Eq. VI.2}$$

This value of growth in nuclear power every year is shown in Fig VI.3 and is tabulated in Table VI.1A. Notice that the growth rate is a discontinuous function of time because of different values of Lambda with different five year periods.

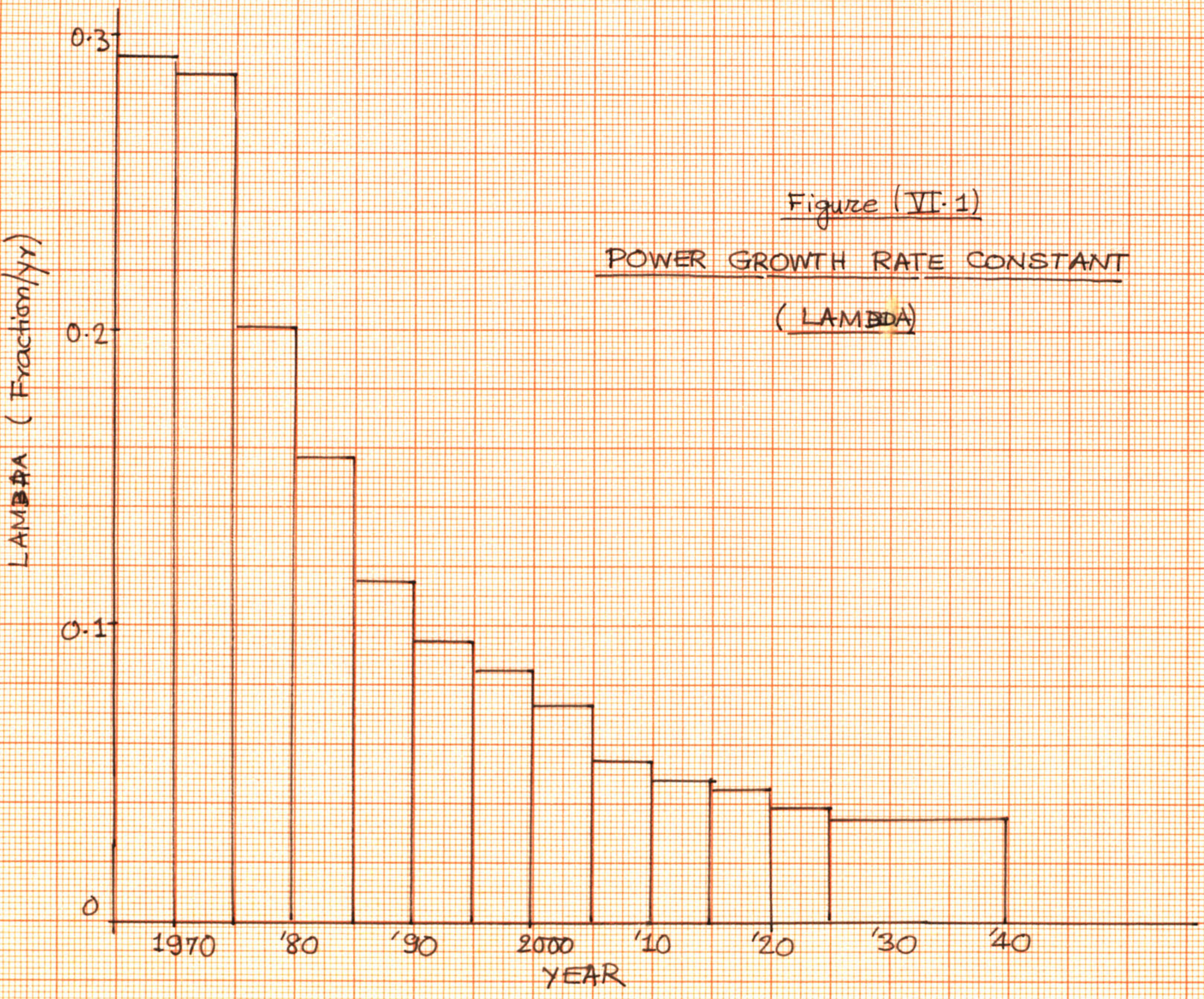
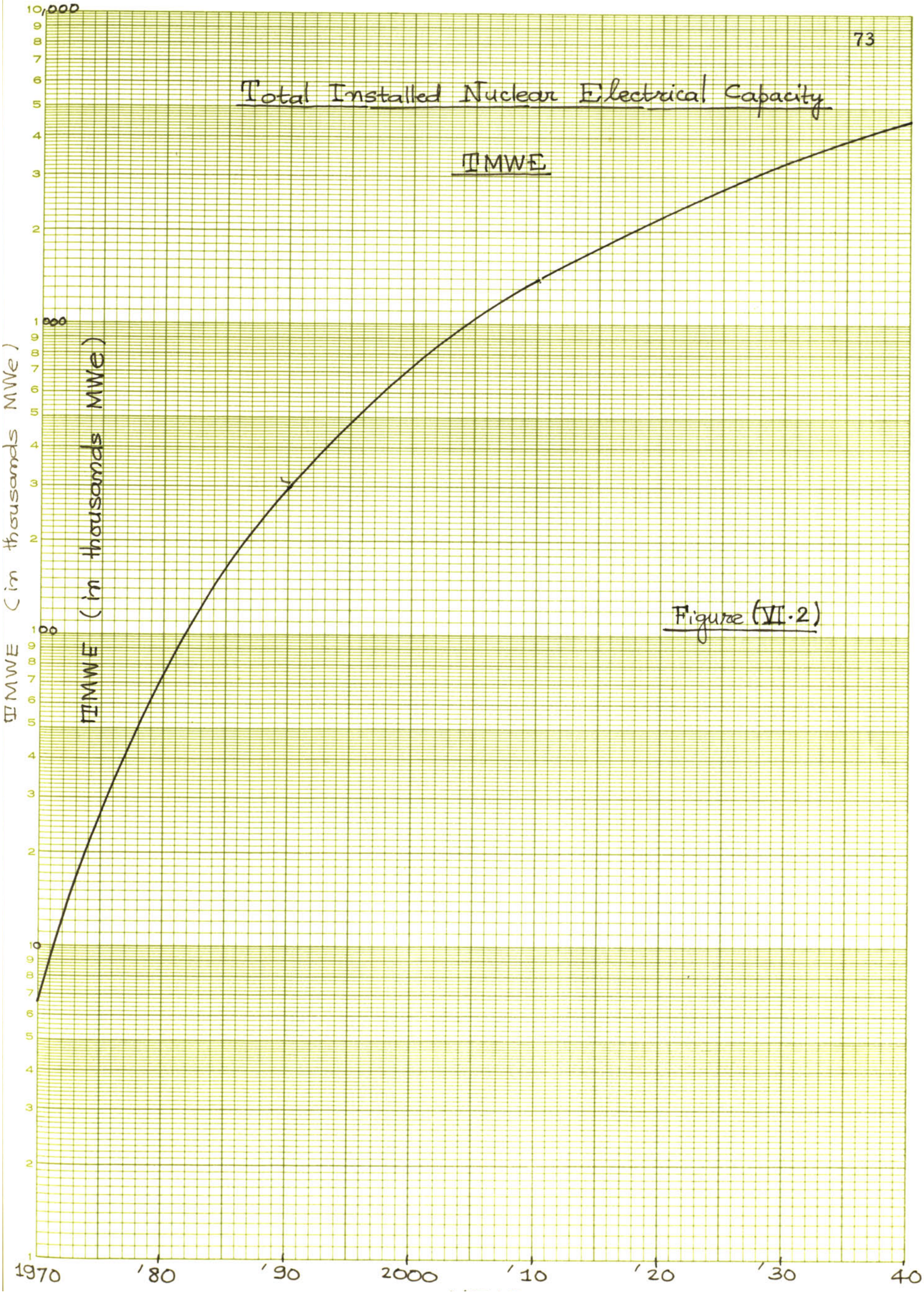


Figure (VI.1)

POWER GROWTH RATE CONSTANT

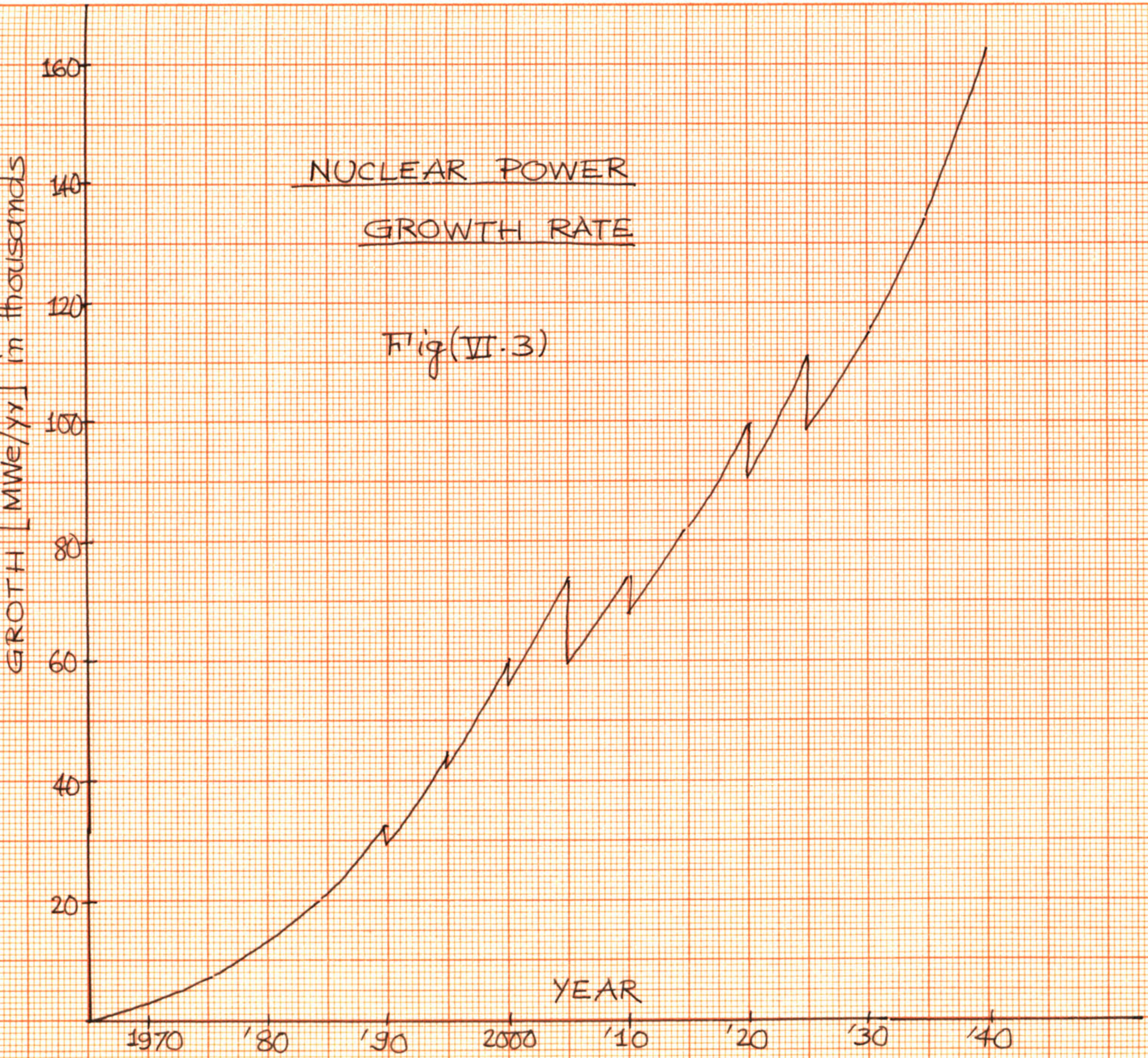
(LAMBDA)



Total Installed Nuclear Electrical Capacity

TMWE

Figure (VI.2)



NUCLEAR POWER GROWTH RATE

Fig(VI.3)

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resume dyn data madtrn
W 1113.3
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Table VI.1A

```
PAGE 1       DATA      GROWTH OF NUCLEAR POWER         02/12/66    1113.3

 TIME             YEAR             TMWE             GROTH            LAMDA
 E+00             E+00             E+03             E+03             E+00
  .000           1964.0               .0              .00           .29327
 2.000           1966.0              2.0              .69           .29327
 4.000           1968.0              3.6             1.23           .29327
 6.000           1970.0              6.5             2.17           .28848
 8.000           1972.0             11.6             3.87           .28848
10.000           1974.0             20.6             6.89           .28848
12.000           1976.0             33.6             7.47           .20066
14.000           1978.0             50.2            11.16           .20066
16.000           1980.0             75.0            12.81           .15769
18.000           1982.0            102.8            17.56           .15769
20.000           1984.0            140.9            24.07           .15769
22.000           1986.0            185.3            22.84           .11621
24.000           1988.0            233.8            28.81           .11621
26.000           1990.0            295.0            29.49           .09527
28.000           1992.0            356.9            35.68           .09527
30.000           1994.0            431.8            43.16           .09527
32.000           1996.0            517.6            46.46           .08595
34.000           1998.0            614.7            55.17           .08595
36.000           2000.0            730.0            55.05           .07270
38.000           2002.0            844.2            63.66           .07270
40.000           2004.0            976.4            73.63           .07270
42.000           2006.0           1109.0            62.30           .05466
44.000           2008.0           1237.1            69.50           .05466
46.000           2010.0           1380.0            67.14           .04751
48.000           2012.0           1517.5            73.83           .04751
50.000           2014.0           1668.8            81.19           .04751
52.000           2016.0           1832.0            85.79           .04577
54.000           2018.0           2007.6            94.02           .04577
56.000           2020.0           2200.0            89.78           .04000
58.000           2022.0           2383.2            97.26           .04000
60.000           2024.0           2581.7           105.36           .04000
62.000           2026.0           2785.5           102.10           .03600
64.000           2028.0           2993.4           109.73           .03600
66.000           2030.0           3216.9           117.92           .03600
68.000           2032.0           3457.1           126.72           .03600
70.000           2034.0           3715.2           136.18           .03600
72.000           2036.0           3992.5           146.35           .03600
74.000           2038.0           4290.6           157.28           .03600
76.000           2040.0           4610.9           169.02           .03600


TYPE CHANGES IF RERUN DESIRED
```

[2] Load Factor :

Fig VI.4a shows the values of load factor [L] between 1965 and year 2040. It is assumed to be 0.80 until 1980 then decrease linearly to 0.70 by year 2000 and remains constant at 0.70 thereafter. Table VI.1C lists these values.

[3] Inventory Requirements :

The uranium inventory requirements per megawatt-electrical capacity installed in light water reactors [ILWRC] and high temperature gas cooled reactors [IHTRC] , bred fuel recycled, are shown in Fig VI.4b in ST of U_3O_8 [STNU] /MWe. ILWRC and IHTRC decrease linearly from their initial values of 1 STNU/MWe and 0.9 STNU/MWe in 1965 to 0.7 STNU/MWe and 0.6 STNU/MWe respectively in year 2000 and remain constant at their lower values thereafter. Without bred Pu recycling, the inventory in LWR's [ILWWR] is assumed to be constant at 1.0 STNU/MWe, throughout. The case of U-233 not recycled in HTGR-Th reactors is not considered throughout this thesis, since it is not economical. The U inventory requirements in HWOCR-U reactors, without Pu recycling [IHWWR] and with recycling [IHWRC] are assumed constant at 0.33 STNU/MWe and 0.20 STNU/MWe respectively. The uranium inventory requirements of a FAST U-235 fueled reactor without Pu recycling [INFUR] is also assumed to be constant at 1.44 STNU/MWe.

[4] Burnup Requirements :

The fuel burnup requirements per megawatt year of electrical

REACTOR PERFORMANCE (DATA)

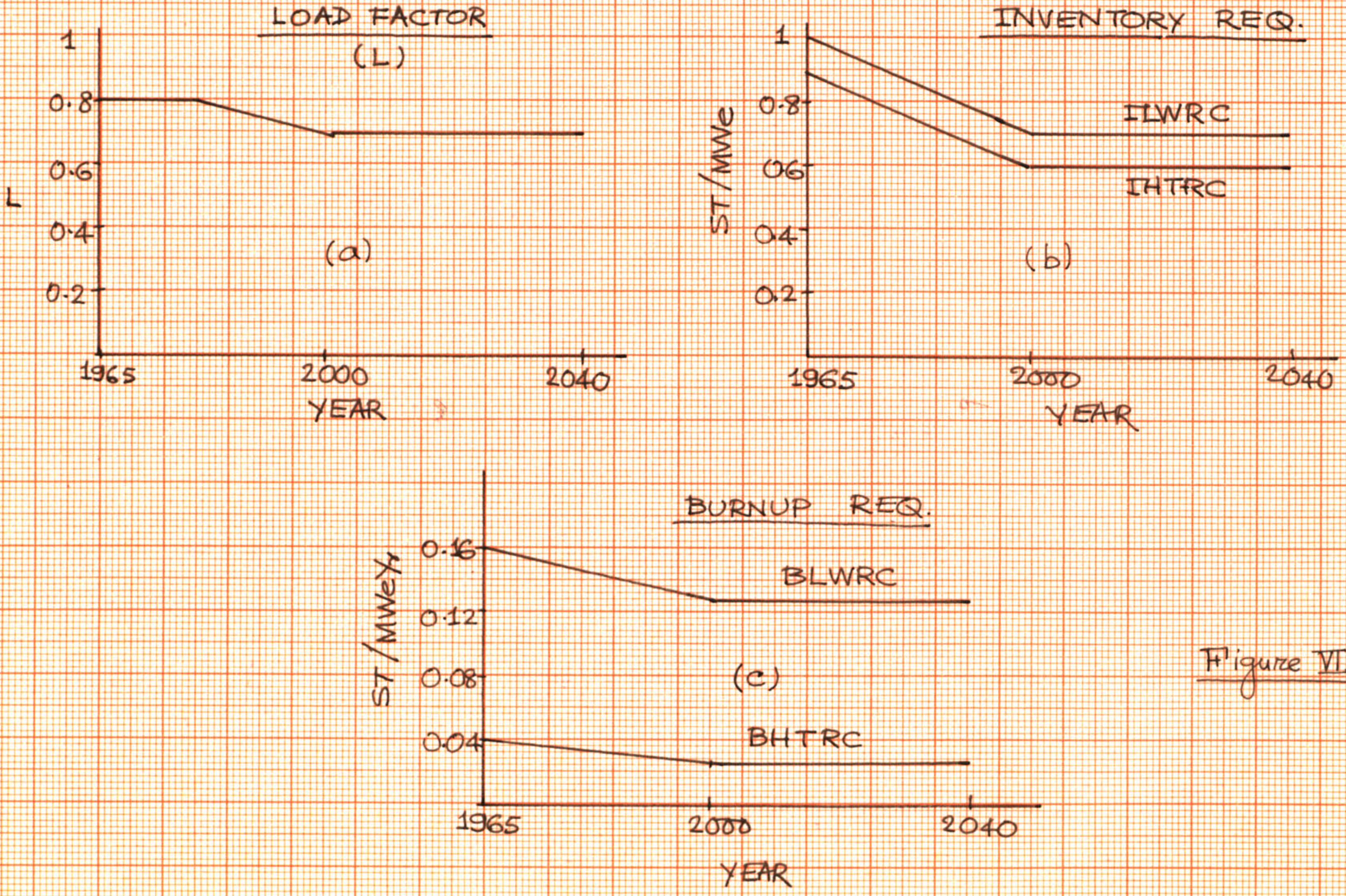

Figure VI. 4 a,b,c

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resume dyn data madtrn
W 1155.5
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Table VI.1B

DATA : INVENTORY REQUIREMENTS.
(ST/MWe)

```
 PAGE 1       DATA      GROWTH OF NUCLEAR POWER          02/12/66   1155.5

   TIME     YEAR    ILWRC    ILWWR    IHWRC    IHWWR    IHTRC    INFUR
   E+00     E+00    E+00     E+00     E+00     E+00     E+00     E+00
    .000  1964.0  1.0000   1.0000   .20000   .33000   .90000   1.4400
   2.000  1966.0   .9829   1.0000   .20000   .33000   .88286   1.4400
   4.000  1968.0   .9657   1.0000   .20000   .33000   .86571   1.4400
   6.000  1970.0   .9486   1.0000   .20000   .33000   .84857   1.4400
   8.000  1972.0   .9314   1.0000   .20000   .33000   .83143   1.4400
  10.000  1974.0   .9143   1.0000   .20000   .33000   .81429   1.4400
  12.000  1976.0   .8971   1.0000   .20000   .33000   .79714   1.4400
  14.000  1978.0   .8800   1.0000   .20000   .33000   .78000   1.4400
  16.000  1980.0   .8629   1.0000   .20000   .33000   .76286   1.4400
  18.000  1982.0   .8457   1.0000   .20000   .33000   .74571   1.4400
  20.000  1984.0   .8286   1.0000   .20000   .33000   .72857   1.4400
  22.000  1986.0   .8114   1.0000   .20000   .33000   .71143   1.4400
  24.000  1988.0   .7943   1.0000   .20000   .33000   .69429   1.4400
  26.000  1990.0   .7771   1.0000   .20000   .33000   .67714   1.4400
  28.000  1992.0   .7600   1.0000   .20000   .33000   .66000   1.4400
  30.000  1994.0   .7429   1.0000   .20000   .33000   .64286   1.4400
  32.000  1996.0   .7257   1.0000   .20000   .33000   .62571   1.4400
  34.000  1998.0   .7086   1.0000   .20000   .33000   .60857   1.4400
  36.000  2000.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  38.000  2002.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  40.000  2004.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  42.000  2006.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  44.000  2008.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  46.000  2010.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  48.000  2012.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  50.000  2014.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  52.000  2016.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  54.000  2018.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  56.000  2020.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  58.000  2022.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  60.000  2024.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  62.000  2026.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  64.000  2028.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  66.000  2030.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  68.000  2032.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  70.000  2034.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  72.000  2036.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  74.000  2038.0   .7000   1.0000   .20000   .33000   .60000   1.4400
  76.000  2040.0   .7000   1.0000   .20000   .33000   .60000   1.4400


TYPE CHANGES IF RERUN DESIRED
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power generated with plutonium recycled in LWR's [BLWRC] and in HTGR-Th reactors [BHTRC] are shown in Fig VI.4c. BLWRC decreases linearly from 0.16 STNU/MWeYr to 0.14 between 1965 and 2000 and remains constant at lower value thereafter. Similarly, BHTRC decreases linearly from 0.04 STNU/MWeYr to 0.025 between 1965 and 2000, and remains constant, thereafter. Without Pu recycling the burnup requirements in LWR's [BLWWR] and in FAST U-235 fueled reactors [BNFUR] are constant at 0.25 STNU/MWeYr and 0.23 STNU/MWeYr, respectively. The burnup requirements in HWOCR-U reactors with Pu recycling [BHWRC] and without recycling [BHWWR] are assumed constant at 0.09 STNU/MWeYr and 0.15 STNU/MWeYr, respectively.

In summary, all these inventory and burnup requirements are as shown in Table I.4 of first chapter. Any range of values shown in there is assumed to decrease linearly between 1965 and year 2000 and remain constant at lower value thereafter. Table VI.1 A, B & C lists all these values.

[5] Total Generated Electrical Power :

Fig VI.5 shows the cumulative electrical power generated [TPGA] from 1965, based on the above values of total installed nuclear power capacity [TMWE] , the growth of nuclear power every year [GROTH] and the load factor [L] . TPGA is computed in MWeYrs, is the total area under the curve of TMWE, multiplied by appropriate load-factor, and bounded by appropriate time axes.

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resume dyn data madtrn
W 1327.9
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Table VI.1C

DATA : BURNUP REQUIREMENTS
(ST/MWeYr)

```
PAGE 1        DATA       GROWTH OF NUCLEAR POWER          02/12/66   1327.9

  TIME     YEAR    BLWRC    BLWWR    BHWRC    BHWWR    BHTRC    BNFUR        L
  E+00     E+00     E+00     E+00     E-03     E+00     E-03     E+00     E+00
   .000   1964.0   .16000   .25000   90.000   .15000   40.000   .23000   .80000
  2.000   1966.0   .15829   .25000   90.000   .15000   39.143   .23000   .80000
  4.000   1968.0   .15657   .25000   90.000   .15000   38.286   .23000   .80000
  6.000   1970.0   .15486   .25000   90.000   .15000   37.429   .23000   .80000
  8.000   1972.0   .15314   .25000   90.000   .15000   36.571   .23000   .80000
 10.000   1974.0   .15143   .25000   90.000   .15000   35.714   .23000   .80000
 12.000   1976.0   .14971   .25000   90.000   .15000   34.857   .23000   .80000
 14.000   1978.0   .14800   .25000   90.000   .15000   34.000   .23000   .80000
 16.000   1980.0   .14629   .25000   90.000   .15000   33.143   .23000   .79500
 18.000   1982.0   .14457   .25000   90.000   .15000   32.286   .23000   .78500
 20.000   1984.0   .14286   .25000   90.000   .15000   31.429   .23000   .77500
 22.000   1986.0   .14114   .25000   90.000   .15000   30.571   .23000   .76500
 24.000   1988.0   .13943   .25000   90.000   .15000   29.714   .23000   .75500
 26.000   1990.0   .13771   .25000   90.000   .15000   28.857   .23000   .74500
 28.000   1992.0   .13600   .25000   90.000   .15000   28.000   .23000   .73500
 30.000   1994.0   .13429   .25000   90.000   .15000   27.143   .23000   .72500
 32.000   1996.0   .13257   .25000   90.000   .15000   26.286   .23000   .71500
 34.000   1998.0   .13086   .25000   90.000   .15000   25.429   .23000   .70500
 36.000   2000.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 38.000   2002.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 40.000   2004.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 42.000   2006.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 44.000   2008.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 46.000   2010.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 48.000   2012.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 50.000   2014.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 52.000   2016.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 54.000   2018.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 56.000   2020.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 58.000   2022.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 60.000   2024.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 62.000   2026.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 64.000   2028.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 66.000   2030.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 68.000   2032.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 70.000   2034.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 72.000   2036.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 74.000   2038.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000
 76.000   2040.0   .13000   .25000   90.000   .15000   25.000   .23000   .70000


TYPE CHANGES IF RERUN DESIRED
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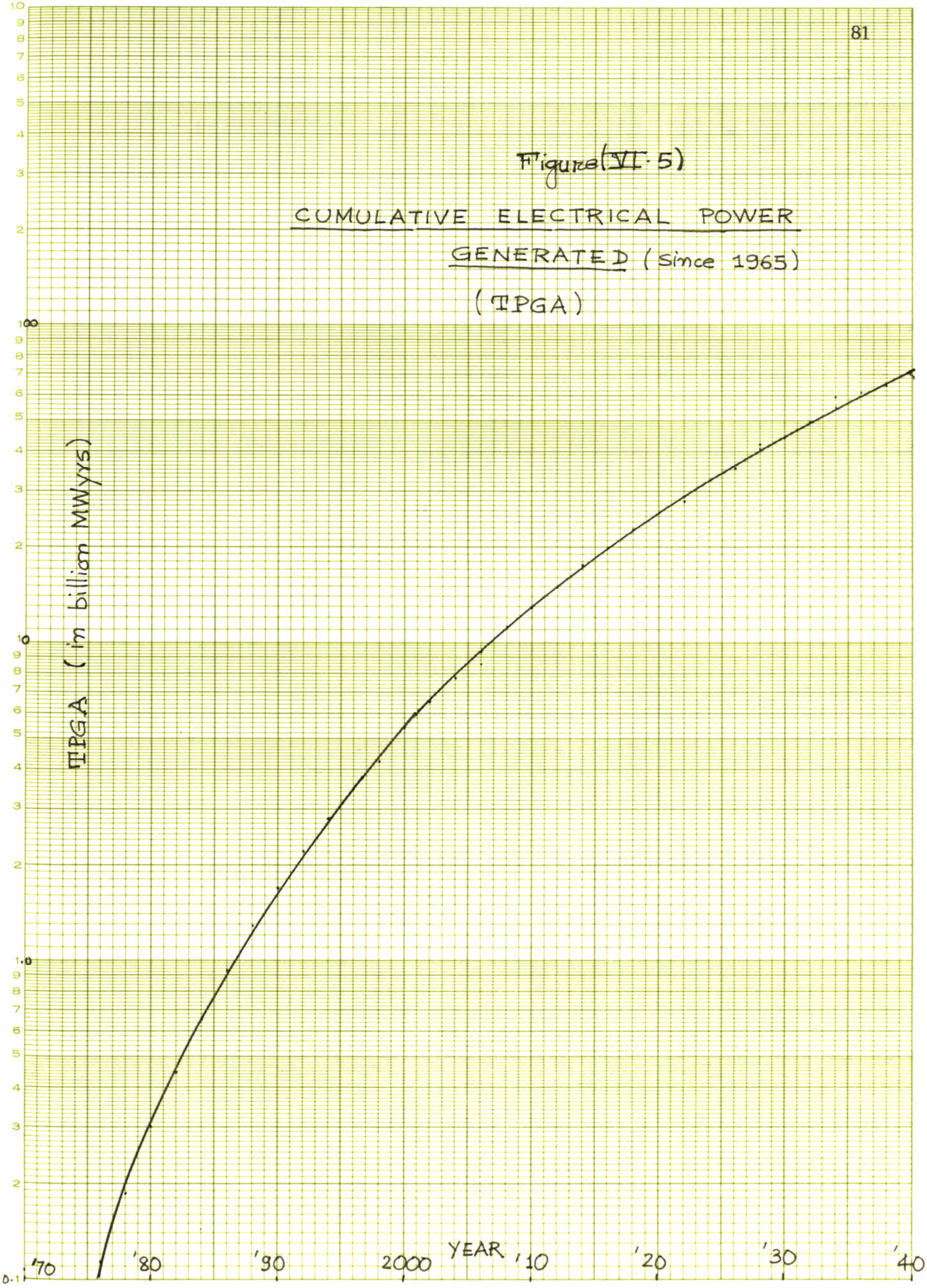

Figure(VI·5)

CUMULATIVE ELECTRICAL POWER GENERATED (since 1965)

(TPGA)

[6] Plutonium Production & Requirements :

The reactor grade fissile plutonium production rate and the breeder plutonium inventory requirements are assumed to be :

Net Pu prduction rate in LWR's :	0.32 kgms/MWeyr
Net Pu production rate in HWDCR-U:	0.35 kgms/MWeyr
Net Pu production rate in Fast U-235	0.83 kgms/MWeyr
Net Pu production rate in Breeders : (after allowing for makeup)	0.43 kgms/MWeyr
The inventory requirement of Pu fueled fast breeder reactors :	4.2 kgms/MWe

[7] Delay :

The delay in plutonium production and its consumption as an inventory because of time required for cooling, reprocessing and refabrication of the irradiated fuel is assumed to be a total of three years.

[8] Uranium Resources and Price:

The uranium resources and its cost of production are as given in Table I.2 and Fig VII.1. It is assumed that :

1. The price of uranium increases linearly with its consumption.
2. low cost uranium will be mined first,
3. values given in Table I.2 are after accounting for losses in minimg, chemical reprocessing, etc,
4. the diffusion plant tailings assay are at 0.25 percent.

Although, the first two assumptions are not strictly realistic, they are fair enough for this study. The tailings assay should have been decrease to a lower value with heavy demand and rising U price, but this computation was not intended into this study. To take allowance for ex-core uranium inventory, it has been required that the uranium be mined one year earlier than it is used in reactors.

[9] Reactor Life Period :

For simplicity of computations, no account was taken of the actual physical life of each reactor. If there came a time when a particular reactor was no longer needed, either for Pu production or uranium requirements, it was assumed that its operation would be terminated, even though the reactor might not have been in operation for its normal physical life. Conversely, in other cases, reactors were kept in operation longer than their normal physical life when they were needed to fulfill particular operating requirements. It is assumed further, that when a reactor is taken out of service, its inventory of uranium would become available to reduce the uranium requirements of the system.

In most of the nuclear power complex systems developed in the next section, no new LWR's are introduced after 1975, and mostly they are retired by year 2000. Also, most of the cases considered do not require a large proportion of uranium consuming reactor installations after the turn of this century. In these respects, the analysis performed in the next section will not be very much affected, had it been corrected for the reactor life of about thirty years. Retiring the uranium reactors after 30 years of their physical life, in fact, will reduce the total uranium requirements producing more favorable results.

VI. C NUCLEAR POWER COMPLEXES : CASE STUDIES

A number of cases are analysed with different assumed nuclear power complexes. They are represented graphically as well as in table forms (computer printouts). In the computer printouts the name of the table and case considered appears on the first line. The variable names computed appear in the first row of columns. A complete description of variable names is listed in the appendix. In the second row of results, a scaling factor is also printed in the form of E+ some digit. The appropriate scaling factor is the ten raised to the power of that digit. [Thus E+03 = 10^3]. In the computations, when the range of the variable is specified, the computer interpolates (linearly) the intermediate values. All variables are computed for every quarter of year but printed every second year. Time and corresponding year are printed in first two columns. All installed capacities are in MWe, electrical power generated in MWeyrs, growth rates in MWe/yr, uranium requirements in Short Tons of U_3O_8 and Pu stockpile in Kgms of reactor grade fissile plutonium.

[1] CASE ALPHA :

In this simplest case, all installed nuclear power capacity consists of only LWR's. Two subcases considered are : (a) Pu not recycled and (b) Pu recycled.

Table VI. 2 lists the total nuclear megawatt-electrical capacity [TMWE] at the start of the year, the growth of nuclear power [GROTH] during the year; cumulative electrical power generated [TPGA] by that year. TUNA1 and TURNA are cumulative uranium requirements by that year without Pu recycling and with recycling. PLSPA is cumulative plutonium stockpile by that year, when it is not recycled. UPRA1 and UPRA are the uranium prices in dollar/lb, without and with Pu recycle, respectively.

It can be concluded that :

With only LWR's in the system, the total power generated, by year 2000, (5.36 million MWeyrs) requires about 1.8 million ST of U_3O_8 (to be mined at least by 1999) when Pu is not recycled and about 1.1 million ST when it is recycled; corresponding uranium prices being about thirty dollars per pound and seventeen dollars per pound, respectively. Without recycling, the Pu stockpile rises to about total of 1.2 million kgms. It is obvious that in such a case without Pu recycling total required uranium is more than one and half times that of when it is recycled, and the price of uranium is almost double. Thus, in a very pessimistic case, such as this, of not having commercial ACR's or Breeders, the problem of fuel requirements is very serious and becomes more serious with time. In any case, plutonium recycling will be advantageous and will eliminate about 12 billion dollars of unintended investment in plutonium stockpile (at the plutonium price of 10 dollars per gram), by year 2000.

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resume dyn alpha madtrn
W 1416.6
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Table VI.2

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PAGE 1      ALPHA      NUCLEAR POWER COMPLEX ALPHA     02/12/66    1416.6

    TIME     YEAR     TMWE     TPGA    TUNA1    TURNA    UPRA1     UPRA    PLSPA
    E+00     E+00     E+03     E+06     E+06     E+06     E+00     E+00     E+06
    .000   1964.0       .0     .000     .000     .000    5.000    5.000     .000
   2.000   1966.0      2.0     .003     .001     .001    5.006    5.005     .000
   4.000   1968.0      3.6     .008     .003     .003    5.022    5.017     .001
   6.000   1970.0      6.5     .017     .008     .006    5.049    5.039     .002
   8.000   1972.0     11.6     .034     .016     .012    5.098    5.076     .004
  10.000   1974.0     20.6     .063     .030     .023    5.185    5.142     .007
  12.000   1976.0     33.6     .113     .051     .039    5.321    5.241     .014
  14.000   1978.0     50.2     .188     .081     .060    5.508    5.374     .025
  16.000   1980.0     75.0     .298     .126     .091    5.788    5.569     .044
  18.000   1982.0    102.8     .451     .183     .129    6.144    5.808     .071
  20.000   1984.0    140.9     .658     .260     .180    6.627    6.128     .111
  22.000   1986.0    185.3     .930     .358     .244    7.239    6.523     .165
  24.000   1988.0    233.8    1.269     .475     .317    7.969    6.981     .238
  26.000   1990.0    295.0    1.692     .621     .407    8.881    7.546     .331
  28.000   1992.0    356.9    2.200     .789     .508    9.928    8.175     .447
  30.000   1994.0    431.8    2.806     .989     .627   14.204    8.918     .591
  32.000   1996.0    517.6    3.526    1.225     .764   19.448    9.777     .763
  34.000   1998.0    614.7    4.369    1.499     .921   25.535   12.683     .968
  36.000   2000.0    730.0    5.357    1.821    1.102   30.303   16.716    1.210
  38.000   2002.0    844.2    6.503    2.182    1.303   31.204   21.178    1.493
  40.000   2004.0    976.4    7.829    2.599    1.535   32.247   26.338    1.826
  42.000   2006.0   1109.0    9.347    3.064    1.792   33.409   30.231    2.212
  44.000   2008.0   1237.1   11.039    3.569    2.070   34.672   30.925    2.658
  46.000   2010.0   1380.0   12.927    4.133    2.379   36.081   31.699    3.162
  48.000   2012.0   1517.5   15.009    4.741    2.712   37.602   32.529    3.724
  50.000   2014.0   1668.8   17.298    5.410    3.077   39.275   33.443    4.350
  52.000   2016.0   1832.0   19.814    6.143    3.477   41.108   34.443    5.038
  54.000   2018.0   2007.6   22.570    6.944    3.914   43.111   35.535    5.795
  56.000   2020.0   2200.0   25.590    7.822    4.393   45.306   36.731    6.625
  58.000   2022.0   2383.2   28.870    8.759    4.901   47.648   38.002    7.536
  60.000   2024.0   2581.7   32.423    9.774    5.451   50.246   39.378    8.531
  62.000   2026.0   2785.5   36.264   10.864    6.041   53.879   40.853    9.609
  64.000   2028.0   2993.4   40.391   12.028    6.670   57.759   42.425   10.778
  66.000   2030.0   3216.9   44.825   13.278    7.346   61.928   44.115   12.038
  68.000   2032.0   3457.1   49.591   14.622    8.073   66.408   45.931   13.391
  70.000   2034.0   3715.2   54.713   16.067    8.853   71.223   47.883   14.846
  72.000   2036.0   3992.5   60.216   17.619    9.692   76.398   49.981   16.409
  74.000   2038.0   4290.6   66.131   19.288   10.594   81.958   52.979   18.089
  76.000   2040.0   4610.9   72.488   21.080   11.563   87.934   56.209   19.894


TYPE CHANGES IF RERUN DESIRED
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[2] CASE BETA :

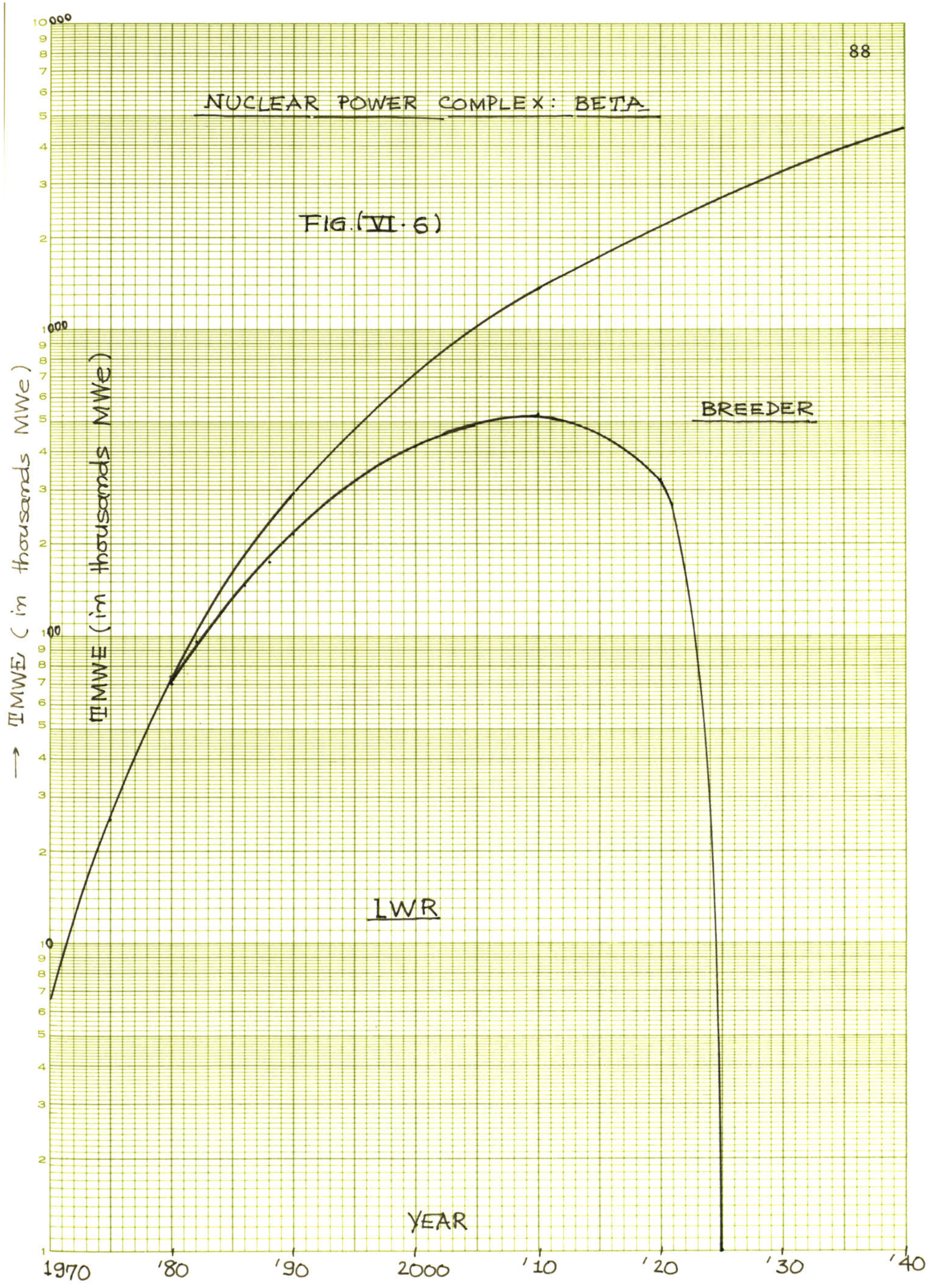
In this case(see Fig VI.6), upto 1979 there are only LWR's. Pu is not recycled but stockpiled for the initial and later growth of of Breeders. Breeders [BB] are introduced in 1980 at an initial growth rate of 1000, 3000, 5000, 8000 and 10,000 MWe [IBRGR] each year until 1984. (since all computations are done for every quarter of year, the intermediate values are linearly interpolated). From 1985, the BNE starts in which the growth of breeders is determined by the plutonium production rate, 3 years earlier, in LWR's and Breeders themselves. Because of the three-years delay, the actual BNE starts from 1988, although, there is a short term BNE between 1985-88 because of balance between Pu production rate between '82-85 and consumption rate between '85-'88. The initial plutonium stockpile [PLSPB] produced from LWR's is consumed in the initial inventory requirements of Breeders until BNE. The Pu stockpile remains constant at 3400 kgms between '85-'88 and then at 3800 kgms between 1988-2025, until breeders become self-sufficient in 2026. In year 2026 thus, the last of light water reactors are retired. . The breeder growth rate and installed capacity becomes equal to TMWE and GROTH and hence, a huge Pu stockpile starts developing from 2026 onwards.

The conclusions are :

In nuclear power complex of case BETA, by year 2000, the cumulative uranium requirements [TURNB] are about one million

NUCLEAR POWER COMPLEX: BETA

FIG.(VI·6)



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resume dyn beta madtrn
W 1506.2
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Table VI.3

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PAGE 1        BETA        NUCLEAR POWER COMPLEX BETA      02/12/66    1506.2

  TIME      YEAR      TMWE        CB        BB      GRBB     TURNB      UPRB     PLSPB
  E+00      E+00      E+03      E+03      E+03      E+03      E+03      E+00      E+03
   .000    1964.0        .0       .00        .0       .00        .0     5.000        .0
  2.000    1966.0       2.0      2.01        .0       .00       1.0     5.006        .0
  4.000    1968.0       3.6      3.62        .0       .00       3.5     5.022        .7
  6.000    1970.0       6.5      6.50        .0       .00       7.9     5.049       1.8
  8.000    1972.0      11.6     11.57        .0       .00      15.7     5.098       3.8
 10.000    1974.0      20.6     20.61        .0       .00      29.6     5.185       7.5
 12.000    1976.0      33.6     33.61        .0       .00      51.3     5.321      14.0
 14.000    1978.0      50.2     50.21        .0       .00      81.3     5.508      25.5
 16.000    1980.0      75.0     74.62        .4      1.00     125.7     5.785      42.2
 18.000    1982.0     102.8     96.93       5.9      5.00     175.7     6.098      46.3
 20.000    1984.0     140.9    120.18      20.8     10.00     232.2     6.451      23.7
 22.000    1986.0     185.3    146.60      38.7      7.34     299.0     6.868       3.4
 24.000    1988.0     233.8    176.85      57.0     10.32     378.2     7.364       3.8
 26.000    1990.0     295.0    214.12      80.9     12.99     473.0     7.956       3.8
 28.000    1992.0     356.9    245.96     111.0     16.35     573.0     8.581       3.8
 30.000    1994.0     431.8    283.36     148.5     20.14     686.4     9.290       3.8
 32.000    1996.0     517.6    323.77     193.9     24.30     812.6    10.280       3.8
 34.000    1998.0     614.7    366.16     248.6     29.26     949.9    13.331       3.8
 36.000    2000.0     730.0    416.35     313.6     34.60    1104.4    16.764       3.8
 38.000    2002.0     844.2    453.70     390.5     40.86    1260.1    20.225       3.8
 40.000    2004.0     976.4    494.70     481.7     48.30    1427.8    23.950       3.8
 42.000    2006.0    1109.0    520.77     588.2     56.38    1592.5    27.611       3.8
 44.000    2008.0    1237.1    524.55     712.5     65.77    1738.2    30.095       3.8
 46.000    2010.0    1380.0    525.32     854.7     74.35    1876.6    30.441       3.8
 48.000    2012.0    1517.5    502.23    1015.3     84.01    1987.2    30.718       3.8
 50.000    2014.0    1668.8    472.51    1196.3     94.28    2077.0    30.942       3.8
 52.000    2016.0    1832.0    433.72    1398.2    105.10    2141.5    31.104       3.8
 54.000    2018.0    2007.6    384.31    1623.2    117.07    2174.9    31.187       3.8
 56.000    2020.0    2200.0    326.70    1873.3    129.92    2175.4    31.189       3.8
 58.000    2022.0    2383.2    232.57    2150.7    144.08    2113.2    31.033       3.8
 60.000    2024.0    2581.7    124.16    2457.6    158.94    1995.3    30.738       3.8
 62.000    2026.0    2785.5       .00    2785.5    102.10    1807.8    30.269       3.8
 64.000    2028.0    2993.4       .00    2993.4    109.73    1807.8    30.269    1002.0
 66.000    2030.0    3216.9       .00    3216.9    117.92    1807.8    30.269    2096.5
 68.000    2032.0    3457.1       .00    3457.1    126.72    1807.8    30.269    3274.0
 70.000    2034.0    3715.2       .00    3715.2    136.18    1807.8    30.269    4539.4
 72.000    2036.0    3992.5       .00    3992.5    146.35    1807.8    30.269    5899.3
 74.000    2038.0    4290.6       .00    4290.6    157.28    1807.8    30.269    7360.8
 76.000    2040.0    4610.9       .00    4610.9    169.02    1807.8    30.269    8931.3


TYPE CHANGES IF RERUN DESIRED
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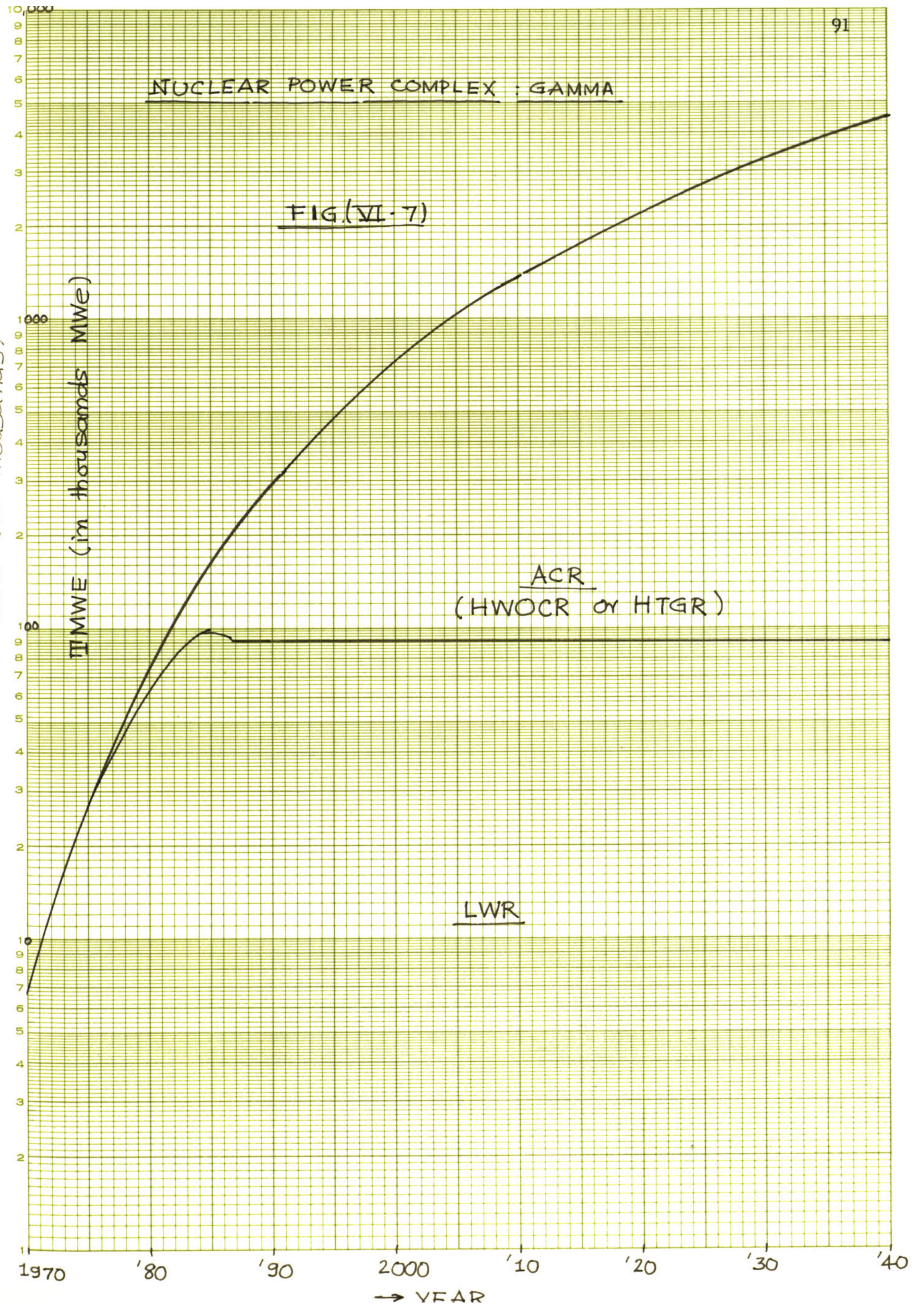
ST costing about 17 dollars per pound. Note that this is almost the same amount if only LWR's were to be installed, with Pu recycling, as in case (b) of ALPHA. The highest U price by year 2040 is about 30 dollars per pound as compared to 88 dollars per pound of case ALPHA (Pu not recycled). Hence, although long-term uranium requirements are reduced in this case, the short term fuel problem is as serious as in the previous case. It should be noted, however, that unintended Pu investments are far reduced in this case as compared to the previous case.

[3] CASE GAMMA :

In this case it is assumed that no commercial breeders will be available at any time. Upto 1975, (see Fig VI. 7) there are only LWR's recycling plutonium and from 1975 onwards, ACR's (also recycling bred fuel) are introduced at a gradually increasing growth rate. In 1975, 10 percent of total growth (new installations) is of ACR's, in 1976 this fraction increases to 20 percent, and so on, until 1984 when all the new installations are of ACR's- and thereafter. The LWR's installed capacity [CC] in this case rises to about 90,000 MWe by 1985 and remains at that level thereafter. The ACR capacity [AC] being the difference between TMWE and LWR capacity after 1985, continues to rise.

Two subcases of case GAMMA corrospond to the type of ACR to be installed, HWOCR-U or HTGR-Th. In either case, the bred fuel is recycled. In Table GAMMA, TURNC and TURND correspond to the cumulative uranium requirements, when HWOCR-U



NUCLEAR POWER COMPLEX : GAMMA

FIG.(VI-7)

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resume dyn gamma madtrn
W 1832.5
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Table VI.4

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PAGE 1      GAMMA       NUCLEAR POWER COMPLEX GAMMA    02/12/66   1832.5

  TIME      YEAR      TMWE       CC        AC      TURNC     TURND      UPRC      UPRD
  E+00      E+00      E+03      E+03      E+03      E+03      E+03      E+00      E+00
   .000    1964.0        .0      .000        .0        .0        .0     5.000     5.000
  2.000    1966.0       2.0     2.011        .0        .8        .8     5.005     5.005
  4.000    1968.0       3.6     3.616        .0       2.7       2.7     5.017     5.017
  6.000    1970.0       6.5     6.500        .0       6.2       6.2     5.039     5.039
  8.000    1972.0      11.6    11.574        .0      12.2      12.2     5.076     5.076
 10.000    1974.0      20.6    20.609        .0      22.7      22.7     5.142     5.142
 12.000    1976.0      33.6    33.032        .6      38.1      38.4     5.238     5.240
 14.000    1978.0      50.2    46.284       3.9      56.8      58.9     5.355     5.368
 16.000    1980.0      75.0    62.664      12.3      81.5      87.6     5.510     5.547
 18.000    1982.0     102.8    77.512      25.3     109.5     120.8     5.684     5.755
 20.000    1984.0     140.9    92.722      48.2     142.7     162.7     5.892     6.017
 22.000    1986.0     185.3    90.000      95.3     181.0     209.3     6.131     6.308
 24.000    1988.0     233.8    90.000     143.8     224.9     257.2     6.405     6.607
 26.000    1990.0     295.0    90.000     205.0     277.5     312.1     6.734     6.951
 28.000    1992.0     356.9    90.000     266.9     337.6     368.1     7.110     7.301
 30.000    1994.0     431.8    90.000     341.8     407.9     431.0     7.550     7.694
 32.000    1996.0     517.6    90.000     427.6     489.6     499.7     8.060     8.123
 34.000    1998.0     614.7    90.000     524.7     583.4     574.2     8.646     8.589
 36.000    2000.0     730.0    90.000     640.0     692.5     657.5     9.328     9.110
 38.000    2002.0     844.2    90.000     754.2     815.5     743.8    10.344     9.649
 40.000    2004.0     976.4    90.000     886.4     956.9     841.5    13.487    10.922
 42.000    2006.0    1109.0    90.000    1019.0    1115.7     944.0    17.015    13.199
 44.000    2008.0    1237.1    90.000    1147.1    1289.5    1048.8    20.877    15.529
 46.000    2010.0    1380.0    90.000    1290.0    1482.7    1164.2    25.172    18.094
 48.000    2012.0    1517.5    90.000    1427.5    1692.7    1282.3    29.839    20.717
 50.000    2014.0    1668.8    90.000    1578.8    1923.2    1410.8    30.558    23.573
 52.000    2016.0    1832.0    90.000    1742.0    2175.4    1549.4    31.189    26.654
 54.000    2018.0    2007.6    90.000    1917.6    2451.0    1698.9    31.877    29.975
 56.000    2020.0    2200.0    90.000    2110.0    2752.5    1861.4    32.631    30.403
 58.000    2022.0    2383.2    90.000    2293.2    3076.0    2026.7    33.440    30.817
 60.000    2024.0    2581.7    90.000    2491.7    3426.1    2204.6    34.315    31.261
 62.000    2026.0    2785.5    90.000    2695.5    3802.8    2391.7    35.257    31.729
 64.000    2028.0    2993.4    90.000    2903.4    4205.6    2587.4    36.264    32.218
 66.000    2030.0    3216.9    90.000    3126.9    4638.2    2796.7    37.346    32.742
 68.000    2032.0    3457.1    90.000    3367.1    5102.7    3020.7    38.507    33.302
 70.000    2034.0    3715.2    90.000    3625.2    5601.5    3260.5    39.754    33.901
 72.000    2036.0    3992.5    90.000    3902.5    6137.2    3517.1    41.093    34.543
 74.000    2038.0    4290.6    90.000    4200.6    6712.5    3791.9    42.531    35.230
 76.000    2040.0    4610.9    90.000    4520.9    7330.3    4086.3    44.076    35.966
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TYPE CHANGES IF RERUN DESIRED
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and HTGR-Th type of ACR's are installed, respectively.

Table VI.4 shows that ,by year 2000, the cumulative U requirements with either type of ACR are almost the same, and are about 40 percent lesser than that required in case ALPHA or BETA. By year 2040, however, HTGR-Th type of ACR's require about 5 million ST and HWOCR-U require about 7 million ST of U O ; almost 30 percent lesser. This is because of lower burnup requirements in HTGR reactors and assumed improvement in its specific fuel rating by year 2000. Although, short term (by year 2000) uranium requirements of case GAMMA are smaller than that of case BETA, the long term (by year 2040) uranium requirements of case GAMMA are higher than that of case BETA. This is because in case BETA a substantial amount of Breeders are installed.

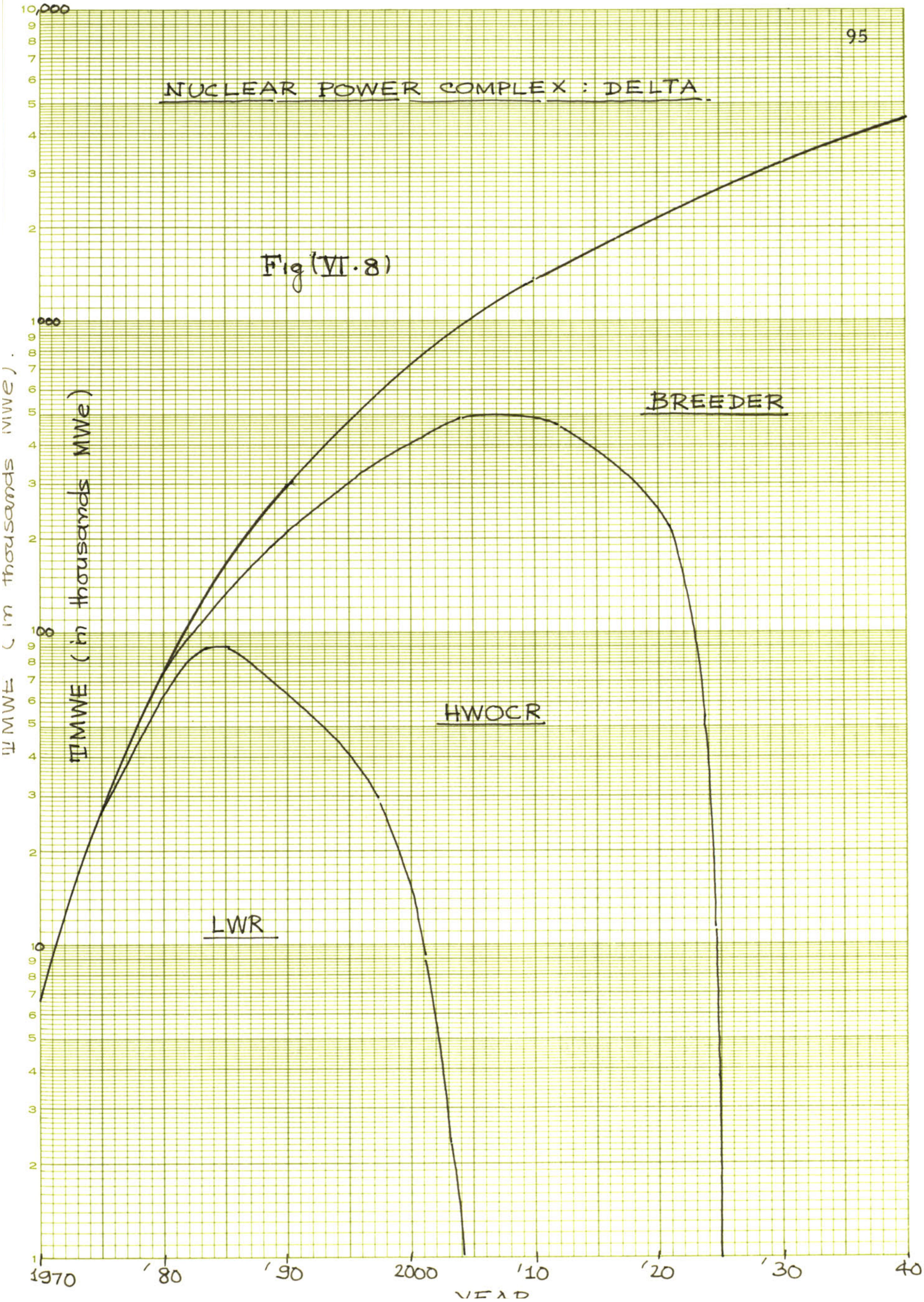
In conclusion :

If no commercial breeders are available, advanced converter reactors would reduce the burden of fuel problem, although such reduction is not very appreciable. In short run (by yr 2000) case GAMMA requires lesser uranium than case ALPHA (with Pu recycling) and case BETA, but in long run the demand increases. HTGR-Th type of ACR's and HWOCR-U type of ACR's require almost same amount of uranium by year 2000. In longer run, however, HTGR-Th type of ACR's require less uranium than HWOCR-U reactors. It should be remembered, however, that there is more flexibility in the use of bred fissile fuel in case of HWOCR-U type of advanced converters.

[4] CASE DELTA :

In this case (see Fig VI. 8), until 1975 there are only LWR's. From 1975, advanced converters of HWOCR-U type are gradually introduced in such a way that in 1975 the growth of HWOCR-U reactors [GRAE] is ten percent of total growth, in 1976 it rises to twenty percent and so on, until 1979 when it becomes fifty percent. The breeders are introduced in 1980 with an initial growth rate [IBRGR] of 1000, 3000, 5000, 8000 and 10,000 MWe/yr. The growth rate of HWOCR-U during '80-84 is sixty percent of remaining growth [GROTH-GRBE] in '80, seventy percent of remaining growth in '81 and so on, until it becomes 100 percent in 1984. The LWR capacity during '75-'85 period is the difference between total nuclear capacity and HWOCR plus breeder capacity combined. No plutonium is recycled in LWR's or HWOCR's; it is stockpiled for initial breeder inventory requirements. From 1986, every year 5000 MWe equivalent of LWR capacity is retired, until it goes to zero by year 2003. From 1985, the breeder growth [GRBE] is equivalent to the net plutonium production rate of the system, the remaining being HWOCR's.

Table VI. 5A,B lists the installed capacities of each individual reactor. It is also seen that the BNE starts from 1985 and continues upto 2025, almost for forty years. The Pu stockpile [PLSPE] remains constant at 4200 kgms during '85-'88 and at 4500 kgms during 1985-2025. The HWOCR's no longer needed



NUCLEAR POWER COMPLEX : DELTA

Fig (VI·8)

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resume dyn delta madtrn
W 1922.5
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Table VI.5 A

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PAGE 1     DELTA      NUCLEAR POWER COMPLEX DELTA     02/12/66   1922.5

   TIME     YEAR     TMWE       CE       AE       BE     GRCE     GRAE     GRBE
  E+00     E+00     E+03     E+03     E+03     E+03     E+00     E+03     E+03
   .000   1964.0       .0     .000      .00       .0       .0     .000      .00
  2.000   1966.0      2.0    2.011      .00       .0    685.4     .000      .00
  4.000   1968.0      3.6    3.616      .00       .0   1232.2     .000      .00
  6.000   1970.0      6.5    6.500      .00       .0   2173.6     .000      .00
  8.000   1972.0     11.6   11.574      .00       .0   3870.2     .000      .00
 10.000   1974.0     20.6   20.609      .00       .0   6891.4     .000      .00
 12.000   1976.0     33.6   33.032      .58       .0   5974.9    1.494      .00
 14.000   1978.0     50.2   46.284     3.92       .0   6694.0    4.463      .00
 16.000   1980.0     75.0   64.528    10.10       .4   4724.1    7.086     1.00
 18.000   1982.0    102.8   77.789    19.14      5.9   2512.0   10.048     5.00
 20.000   1984.0    140.9   91.497    28.68     20.8       .0   14.071    10.00
 22.000   1986.0    185.3   86.497    59.87     39.0  -5000.0   20.351     7.49
 24.000   1988.0    233.8   76.497    99.73     57.6  -5000.0   23.263    10.55
 26.000   1990.0    295.0   66.497   146.29     82.2  -5000.0   21.057    13.43
 28.000   1992.0    356.9   56.497   186.96    113.5  -5000.0   23.656    17.02
 30.000   1994.0    431.8   46.497   232.71    152.6  -5000.0   27.113    21.05
 32.000   1996.0    517.6   36.497   281.00    200.1  -5000.0   26.005    25.45
 34.000   1998.0    614.7   26.497   330.74    257.5  -5000.0   29.479    30.69
 36.000   2000.0    730.0   16.497   387.76    325.7  -5000.0   23.756    36.29
 38.000   2002.0    844.2    6.497   431.36    406.4  -5000.0   25.825    42.84
 40.000   2004.0    976.4     .000   474.49    501.9       .0   23.031    50.60
 42.000   2006.0   1109.0     .000   495.58    613.4       .0    3.319    58.98
 44.000   2008.0   1237.1     .000   493.80    743.3       .0     .843    68.66
 46.000   2010.0   1380.0     .000   488.67    891.3       .0  -10.196    77.34
 48.000   2012.0   1517.5     .000   459.49   1058.1       .0  -13.253    87.09
 50.000   2014.0   1668.8     .000   423.56   1245.2       .0  -16.187    97.38
 52.000   2016.0   1832.0     .000   378.62   1453.3       .0  -22.358   108.15
 54.000   2018.0   2007.6     .000   323.21   1684.4       .0  -26.020   120.04
 56.000   2020.0   2200.0     .000   259.84   1940.2       .0  -42.963   132.75
 58.000   2022.0   2383.2     .000   160.28   2222.9       .0  -49.451   146.71
 60.000   2024.0   2581.7     .000    46.94   2534.8       .0  -55.916   161.28
 62.000   2026.0   2785.5     .000      .00   2785.5       .0     .000   102.10
 64.000   2028.0   2993.4     .000      .00   2993.4       .0     .000   109.73
 66.000   2030.0   3216.9     .000      .00   3216.9       .0     .000   117.92
 68.000   2032.0   3457.1     .000      .00   3457.1       .0     .000   126.72
 70.000   2034.0   3715.2     .000      .00   3715.2       .0     .000   136.18
 72.000   2036.0   3992.5     .000      .00   3992.5       .0     .000   146.35
 74.000   2038.0   4290.6     .000      .00   4290.6       .0     .000   157.28
 76.000   2040.0   4610.9     .000      .00   4610.9       .0     .000   169.02


TYPE CHANGES IF RERUN DESIRED
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resume dyn delta madtrn
W 2027.2
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Table VI.5 B

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PAGE 1       DELTA       NUCLEAR POWER COMPLEX DELTA     02/12/66    2027.3

  TIME             YEAR             TURNE              UPRE             PLSPE
  E+00             E+00             E+03               E+00             E+03
   .000           1964.0               .0             5.000                .0
  2.000           1966.0              1.0             5.006                .0
  4.000           1968.0              3.5             5.022                .7
  6.000           1970.0              7.9             5.049               1.8
  8.000           1972.0             15.7             5.098               3.8
 10.000           1974.0             29.6             5.185               7.5
 12.000           1976.0             50.9             5.318              14.0
 14.000           1978.0             78.2             5.489              25.5
 16.000           1980.0            117.1             5.732              42.2
 18.000           1982.0            158.5             5.990              46.6
 20.000           1984.0            204.6             6.278              24.5
 22.000           1986.0            255.7             6.598               4.2
 24.000           1988.0            304.8             6.905               4.5
 26.000           1990.0            360.4             7.252               4.5
 28.000           1992.0            418.9             7.618               4.5
 30.000           1994.0            483.1             8.019               4.5
 32.000           1996.0            553.0             8.456               4.5
 34.000           1998.0            628.0             8.925               4.5
 36.000           2000.0            710.7             9.442               4.5
 38.000           2002.0            795.2             9.970               4.5
 40.000           2004.0            885.3            11.895               4.5
 42.000           2006.0            983.2            14.071               4.5
 44.000           2008.0           1074.1            16.090               4.5
 46.000           2010.0           1161.5            18.033               4.5
 48.000           2012.0           1236.9            19.709               4.5
 50.000           2014.0           1301.6            21.147               4.5
 52.000           2016.0           1353.5            22.300               4.5
 54.000           2018.0           1389.6            23.102               4.5
 56.000           2020.0           1408.6            23.525               4.5
 58.000           2022.0           1398.1            23.290               4.5
 60.000           2024.0           1358.5            22.411               4.5
 62.000           2026.0           1327.1            21.714             474.2
 64.000           2028.0           1327.1            21.714            1485.1
 66.000           2030.0           1327.1            21.714            2580.8
 68.000           2032.0           1327.1            21.714            3758.4
 70.000           2034.0           1327.1            21.714            5023.8
 72.000           2036.0           1327.1            21.714            6383.7
 74.000           2038.0           1327.1            21.714            7845.1
 76.000           2040.0           1327.1            21.714            9415.6


TYPE CHANGES IF RERUN DESIRED
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after 2025, are completely retired; the breeder growth [GRBE] becoming equal to total growth and breeder capacity equal to total nuclear capacity. Thus, a huge plutonium stockpile starts developing from 2026 reaching a level of almost ten million kilograms by year 2040.

The cumulative uranium requirements [URNAE] in this case are about 710, 000 ST by 2000 and about 1400, 000 ST by 2020. The uranium price is about nine dollars by 2000 and about twenty-three dollars by 2020. Comparing these figures with the results of case ALPHA, it is obvious that this case requires considerably smaller amounts of uranium.

In conclusion :

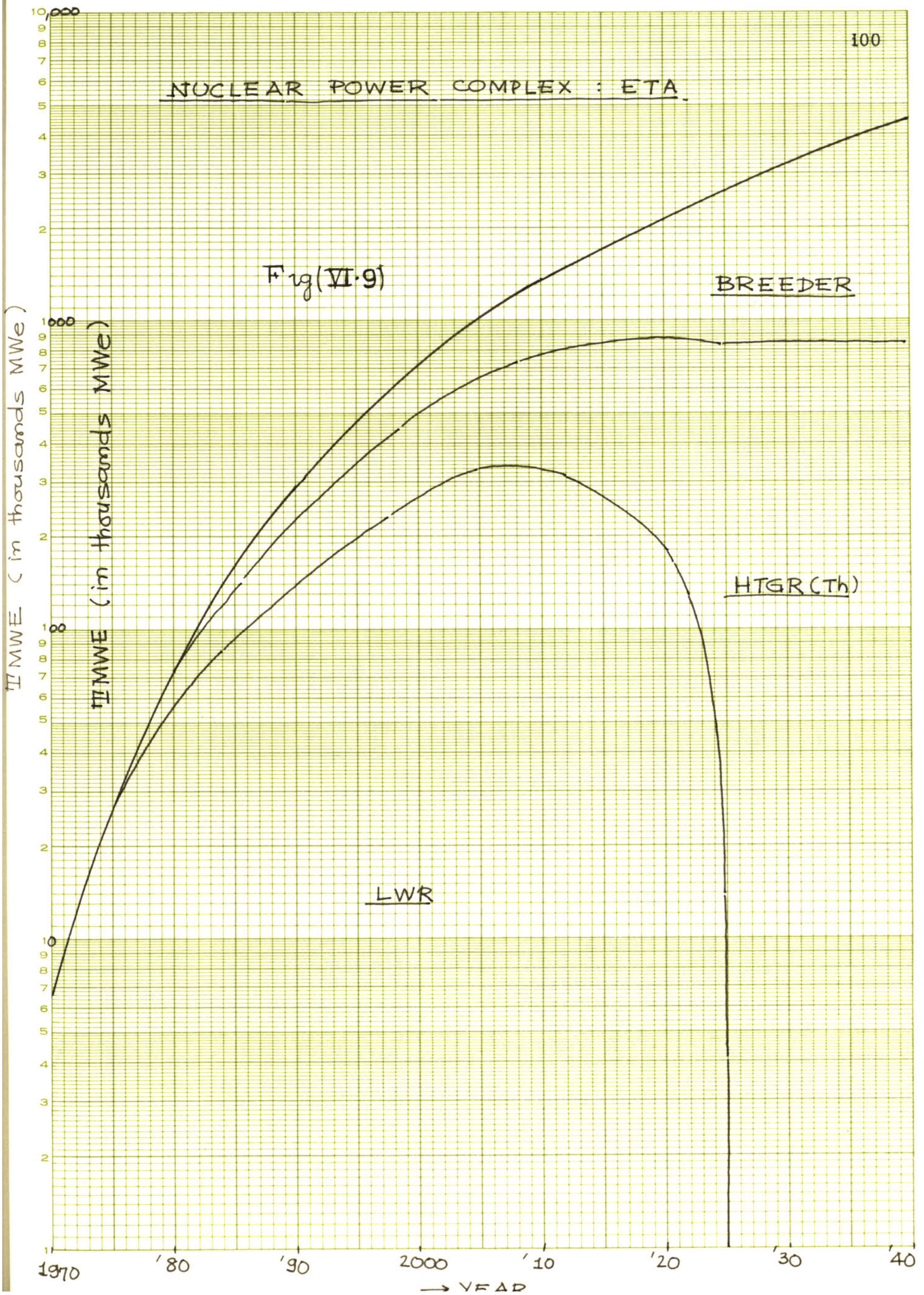
With the nuclear power complex DELTA, upto year 2000, not only the unintended plutonium stockpile is negligible but also the uranium requirements are very small; the uranium price being even lesser than $10/lb . Hence, with the introduction of ACR's in 1975 and Breeders in 1980 and with a BNE condition from 1985, the system will not even require the intermediate-cost U resources.

[5] CASE ETA :

In the previous case of BNE, the choice of ACR's was HWOCR-U, and needs a comparative justification. The proper choice of ACR will be a major factor affecting uranium utilization, plutonium utilization and the growth of breeders. Three more complexes ETA, THETA and ZETA are developed for this purpose.

In the nuclear complex ETA, as before, there are only LWR's upto 1975 (see Fig VI. 9). In 1976, ten percent of total growth goes in HTGR-Th installations, in '77, twenty percent and so on, until 1980 when the growth HTGR-Th is fifty percent of total growth. Between 1975 to '80, the LWR capacity is the difference betwwen total nuclear capacity and HTGR capacity. Pu produced in LWR's is not recycled but stockpiled for breeder inventory requirements, however, bred fissile U-233 in HTGR-Th reactors is recycled. Breeders are introduced from 1980 at an initial growth rate of IBRGR every year until 1984. The growth rate in HTGR's from 1980 is assumed to be one-half of total growth every year until breeders become self - sufficient in their plutonium requirements in 2026. The growth rate of LWR's, from 1980, is remaining growth [GROTH - GRBEX - GRAEX] and continues to be so, until they are no longer needed for plutonium production required in Breeders. This becomes in 2025, and then LWR capacity is reduced to zero. The growth rate in HTGR's is assumed to be zero from 2025 onwards, the breeder growth and power capacity becoming equal to total growth and power capacity.

Table VI. 6A, B lists the various reactor installed capacities and the growth rates. It was assumed that LWR's do not recycle the bred Pu, but HTGR-Th reactors recycle their bred U-233.



NUCLEAR POWER COMPLEX : ETA

Fig(VI·9)

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resume dyn eta madtrn
W 2247.5
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Table VI. 6 A

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 PAGE 1         ETA       NUCLEAR POWER COMPLEX  ETA       02/12/66   2247.5

   TIME      YEAR      TMWE       CEX       AEX       BEX     GRCEX     GRAEX     GRBEX
   E+00      E+00      E+03      E+03      E+03      E+03      E+03      E+03      E+03
    .000    1964.0        .0       .00       .00        .0      .000      .000       .00
   2.000    1966.0       2.0      2.01       .00        .0      .685      .000       .00
   4.000    1968.0       3.6      3.62       .00        .0     1.232      .000       .00
   6.000    1970.0       6.5      6.50       .00        .0     2.174      .000       .00
   8.000    1972.0      11.6     11.57       .00        .0     3.870      .000       .00
  10.000    1974.0      20.6     20.61       .00        .0     6.891      .000       .00
  12.000    1976.0      33.6     32.84       .77        .0     5.975     1.494       .00
  14.000    1978.0      50.2     46.09      4.11        .0     6.694     4.463       .00
  16.000    1980.0      75.0     62.45     12.18        .4     5.405     6.405      1.00
  18.000    1982.0     102.8     75.38     21.56       5.9     3.780     8.780      5.00
  20.000    1984.0     140.9     85.76     34.41      20.8     2.036    12.036     10.00
  22.000    1986.0     185.3    100.10     49.25      36.0     5.893    11.419      5.53
  24.000    1988.0     233.8    118.92     65.28      49.6     6.604    14.407      7.80
  26.000    1990.0     295.0    142.07     85.50      67.4     5.139    14.743      9.60
  28.000    1992.0     356.9    161.75    105.76      89.4     5.964    17.838     11.87
  30.000    1994.0     431.8    185.16    130.27     116.4     7.143    21.582     14.44
  32.000    1996.0     517.6    210.60    158.27     148.8     5.968    23.228     17.26
  34.000    1998.0     614.7    237.42    189.89     187.4     6.961    27.584     20.62
  36.000    2000.0     730.0    269.46    227.43     233.1     3.280    27.524     24.24
  38.000    2002.0     844.2    293.04    264.40     286.8     3.352    31.832     28.48
  40.000    2004.0     976.4    319.06    307.16     350.2     3.278    36.813     33.54
  42.000    2006.0    1109.0    335.09    349.90     424.0    -7.886    31.152     39.04
  44.000    2008.0    1237.1    336.16    391.00     509.9   -10.668    34.750     45.42
  46.000    2010.0    1380.0    335.16    436.84     608.0   -17.702    33.571     51.27
  48.000    2012.0    1517.5    318.05    480.81     718.7   -20.947    36.917     57.86
  50.000    2014.0    1668.8    296.39    529.16     843.3   -24.273    40.596     64.87
  52.000    2016.0    1832.0    268.52    581.29     982.1   -29.361    42.897     72.26
  54.000    2018.0    2007.6    233.41    637.38    1136.8   -33.417    47.009     80.43
  56.000    2020.0    2200.0    192.67    698.85    1308.5   -44.310    44.892     89.20
  58.000    2022.0    2383.2    127.18    757.22    1498.8   -50.232    48.631     98.86
  60.000    2024.0    2581.7     51.92    820.44    1709.4   -56.332    52.681    109.01
  62.000    2026.0    2785.5       .00    854.00    1931.5      .000      .000    102.10
  64.000    2028.0    2993.4       .00    854.00    2139.4      .000      .000    109.73
  66.000    2030.0    3216.9       .00    854.00    2362.9      .000      .000    117.92
  68.000    2032.0    3457.1       .00    854.00    2603.1      .000      .000    126.72
  70.000    2034.0    3715.2       .00    854.00    2861.2      .000      .000    136.18
  72.000    2036.0    3992.5       .00    854.00    3138.5      .000      .000    146.35
  74.000    2038.0    4290.6       .00    854.00    3436.6      .000      .000    157.28
  76.000    2040.0    4610.9       .00    854.00    3756.9      .000      .000    169.02


TYPE CHANGES IF RERUN DESIRED
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resume dyn eta madtrn
W 2327.3
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Table VI. 6 B

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 PAGE 1          ETA       NUCLEAR POWER COMPLEX  ETA      02/12/66    2327.3

   TIME              YEAR              TURNX              UPREX              PSPEX
   E+00              E+00              E+03               E+00               E+03
    .000            1964.0               .0              5.000                 .0
   2.000            1966.0              1.0              5.006                 .0
   4.000            1968.0              3.5              5.022                 .7
   6.000            1970.0              7.9              5.049                1.8
   8.000            1972.0             15.7              5.098                3.8
  10.000            1974.0             29.6              5.185                7.5
  12.000            1976.0             51.0              5.319               14.0
  14.000            1978.0             79.3              5.496               25.5
  16.000            1980.0            118.7              5.742               41.5
  18.000            1982.0            160.0              6.000               43.1
  20.000            1984.0            202.9              6.268               13.7
  22.000            1986.0            253.7              6.586               -6.6
  24.000            1988.0            315.0              6.969               -5.1
  26.000            1990.0            387.6              7.422               -5.1
  28.000            1992.0            463.4              7.896               -5.1
  30.000            1994.0            549.5              8.434               -5.1
  32.000            1996.0            645.0              9.031               -5.1
  34.000            1998.0            748.8              9.680               -5.1
  36.000            2000.0            865.7             11.461               -5.1
  38.000            2002.0            983.9             14.087               -5.1
  40.000            2004.0           1112.6             16.946               -5.1
  42.000            2006.0           1240.1             19.780               -5.1
  44.000            2008.0           1355.1             22.337               -5.1
  46.000            2010.0           1467.5             24.833               -5.1
  48.000            2012.0           1561.5             26.921               -5.1
  50.000            2014.0           1643.5             28.746               -5.1
  52.000            2016.0           1710.7             30.027               -5.1
  54.000            2018.0           1759.1             30.148               -5.1
  56.000            2020.0           1788.0             30.220               -5.1
  58.000            2022.0           1774.9             30.187               -5.1
  60.000            2024.0           1726.9             30.067               -5.1
  62.000            2026.0           1703.8             30.010              228.7
  64.000            2028.0           1733.7             30.084              738.9
  66.000            2030.0           1763.6             30.159             1320.5
  68.000            2032.0           1793.5             30.234             1984.0
  70.000            2034.0           1823.4             30.308             2735.3
  72.000            2036.0           1853.3             30.383             3581.1
  74.000            2038.0           1883.2             30.458             4528.4
  76.000            2040.0           1913.1             30.533             5584.8


TYPE CHANGES IF RERUN DESIRED
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It is for this reason that, the initial plutonium requirements for breeder installations are higher than the available plutonium stockpile, by that time. Hence, in this case atleast 5100 kgms of plutonium will have to be supplied from external sources.

Although total uranium requirements ,by year 2000, are little higher in this case [TURNX] compared to that of case DELTA, the difference increases with time. The maximum uranium requirements by year 2040, in this case are almost fifty percent higher than that of DELTA. The maximum uranium price is about thirty dollars per pound, almost fifty percent higher than that of DELTA.

The conclusion is that,

In a nuclear power complex, the HTGR-Th type of advanced converter reactors are less suitable than HWOCR-U type, for a long-term BNE.

[6] CASE THETA :

In this case the choice of advanced converter is assumed to be FAST U-235 fueled reactors. They produce almost two and half times as much Pu as produced by LWR's or HWOCR's. Althogh their uranium inventory requirements are higher by almost 45 percent than that of LWR's, it is anticipated that their proportion in the entire nuclear complex will remain lower because of their high plutonium production rate.

In this case (see Fig VI.10) the structure of the nuclear power complex (i. e. assumptions) is identically the same as in case DELTA, except that now FAST U-235 are substituted for HWOCR-U.

The FAST U-235 reactors introduced in 1975 at an increasing fraction of total growth rate attain a highest value of about 242,000 MWe capacity by year 2004 and then decrease at a very fast rate by year 2013, when they reach zero capacity. The highest HWOCR capacity in case DELTA was about 500,000; which is more than twice the maximum FAST U-235 capacity of the present case. The breeder installations in THETA are much higher than in DELTA, because of higher plutonium production rate in the fast uranium reactors. Thus, the proportion of ACR's [FAST U-235 reactors] in this case is much smaller and the prportion of breeder reactors is much higher than those in DELTA.

The Pu stockpile during BNE is at 16,000 kgms of plutonium, almost four times higher than in DELTA. The stockpile increases very rapidly after year 2015, reaching almost 13 million kilograms level by year 2040. This huge stockpiling could have been prevented by late introduction of FAST U-235 and Breeder reactors in the nuclear complex. or by exporting it.

The merit of this case is in its minimum uranium requirements. The maximum U price, even after the turn of this century does not exceed $10/lb. This maximum price is lesser than one half of that in the case DELTA. If in extension to BNE,

NUCLEAR POWER COMPLEX : THETA

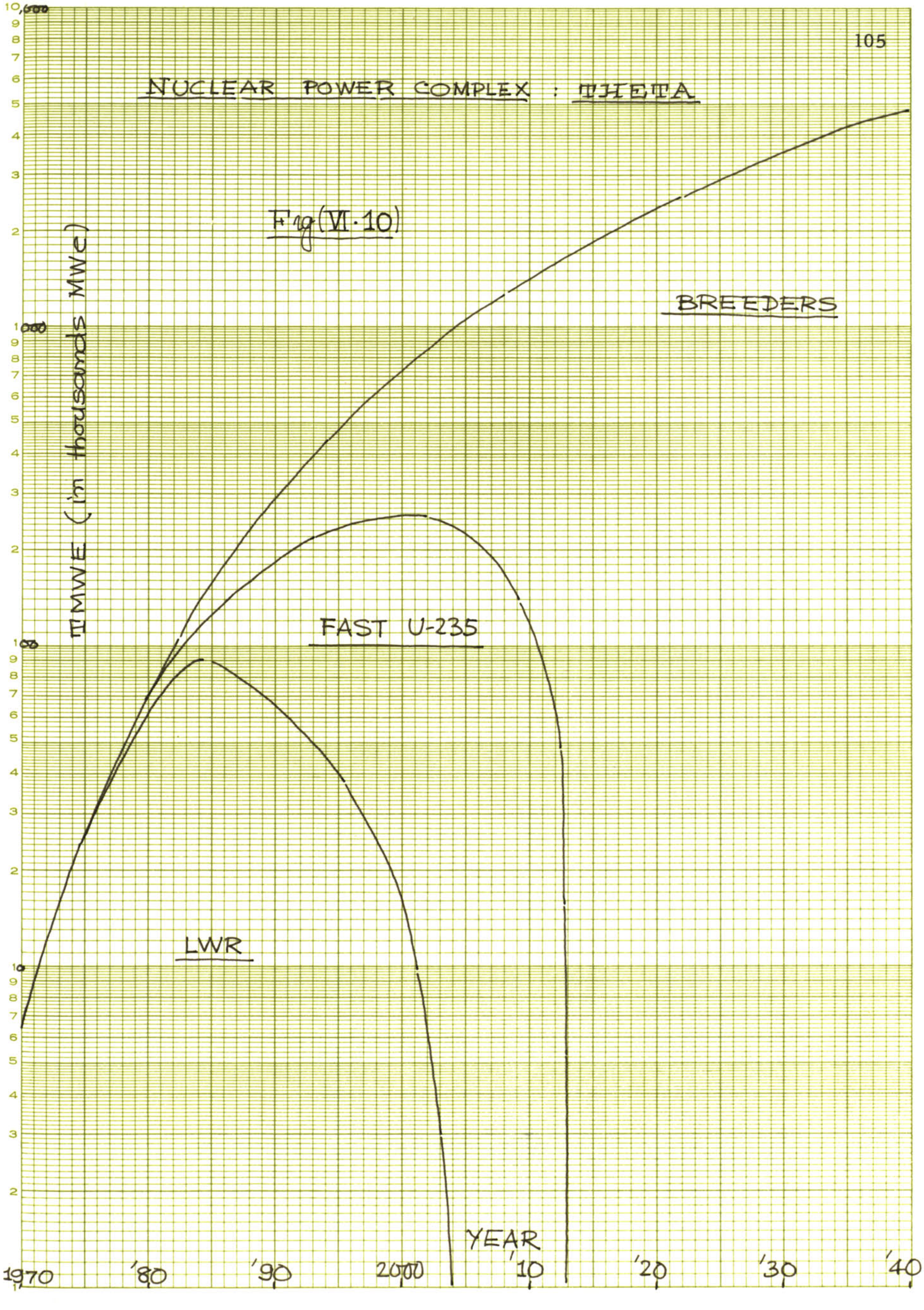

Fig (VI·10)

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resume dyn theta madtrn
W 2117.5
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Table VI. 7 A

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PAGE 1       THETA       NUCLEAR POWER COMPLEX THETA     02/12/66    2117.6

    TIME      YEAR      TMWE       CEY       AEY       BEY      GRCY      GRAY      GRBY
    E+00      E+00      E+03      E+03      E+03      E+03      E+00      E+03      E+03
    .000    1964.0        .0      .000       .00        .0        .0      .000       .00
   2.000    1966.0       2.0     2.011       .00        .0     685.4      .000       .00
   4.000    1968.0       3.6     3.616       .00        .0    1232.2      .000       .00
   6.000    1970.0       6.5     6.500       .00        .0    2173.6      .000       .00
   8.000    1972.0      11.6    11.574       .00        .0    3870.2      .000       .00
  10.000    1974.0      20.6    20.609       .00        .0    6891.4      .000       .00
  12.000    1976.0      33.6    33.032       .58        .0    5974.9     1.494       .00
  14.000    1978.0      50.2    46.284      3.92        .0    6694.0     4.463       .00
  16.000    1980.0      75.0    64.528     10.10        .4    4724.1     7.086      1.00
  18.000    1982.0     102.8    77.789     19.14       5.9    2512.0    10.048      5.00
  20.000    1984.0     140.9    91.497     28.68      20.8        .0    14.071     10.00
  22.000    1986.0     185.3    86.497     56.19      42.6   -5000.0    17.952      9.89
  24.000    1988.0     233.8    76.497     89.90      67.4   -5000.0    19.694     14.12
  26.000    1990.0     295.0    66.497    125.79     102.7   -5000.0    14.644     19.84
  28.000    1992.0     356.9    56.497    149.89     150.5   -5000.0    14.233     26.44
  30.000    1994.0     431.8    46.497    173.23     212.1   -5000.0    15.043     33.12
  32.000    1996.0     517.6    36.497    194.80     286.3   -5000.0    11.881     39.58
  34.000    1998.0     614.7    26.497    213.62     374.6   -5000.0    13.189     46.98
  36.000    2000.0     730.0    16.497    236.03     477.5   -5000.0     5.835     54.21
  38.000    2002.0     844.2     6.497    241.58     596.2   -5000.0     6.103     62.56
  40.000    2004.0     976.4      .000    242.83     733.5        .0     1.652     71.97
  42.000    2006.0    1109.0      .000    219.99     889.0        .0   -18.989     81.29
  44.000    2008.0    1237.1      .000    173.12    1064.0        .0   -21.823     91.32
  46.000    2010.0    1380.0      .000    126.23    1253.8        .0   -29.958     97.10
  48.000    2012.0    1517.5      .000     61.61    1455.9        .0   -29.752    103.58
  50.000    2014.0    1668.8      .000       .00    1668.8        .0      .000     81.19
  52.000    2016.0    1832.0      .000       .00    1832.0        .0      .000     85.79
  54.000    2018.0    2007.6      .000       .00    2007.6        .0      .000     94.02
  56.000    2020.0    2200.0      .000       .00    2200.0        .0      .000     89.78
  58.000    2022.0    2383.2      .000       .00    2383.2        .0      .000     97.26
  60.000    2024.0    2581.7      .000       .00    2581.7        .0      .000    105.36
  62.000    2026.0    2785.5      .000       .00    2785.5        .0      .000    102.10
  64.000    2028.0    2993.4      .000       .00    2993.4        .0      .000    109.73
  66.000    2030.0    3216.9      .000       .00    3216.9        .0      .000    117.92
  68.000    2032.0    3457.1      .000       .00    3457.1        .0      .000    126.72
  70.000    2034.0    3715.2      .000       .00    3715.2        .0      .000    136.18
  72.000    2036.0    3992.5      .000       .00    3992.5        .0      .000    146.35
  74.000    2038.0    4290.6      .000       .00    4290.6        .0      .000    157.28
  76.000    2040.0    4610.9      .000       .00    4610.9        .0      .000    169.02

TYPE CHANGES IF RERUN DESIRED
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resume dyn theta madtrn
W 2201.6
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Table VI. 7 B

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PAGE 1       THETA       NUCLEAR POWER COMPLEX THETA     02/12/66   2201.6

   TIME            YEAR            TRNEY           UPREY           PSPEY
   E+00            E+00            E+03            E+00            E+06
    .000          1964.0             .00          5.0000            .000
   2.000          1966.0            1.01          5.0063            .000
   4.000          1968.0            3.46          5.0217            .001
   6.000          1970.0            7.88          5.0493            .002
   8.000          1972.0           15.70          5.0981            .004
  10.000          1974.0           29.62          5.1851            .007
  12.000          1976.0           51.53          5.3220            .014
  14.000          1978.0           82.93          5.5183            .025
  16.000          1980.0          129.74          5.8109            .043
  18.000          1982.0          183.23          6.1452            .051
  20.000          1984.0          243.14          6.5196            .038
  22.000          1986.0          307.36          6.9210            .017
  24.000          1988.0          382.04          7.3878            .016
  26.000          1990.0          461.75          7.8859            .016
  28.000          1992.0          528.47          8.3030            .016
  30.000          1994.0          591.29          8.6956            .016
  32.000          1996.0          649.35          9.0584            .016
  34.000          1998.0          699.40          9.3713            .016
  36.000          2000.0          748.32          9.6770            .016
  38.000          2002.0          772.65          9.8291            .016
  40.000          2004.0          785.43          9.9089            .016
  42.000          2006.0          763.74          9.7734            .016
  44.000          2008.0          694.90          9.3431            .016
  46.000          2010.0          603.49          8.7718            .016
  48.000          2012.0          469.76          7.9360            .016
  50.000          2014.0          308.79          6.9299            .016
  52.000          2016.0          308.79          6.9299            .533
  54.000          2018.0          308.79          6.9299           1.081
  56.000          2020.0          308.79          6.9299           1.680
  58.000          2022.0          308.79          6.9299           2.413
  60.000          2024.0          308.79          6.9299           3.219
  62.000          2026.0          308.79          6.9299           4.124
  64.000          2028.0          308.79          6.9299           5.139
  66.000          2030.0          308.79          6.9299           6.235
  68.000          2032.0          308.79          6.9299           7.412
  70.000          2034.0          308.79          6.9299           8.678
  72.000          2036.0          308.79          6.9299          10.038
  74.000          2038.0          308.79          6.9299          11.499
  76.000          2040.0          308.79          6.9299          13.070


TYPE CHANGES IF RERUN DESIRED
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from 2015 onwards, an IBNE is put in effect, the uranium requirements can be decreased still further.

In conclusion :

With nuclear power complex THETA, the uranium requirements are at their minimum, the maximum uranium price, even after the turn of the century, being $10/lb. A substantial amount of plutonium stockpile will be available, in addition, for research, defense, exports and industrial purposes. Only fast reactors need to be developed, eliminating the investments in other advanced converter development. The concern, if at all, is not of long-term fuel scarcity but of not using the country's economic resources completely. It is also not required to have fast reactors by 1980.

[7] CASE ZETA :

In this case, in addition to FAST U-235 fueled reactors there are some HTGR-Th type of converters. The purpose of HTGR installations is to utilise some more economic uranium resources and defer the development of fast breeder reactors. Capital costs of fast U-235 reactors will be higher than in HTGR reactors, and thus it may be economical to have HTGR's in the complex.

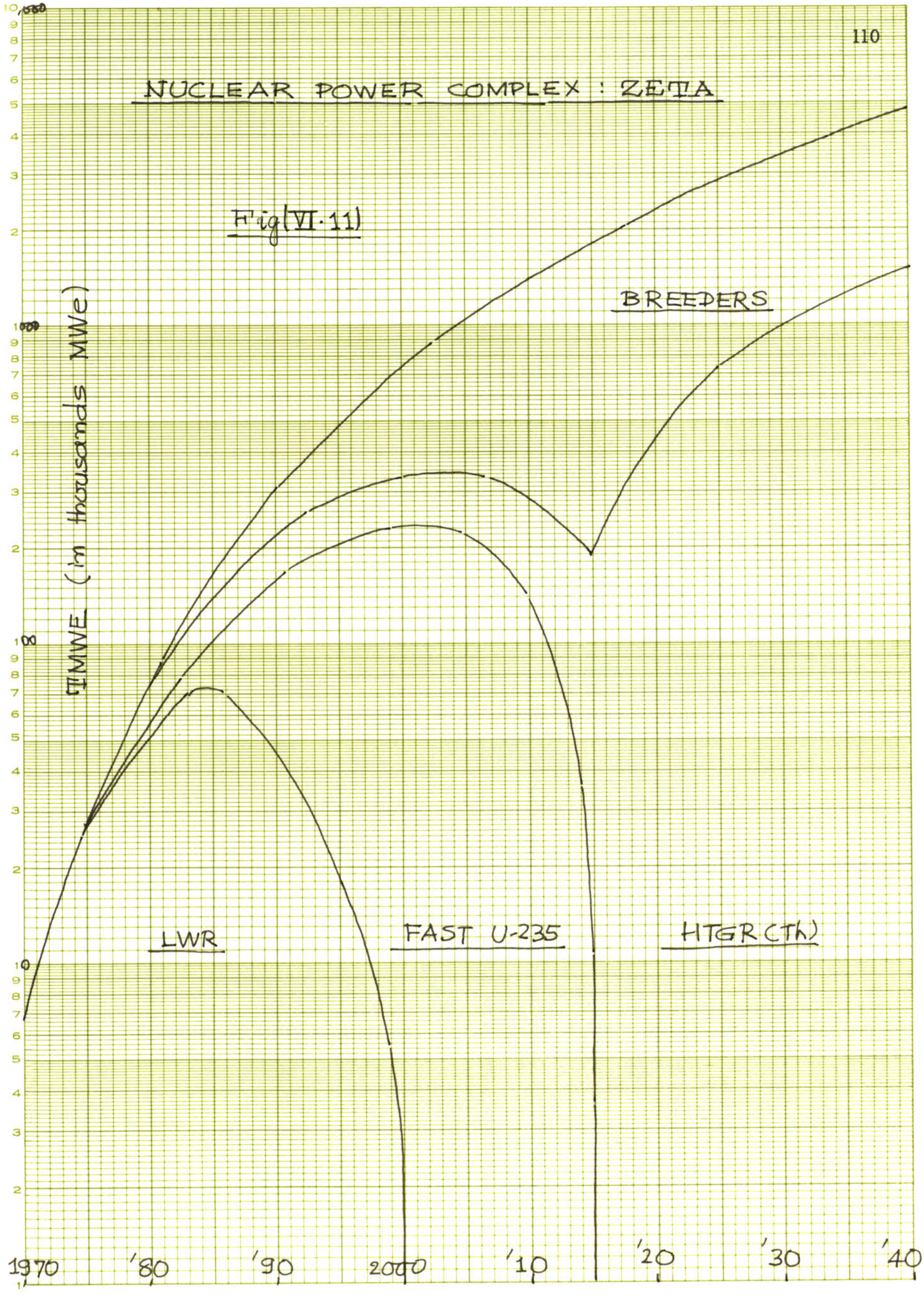
The basic assumptions of LWR installations are retained in this case also. Fig(VI. 11) shows the various assumed nuclear power capacities. From 1975, both HTGR-Th and FAST

U-235 reactors are introduced. The growth of HTGR-Th reactors is assumed to be 4000 MWe/yr during '75-'99, 5000 MWe/yr during 2000-2014 and 50,000 MWe/yr during 2015 to 2040. The FAST U-235 reactor growth [GRAZ] between 1975 to '85 is the increasing fraction of growth of left after deducting for the combined initial growth of breeders [GRBZ] and HTGR's. After 1985, the growth of FAST U-235 reactors [GRAZ] is determined by the balance between total GROTH and combined growth of LWR's, Breeders and HTGR's.

The BNE starts from 1985 and lasts for about 30 years, same as in THETA. FAST U-235 reactors no longer needed for Pu production are thus retired completely by year 2015. After year 2015, there is a constant growth of 50,000 (rather too high) MWe/yr in HTGR reactors, the rest being that of breeders.

Table VI. 8 A & B lists the various installed power capacities , uranium requirements and the Pu stock-pile. The Pu stockpile remains constant at 2000 kgms during BNE (1985-2015), and increases rapidly thereafter. The level of Pu stockpile reaches almost 13 million kgms by 2040.

The cumulative uranium requirements increase as compared to previous case (because of additional HTGR installations) but still the low cost uranium resources are available upto 2026. If IBNE is put in effect after BNE, the higher uranium requirements after 2026 will be largely reduced, and it will be possible to maintain a low uranium price upto 2040.



NUCLEAR POWER COMPLEX : ZETA

Fig(VI·11)

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resume dyn zeta madtrn
W 2338.3
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Table VI.8 A

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PAGE 1        ZETA        NUCLEAR POWER COMPLEX : ZETA   02/12/66   2338.4

  TIME      YEAR      TMWE       CEZ      HTGR       AEZ       BEZ      GRCZ      GRHT
  E+00      E+00      E+03      E+03      E+03      E+03      E+03      E+00      E+03
   .000    1964.0        .0      .000        .0       .00        .0        .0      .000
  2.000    1966.0       2.0     2.011        .0       .00        .0     685.4      .000
  4.000    1968.0       3.6     3.616        .0       .00        .0    1232.2      .000
  6.000    1970.0       6.5     6.500        .0       .00        .0    2173.6      .000
  8.000    1972.0      11.6    11.574        .0       .00        .0    3870.2      .000
 10.000    1974.0      20.6    20.609        .0       .00        .0    6891.4      .000
 12.000    1976.0      33.6    29.582       4.0       .03        .0    2774.9     4.000
 14.000    1978.0      50.2    37.134      12.0      1.07        .0    4294.0     4.000
 16.000    1980.0      75.0    50.378      20.0      4.25        .4    3124.1     4.000
 18.000    1982.0     102.8    61.139      28.0      7.79       5.9    1712.0     4.000
 20.000    1984.0     140.9    74.178      36.0     12.75      18.0        .0     4.000
 22.000    1986.0     185.3    69.000      44.0     38.92      33.4   -5000.0     4.000
 24.000    1988.0     233.8    59.000      52.0     72.20      50.6   -5000.0     4.000
 26.000    1990.0     295.0    49.000      60.0    108.94      77.1   -5000.0     4.000
 28.000    1992.0     356.9    39.000      68.0    135.05     114.9   -5000.0     4.000
 30.000    1994.0     431.8    29.000      76.0    161.35     165.5   -5000.0     4.000
 32.000    1996.0     517.6    19.000      84.0    186.63     228.0   -5000.0     4.000
 34.000    1998.0     614.7     9.000      92.0    209.77     303.9   -5000.0     4.000
 36.000    2000.0     730.0      .000     100.0    235.99     394.0        .0     5.000
 38.000    2002.0     844.2      .000     110.0    234.73     499.5        .0     5.000
 40.000    2004.0     976.4      .000     120.0    233.68     622.7        .0     5.000
 42.000    2006.0    1109.0      .000     130.0    217.61     761.4        .0     5.000
 44.000    2008.0    1237.1      .000     140.0    179.19     917.9        .0     5.000
 46.000    2010.0    1380.0      .000     150.0    141.28    1088.7        .0     5.000
 48.000    2012.0    1517.5      .000     160.0     85.96    1271.6        .0     5.000
 50.000    2014.0    1668.8      .000     170.0     31.04    1467.8        .0     5.000
 52.000    2016.0    1832.0      .000     225.0       .00    1607.0        .0    50.000
 54.000    2018.0    2007.6      .000     325.0       .00    1682.6        .0    50.000
 56.000    2020.0    2200.0      .000     425.0       .00    1775.0        .0    50.000
 58.000    2022.0    2383.2      .000     525.0       .00    1858.2        .0    50.000
 60.000    2024.0    2581.7      .000     625.0       .00    1956.7        .0    50.000
 62.000    2026.0    2785.5      .000     725.0       .00    2060.5        .0    50.000
 64.000    2028.0    2993.4      .000     825.0       .00    2168.4        .0    50.000
 66.000    2030.0    3216.9      .000     925.0       .00    2291.9        .0    50.000
 68.000    2032.0    3457.1      .000    1025.0       .00    2432.1        .0    50.000
 70.000    2034.0    3715.2      .000    1125.0       .00    2590.2        .0    50.000
 72.000    2036.0    3992.5      .000    1225.0       .00    2767.5        .0    50.000
 74.000    2038.0    4290.6      .000    1325.0       .00    2965.6        .0    50.000
 76.000    2040.0    4610.9      .000    1425.0       .00    3185.9        .0    50.000


TYPE CHANGES IF RERUN DESIRED
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resume dyn zeta madtrn
W 2347.4
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Table VI. 8 B

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PAGE 1       ZETA       NUCLEAR POWER COMPLEX : ZETA    02/12/66    2347.4

   TIME      YEAR    GROTH      GRAZ      GRBZ    TURNZ    UPREZ     PSPEZ
   E+00      E+00    E+03       E+03      E+03    E+03     E+00      E+06
   .000    1964.0      .00      .000       .00       .0    5.000      .000
  2.000    1966.0      .69      .000       .00      1.0    5.006      .000
  4.000    1968.0     1.23      .000       .00      3.5    5.022      .001
  6.000    1970.0     2.17      .000       .00      7.9    5.049      .002
  8.000    1972.0     3.87      .000       .00     15.7    5.098      .004
 10.000    1974.0     6.89      .000       .00     29.6    5.185      .007
 12.000    1976.0     7.47      .694       .00     49.9    5.312      .014
 14.000    1978.0    11.16     2.863       .00     75.4    5.471      .025
 16.000    1980.0    12.81     4.686      1.00    113.2    5.707      .040
 18.000    1982.0    17.56     6.848      5.00    153.8    5.961      .039
 20.000    1984.0    24.07    12.071      8.00    202.0    6.263      .021
 22.000    1986.0    22.84    17.257      6.58    259.6    6.623      .003
 24.000    1988.0    28.81    19.699     10.11    328.8    7.055      .002
 26.000    1990.0    29.49    15.307     15.18    405.2    7.532      .002
 28.000    1992.0    35.68    15.435     21.24    471.2    7.945      .002
 30.000    1994.0    43.16    16.678     27.49    535.7    8.348      .002
 32.000    1996.0    46.46    13.863     33.59    597.9    8.737      .002
 34.000    1998.0    55.17    15.449     40.72    654.5    9.091      .002
 36.000    2000.0    55.05     2.317     47.73    712.3    9.452      .002
 38.000    2002.0    63.66     2.762     55.90    741.6    9.635      .002
 40.000    2004.0    73.63     4.199     64.43    762.7    9.767      .002
 42.000    2006.0    62.30   -15.106     72.41    759.7    9.748      .002
 44.000    2008.0    69.50   -17.458     81.96    714.9    9.468      .002
 46.000    2010.0    67.14   -25.400     87.54    651.5    9.072      .002
 48.000    2012.0    73.83   -25.061     93.89    549.5    8.435      .002
 50.000    2014.0    81.19   -23.985    100.18    424.0    7.650      .002
 52.000    2016.0    85.79      .000     35.79    388.1    7.425      .435
 54.000    2018.0    94.02      .000     44.02    458.3    7.865     1.310
 56.000    2020.0    89.78      .000     39.78    532.1    8.326     2.187
 58.000    2022.0    97.26      .000     47.26    609.4    8.809     3.137
 60.000    2024.0   105.36      .000     55.36    690.2    9.314     4.099
 62.000    2026.0   102.10      .000     52.10    774.5    9.840     5.101
 64.000    2028.0   109.73      .000     59.73    862.2   11.383     6.152
 66.000    2030.0   117.92      .000     67.92    953.5   13.412     7.224
 68.000    2032.0   126.72      .000     76.72   1048.3   15.518     8.317
 70.000    2034.0   136.18      .000     86.18   1146.6   17.702     9.438
 72.000    2036.0   146.35      .000     96.35   1248.4   19.964    10.593
 74.000    2038.0   157.28      .000    107.28   1353.6   22.303    11.790
 76.000    2040.0   169.02      .000    119.02   1462.4   24.721    13.035

TYPE CHANGES IF RERUN DESIRED
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In conclusion,

With nuclear power complex ZETA, in addition to the advantages of case THETA, it will be possible to defer the early development of plutonium fuel,utilise more of economically available nuclear resources, [uranium as well as thorium]. It will be necessary, however, to develope commercial HTGR-Th reactors as compared to case THETA.

[8] CASE KAPPA :

In all of the above cases it was assumed that the commercial breeders will be available by year 1980. Many optimistic as well as pessimistic views are expressed by the experts in the field. The answers to the following two questions are sought in the following two cases :

Q.1 : Should AEC invest a large sum of money in early and expeditious development of breeders, so that they are available by 1980. ?

Q.2 : What will be the effect of late introduction of breeders say by 1990 or year 2000 ?

In case KAPPA, [see Fig VI.12] , the following assumptions are made :

1965-1974 : only LWR's installed, equal to TMWE

1975-1984 : HWOCR introduced at 10% of total growth in '75, 20% in '76 and so on, the rest of growth is of LWR's.

1985-1989 : LWR's are retired at a constant rate of 5000 MWe/yr, all new growth is of HWOCR's.

1990-1994 : Breeders introduced at an initial growth rate of

IBRGR. LWR's retired at a constant rate of 5000 MWe/yr. The balancing growth is of HWOCR's.

1995-2027 : (BNE) LWR's retired at 5000 MWe/yr until 2003. Breeder growth determined by BNE condition, the rest being HWOCR's.

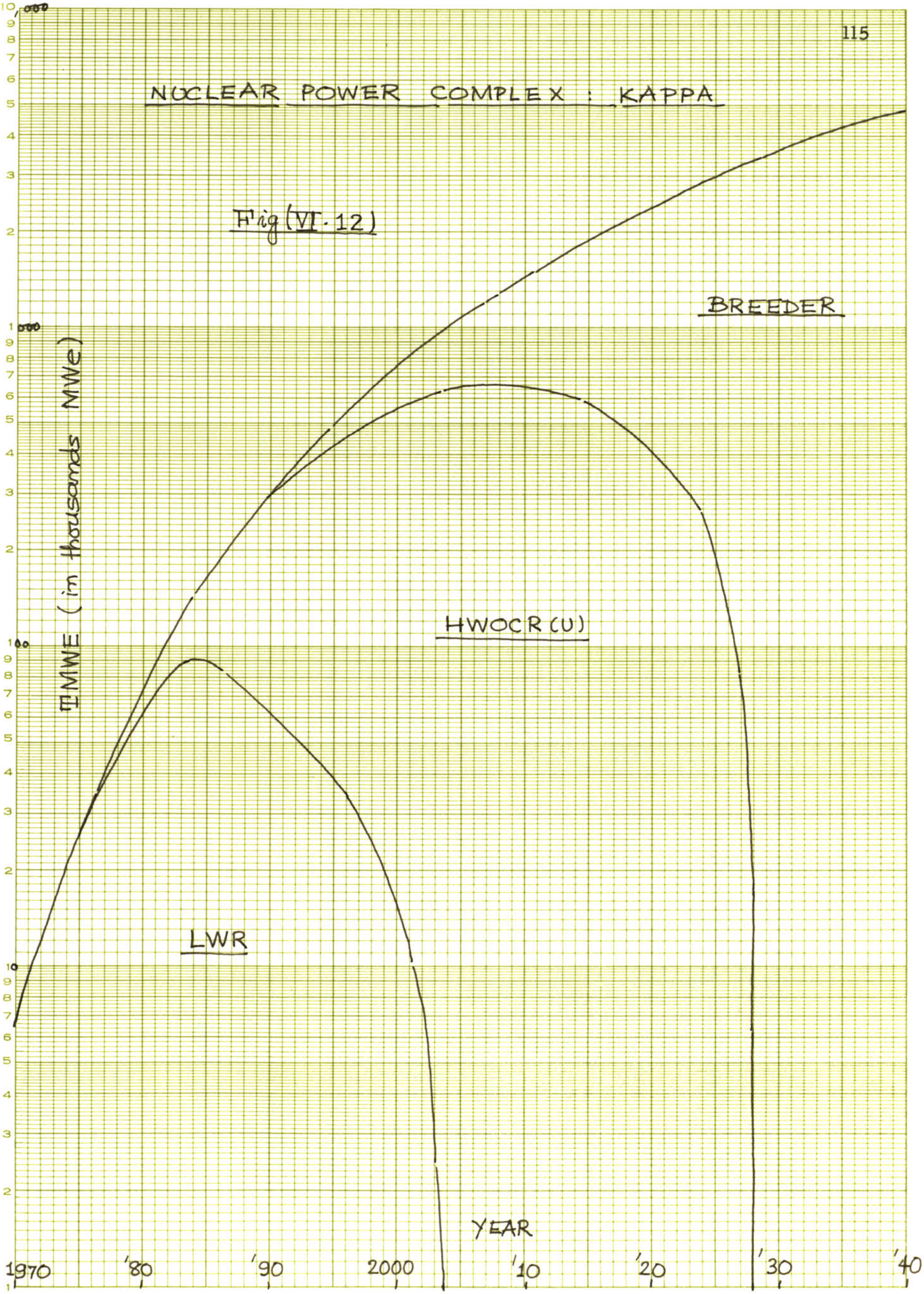
2028-2040 : All new installations of breeders. No HWOCRs

All the installed capacities and growth rates are tabulated in Table VI. 9 A and B.

The BNE starts in 1995 and lasts until 2028, for about 32 years, as compared to 40 years in case DELTA. The Pu stockpile during BNE is at 481,000 kgms, almost 1000 times that of case DELTA. This huge plutonium stockpile could have been reduced by a higher initial growth rate of breeders. The Pu stockpile still increases further after BNE, and could be eliminated by setting the IBNE condition in the complex. The cumulative uranium requirements of this case are such that the U price is about $ 12/lb by year 2000 and $ 30/lb by year 2040. If the excess Pu is fed in ACRs, the uranium price could be lower.

Thus, in conclusion :

With a nuclear power complex of case KAPPA, even though breeders are introduced in 1990, the uranium price is not very high, at least by year 2000. A huge Pu stockpile is available, which can be used to decrease the U requirements still further. Hence, it is not really necessary to speedup the breeder reactor development programme, if commercial ACRs are available by 1975.



NUCLEAR POWER COMPLEX : KAPPA

Fig (VI.12)

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resume dyn kappa madtrn
W 1218.6
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Table VI.9 A

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 PAGE 1      KAPPA      NUCLEAR POWER COMPLEX: KAPPA    02/13/66   1218.7

    TIME     YEAR     TMWE       CF       AF       BF     GRCF     GRAF     GRBF
    E+00     E+00     E+03     E+03     E+03     E+03     E+00     E+03     E+03
    .000   1964.0       .0     .000      .00       .0       .0     .000      .00
   2.000   1966.0      2.0    2.011      .00       .0    685.4     .000      .00
   4.000   1968.0      3.6    3.616      .00       .0   1232.2     .000      .00
   6.000   1970.0      6.5    6.500      .00       .0   2173.6     .000      .00
   8.000   1972.0     11.6   11.574      .00       .0   3870.2     .000      .00
  10.000   1974.0     20.6   20.609      .00       .0   6891.4     .000      .00
  12.000   1976.0     33.6   32.841      .77       .0   5974.9    1.494      .00
  14.000   1978.0     50.2   46.094     4.11       .0   6694.0    4.463      .00
  16.000   1980.0     75.0   62.473    12.53       .0   5124.1    7.686      .00
  18.000   1982.0    102.8   77.321    25.49       .0   3512.0   14.048      .00
  20.000   1984.0    140.9   92.532    48.40       .0       .0   24.071      .00
  22.000   1986.0    185.3   86.500    78.08       .0  -5000.0   27.838      .00
  24.000   1988.0    233.8   76.500   110.13       .0  -5000.0   33.813      .00
  26.000   1990.0    295.0   66.500   228.12       .4  -5000.0   33.486     1.00
  28.000   1992.0    356.9   56.500   294.54      5.9  -5000.0   35.675     5.00
  30.000   1994.0    431.8   46.500   364.59     20.8  -5000.0   38.164    10.00
  32.000   1996.0    517.6   36.500   414.70     66.4  -5000.0   27.716    23.74
  34.000   1998.0    614.7   26.500   468.11    120.1  -5000.0   31.290    28.88
  36.000   2000.0    730.0   16.500   528.77    184.7  -5000.0   25.589    34.46
  38.000   2002.0    844.2    6.500   576.07    261.7  -5000.0   27.681    40.98
  40.000   2004.0    976.4     .000   622.97    353.4       .0   24.936    48.69
  42.000   2006.0   1109.0     .000   647.94    461.0       .0    5.274    57.03
  44.000   2008.0   1237.1     .000   650.13    587.0       .0    2.849    66.65
  46.000   2010.0   1380.0     .000   649.08    730.9       .0   -8.138    75.28
  48.000   2012.0   1517.5     .000   624.09    893.5       .0  -11.142    84.97
  50.000   2014.0   1668.8     .000   592.45   1076.4       .0  -14.021    95.21
  52.000   2016.0   1832.0     .000   551.91   1280.0       .0  -20.135   105.93
  54.000   2018.0   2007.6     .000   501.01   1506.5       .0  -23.739   117.76
  56.000   2020.0   2200.0     .000   442.28   1757.7       .0  -40.622   130.41
  58.000   2022.0   2383.2     .000   347.48   2035.8       .0  -47.050   144.31
  60.000   2024.0   2581.7     .000   239.01   2342.7       .0  -53.451   158.81
  62.000   2026.0   2785.5     .000   106.54   2679.0       .0  -71.733   173.84
  64.000   2028.0   2993.4     .000      .00   2993.4       .0     .000   109.73
  66.000   2030.0   3216.9     .000      .00   3216.9       .0     .000   117.92
  68.000   2032.0   3457.1     .000      .00   3457.1       .0     .000   126.72
  70.000   2034.0   3715.2     .000      .00   3715.2       .0     .000   136.18
  72.000   2036.0   3992.5     .000      .00   3992.5       .0     .000   146.35
  74.000   2038.0   4290.6     .000      .00   4290.6       .0     .000   157.28
  76.000   2040.0   4610.9     .000      .00   4610.9       .0     .000   169.02


TYPE CHANGES IF RERUN DESIRED
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resume dyn kappa madtrn
W 1254.1
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Table VI. 9 B

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 PAGE 1       KAPPA      NUCLEAR POWER COMPLEX: KAPPA   02/13/66    1254.2

  TIME            YEAR          TURNF           UPRF          PLSPF
  E+00            E+00          E+03            E+00          E+03
   .000          1964.0            .0           5.000            .0
  2.000          1966.0           1.0           5.006            .0
  4.000          1968.0           3.5           5.022            .7
  6.000          1970.0           7.9           5.049           1.8
  8.000          1972.0          15.7           5.098           3.8
 10.000          1974.0          29.6           5.185           7.5
 12.000          1976.0          50.7           5.317          14.0
 14.000          1978.0          78.0           5.488          25.5
 16.000          1980.0         115.7           5.723          43.8
 18.000          1982.0         160.6           6.004          71.3
 20.000          1984.0         216.3           6.352         111.6
 22.000          1986.0         276.0           6.725         166.9
 24.000          1988.0         333.5           7.085         240.6
 26.000          1990.0         397.6           7.485         324.6
 28.000          1992.0         486.7           8.042         398.5
 30.000          1994.0         586.2           8.664         486.4
 32.000          1996.0         685.5           9.284         481.1
 34.000          1998.0         790.8           9.942         481.3
 36.000          2000.0         904.1          12.313         481.3
 38.000          2002.0        1020.0          14.890         481.3
 40.000          2004.0        1142.2          17.605         481.3
 42.000          2006.0        1273.2          20.515         481.3
 44.000          2008.0        1397.9          23.287         481.3
 46.000          2010.0        1520.1          26.002         481.3
 48.000          2012.0        1631.2          28.471         481.3
 50.000          2014.0        1732.5          30.081         481.3
 52.000          2016.0        1821.9          30.305         481.3
 54.000          2018.0        1896.6          30.491         481.3
 56.000          2020.0        1955.1          30.638         481.3
 58.000          2022.0        1985.1          30.713         481.3
 60.000          2024.0        1987.2          30.718         481.3
 62.000          2026.0        1955.2          30.638         481.3
 64.000          2028.0        1881.4          30.454         481.3
 66.000          2030.0        1881.4          30.454        1567.4
 68.000          2032.0        1881.4          30.454        2744.5
 70.000          2034.0        1881.4          30.454        4009.9
 72.000          2036.0        1881.4          30.454        5369.8
 74.000          2038.0        1881.4          30.454        6831.2
 76.000          2040.0        1881.4          30.454        8401.7


TYPE CHANGES IF RERUN DESIRED
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[9] CASE SIGMA :

This case assumes even a later introduction of Breeders-- in year 2000. Assumptions of the complex are :

1965-1979 : Only LWR installed equal to TMWE, no Pu recycling.

1980-1999 : LWR capacity decreases linearly to zero by 2000. HWOCR growth equal to total new growth plus equivalent to retiring LWR capacity. Pu produced in LWRs is not recycled but stockpiled, however, Pu produced in HWOCRs is recycled.

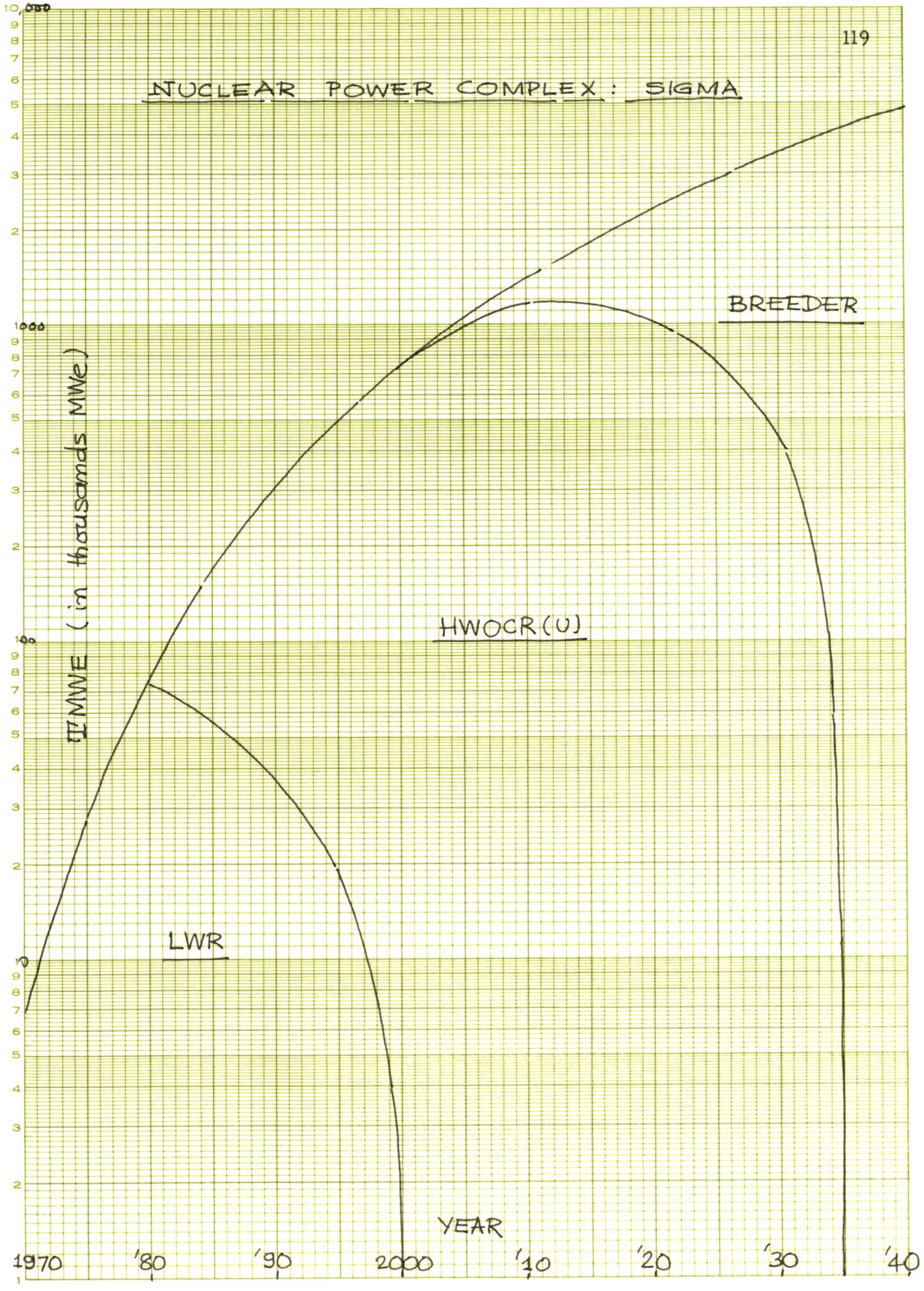
2000-2004 : Breeders introduced at an initial growth rate IBRGR, rest are HWOCRs, Pu in HWOCR still recycled.

2005-2035 : Breeders growth determined by the BNE condition, no Pu recycling in HWOCRs, HWOCR growth equal to balance between total growth and breeder growth.

2036-2040 : No new HWOCR, total growth is of breeders.

Table VI. 10A,B lists the installed capacities in each of these cases. Fig VI. 13 shows them graphically.

The plutonium stockpile during BNE is at 128,000 kgms of Pu, and increases to 3836,000 kgms by year 2040. The uranium requirements in this case are such that, the uranium price is about $9/lb by year 2000 and increases later. The rapidly rising uranium price after year 2000 can be reduced by using the excess plutonium as makeup fuel in HWOCRs and by increasing the proportion of breeders after year 2000.



NUCLEAR POWER COMPLEX : SIGMA

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resume dyn sigma madtrn
W 1514.7
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Table VI.10 A

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 PAGE 1      SIGMA      NUCLEAR POWER COMPLEX: SIGMA   02/13/66   1514.7

     TIME     YEAR     TMWE       CS       AS       BS     GRCS     GRAS     GRBS
    E+00     E+00     E+03     E+03     E+03     E+03     E+03     E+03     E+03
     .000   1964.0       .0     .000       .0       .0     .000     .000      .00
    2.000   1966.0      2.0    2.011       .0       .0     .685     .000      .00
    4.000   1968.0      3.6    3.616       .0       .0    1.232     .000      .00
    6.000   1970.0      6.5    6.500       .0       .0    2.174     .000      .00
    8.000   1972.0     11.6   11.574       .0       .0    3.870     .000      .00
   10.000   1974.0     20.6   20.609       .0       .0    6.891     .000      .00
   12.000   1976.0     33.6   33.611       .0       .0    7.469     .000      .00
   14.000   1978.0     50.2   50.208       .0       .0   11.157     .000      .00
   16.000   1980.0     75.0   75.000       .0       .0   12.810     .000      .00
   18.000   1982.0    102.8   67.500     35.3       .0   -3.571   21.131      .00
   20.000   1984.0    140.9   60.000     80.9       .0   -3.571   27.642      .00
   22.000   1986.0    185.3   52.500    132.8       .0   -3.571   26.409      .00
   24.000   1988.0    233.8   45.000    188.8       .0   -3.571   32.384      .00
   26.000   1990.0    295.0   37.500    257.5       .0   -3.571   33.057      .00
   28.000   1992.0    356.9   30.000    326.9       .0   -3.571   39.246      .00
   30.000   1994.0    431.8   22.500    409.3       .0   -3.571   46.735      .00
   32.000   1996.0    517.6   15.000    502.6       .0   -3.571   50.027      .00
   34.000   1998.0    614.7    7.500    607.2       .0   -3.571   58.740      .00
   36.000   2000.0    730.0     .000    729.6       .4     .000   54.048     1.00
   38.000   2002.0    844.2     .000    838.4      5.9     .000   58.663     5.00
   40.000   2004.0    976.4     .000    955.6     20.8     .000   63.626    10.00
   42.000   2006.0   1109.0     .000   1078.8     30.2     .000   59.594     2.71
   44.000   2008.0   1237.1     .000   1154.8     82.2     .000    7.878    61.62
   46.000   2010.0   1380.0     .000   1165.7    214.3     .000   -1.648    68.79
   48.000   2012.0   1517.5     .000   1154.1    363.4     .000   -4.338    78.17
   50.000   2014.0   1668.8     .000   1136.3    532.5     .000   -7.044    88.24
   52.000   2016.0   1832.0     .000   1109.9    722.0     .000  -12.977    98.77
   54.000   2018.0   2007.6     .000   1073.6    934.0     .000  -16.393   110.41
   56.000   2020.0   2200.0     .000   1029.8   1170.2     .000  -33.086   122.87
   58.000   2022.0   2383.2     .000    950.3   1432.9     .000  -39.316   136.58
   60.000   2024.0   2581.7     .000    857.6   1724.2     .000  -45.516   150.88
   62.000   2026.0   2785.5     .000    741.2   2044.3     .000  -63.591   165.70
   64.000   2028.0   2993.4     .000    597.8   2395.6     .000  -72.092   181.82
   66.000   2030.0   3216.9     .000    437.6   2779.3     .000  -80.069   197.99
   68.000   2032.0   3457.1     .000    260.1   3197.0     .000  -88.742   215.46
   70.000   2034.0   3715.2     .000     63.9   3651.3     .000  -98.133   234.32
   72.000   2036.0   3992.5     .000       .0   3992.5     .000     .000   146.35
   74.000   2038.0   4290.6     .000       .0   4290.6     .000     .000   157.28
   76.000   2040.0   4610.9     .000       .0   4610.9     .000     .000   169.02


TYPE CHANGES IF RERUN DESIRED
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resume dyn sigma madtrn
W 1507.9
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Table VI.10 B

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PAGE 1      SIGMA      NUCLEAR POWER COMPLEX: SIGMA   02/13/66   1508.0

   TIME           YEAR          TURNS          UPRFS          PLSPS
   E+00           E+00          E+03           E+00           E+03
    .000         1964.0            .0          5.000             .0
   2.000         1966.0           1.0          5.006             .0
   4.000         1968.0           3.5          5.022             .7
   6.000         1970.0           7.9          5.049            1.8
   8.000         1972.0          15.7          5.098            3.8
  10.000         1974.0          29.6          5.185            7.5
  12.000         1976.0          51.3          5.321           14.0
  14.000         1978.0          81.3          5.508           25.5
  16.000         1980.0         126.1          5.788           43.7
  18.000         1982.0         167.5          6.047           71.0
  20.000         1984.0         201.1          6.257          107.5
  22.000         1986.0         239.4          6.496          140.9
  24.000         1988.0         282.2          6.764          170.2
  26.000         1990.0         332.1          7.076          195.4
  28.000         1992.0         388.0          7.425          216.6
  30.000         1994.0         452.5          7.828          234.1
  32.000         1996.0         526.8          8.292          247.7
  34.000         1998.0         611.8          8.824          257.7
  36.000         2000.0         710.6          9.441          262.6
  38.000         2002.0         827.0         10.600          242.4
  40.000         2004.0         958.5         13.523          180.7
  42.000         2006.0        1156.8         17.930          145.5
  44.000         2008.0        1409.6         23.547          128.4
  46.000         2010.0        1643.4         28.741          128.4
  48.000         2012.0        1869.3         30.423          128.4
  50.000         2014.0        2088.5         30.971          128.4
  52.000         2016.0        2298.8         31.497          128.4
  54.000         2018.0        2497.5         31.994          128.4
  56.000         2020.0        2683.4         32.459          128.4
  58.000         2022.0        2844.1         32.860          128.4
  60.000         2024.0        2980.2         33.200          128.4
  62.000         2026.0        3085.7         33.464          128.4
  64.000         2028.0        3152.9         33.632          128.4
  66.000         2030.0        3180.5         33.701          128.4
  68.000         2032.0        3164.6         33.662          128.4
  70.000         2034.0        3100.8         33.502          128.4
  72.000         2036.0        3049.4         33.374          810.0
  74.000         2038.0        3049.4         33.374         2265.5
  76.000         2040.0        3049.4         33.374         3836.0


TYPE CHANGES IF RERUN DESIRED
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This nuclear power complex could be improved to reduce the uranium requirements after year 2000, by introducing HWOCRs earlier and increasing the initial growth of breeders during 2000-2004. With these changes, the proportion of LWR's will be reduced before the turn of the century and a higher proportion of breeders after the turn of the century.

Hence, in nuclear power complex SIGMA, even though breeders are introduced as late as in year 2000, the low cost uranium resources will be available by the end of this century. Following a BNE say upto year 2025 and then burning excess of plutonium in HWOCRs will help reduce the higher uranium requirements and utilise available excess plutonium.

In conclusion :

In a nuclear power complex, with the proper policy of BNE and IBNE included, even if commercial breeders were not available until end of this century, there does not seem to be an acute problem of fuel scarcity, as has been often speculated. With the following additional facts, that :

1. from the point of view of fissile requiremments, high rating thermal converter systems are less demanding than high gain fast breeder systems, in the event of a quick rate of growth of installed nuclear power,

2. with an international uranium market, or uranium from sea water and additional discoveries, there will be more uranium resources,

3. those reactor systems which have the highest potentialities to achieve low fuel and capital costs and benefit directly from conventional generating equipment capital cost reductions will remain very attractive to nuclear power industries,

4. too early introduction of breeders may develope a huge plutonium stockpile later on and thus depreciate Pu,

5. with low load factors the economic penalty in installing highly capital intensive breeders will increase,

it will be difficult to justify the huge investments in "expeditious" breeder development programme. At this point, it may be even logical to know how much would be the penalty for having breeders ?

VI. D SUMMARY :

Table VI.11 and VI12 summarise the assumptions of various nuclear power complex systems developed in this chapter. Table VI.13 summarises the important results obtained through the computer code DYNUCLEAR.

Summary of Assumptions in Nuclear Power Complexes

Case	1965-1974	1975-1979	1980-1984	1985-2025	2026-2040
ALPHA	Only light water reactors throughout Two subcases : without and with plutonium recycling				
BETA	Only LWRs (Pu not recycled)		Breeders introduced at IBRGR* growth rate, rest LWRs	BNE between LWR & Breed	Breeder growth and capacity equals to total
GAMMA	Only LWRs (Pu recycle)	ACRs introduced at 10%, 20%, of total growth every year. Rest are LWRs. ACR: HWOCR, HTGR		All new growth from ACRs. No new LWRs, Bred fuel is recycled.	
DELTA	Only LWRs (No Pu recycling)	HWOCR introduced at 10%, 20%, and so on of new growth, rest are LWRs, No recy.	Breeders introduced at IBRGR,* HWOCR growth is 60%, 70%, & so on of remaining growth, rest are LWRs, No recycling	BNE between HWOCR and LWRs.	Breeder capacity and growth equal to total growth & capacity.
ETA	Only LWRs (No Pu recycling)	HTGR introduced at 10%, 20%, & so on of total growth, rest LWRs, U-233 recycled, Pu not recycled.	Breeders introduced at IBRGR,* HTGR growth is half of total growth, rest are LWRs, U-233 recyc. but not Pu.	BNE between Breeders & LWRs, HTGR growth at half of total growth U-233 recycled	Breeder growth equal to total growth, no new HTGR reactors.

* IBRGR is 1000, 3000, 5000, 8000 and 10,000 MWe/yr

Table VI.11

Summary of Assumptions in Nuclear Power Complexes

CASE	1965-1974	1975-1984	1985-1989	1990-1994	1995-2027	2028-2040
KAPPA	Only LWR (Pu not recycled) throughout	HWOCR introduced at 10%, 20% & so on of total growth, rest LWRs	New growth is of HWOCR LWR retired at 5000 MWe/yr Rest HWOCR	Breeders introduced at IBRGR	BNE between Breeders and HWOCR and LWRs	Breeder capacity and growth is equal to toal capacity, growth.

CASE	1965-1979	1980-1999	2000-2004	2005-2035	2036-2040
SIGMA	Only LWR (Pu not recycled)	LWR capacity decrease linearly HWOCR are the rest of toal cap. Pu in HWOCR is recycled but is not recycled in LWRs	Breeders introduced at IBRGR Rest are HWOCR recycling Pu.	BNE between Breeders and the HWOCR No recycling.	Breeder capacity and growth equal to total

CASE	1965-1974	1975-1979	1980-1984	1985-2014	2015-2040
THETA	Only LWR (No Pu recycling throughout)	Fast U-235 reactor introduced at 10%, 20 % etc of total growth, rest : LWR	Breeders introduced at IBRGR, Fast U-235 at 60 %, 70 %, of total growth Rest are LWRs	BNE between Breeders and Fast U-235.	Breeder capacity and growth is equal to total
ZETA	Only LWR (No Pu recycling throughout)	HTGR introduced at 4000 MWe/yr Fast U-235 introduced at 10 %, 20 % etc of remaining growth. rest LWRs	Breeders introduced at IBRGR, HTGR growth is LWRs retired 5000 mwe/yr Rest are Fast U-235. No recycling.	BNE between Breeders and LWR and Fast U-235 reactor HTGR growth at 5000 MWe/yr	Breeder capacity and growth equal to after deducting 50,000 MWe/yr = HTGR growth.

Table VI.12

Summary of Results of Nuclear Power Complexes

CASE	LWR capacity MWe x10^{-3}		ACR capacity MWe x10^{-3}		Breeder cap. MWe x10^{-3}		Duration of BNE	Uranium Price $/lb		Plutonium StockPile kgms x 10	
	Max	Min	Max	Min	Max	Min		by 2000	by 2040	in BNE	by 2040
ALPHA a)With recy b)Without rec	all LWR		-		-		-	16.7 30.3	56.2 88.0	0	0 19,900
BETA	525 (2010)	0			4610 (2040)	0 (1980)	1985-2025	16.7	30.3	3.8	8,931
GAMMA 1) HWOCR 2) HTGR	90 (1985)		4540 (2040)		-		-	9.33 9.11	44.10 36.0	-	-
DELTA	92 (1984)	0 (2003)	500 (2006)	0 (2025)	4610 (2040)	0 (1979)	1985-2025	9.50	23.50	4.5	9,415
ETA	336 (2008)	0 (2026)	854 (2026)	-	3760 (2040)	0 (1979)	1985-2025	11.40	30.50	-5.1	5585
KAPPA	90 (1984)	0 (2003)	650 (2010)	0 (2027)	4610 (2040)	0 (1989)	1995-2027	12.13	30.15	481	8400
SIGMA	75 (1980)	0 (2000)	1165 (2010)	0 (2034)	4610 (2040)	0 (1999)	2005-2035	9.4	33.4	128	3840
THETA	90 (1984)	0 (2003)	242 (2004)	0 (2014)	4610 (2040)	0 (1979)	1985-2015	9.17	7.10	16	1300
ZETA	74 (1974)	0 (2000)	236 (2000)	0 (2016)	3186 (2040)	0 (1979)	1985-2015	9.14	24.17	2	1303

Table VI.13

CHAPTER VII

URANIUM VALUE ANALYSIS

The problem of uranium value becomes much more important in a dynamic system of moving targets. Steeply rising U prices will make the nuclear fuel cycle cost rise rapidly and thus the basic advantage of nuclear power of low fuel costs may be lost. At some point, the power generating idustries may even prefer to have the fossil fuel plants. It is thus important for nuclear power planning that the U prices do not soar very much.

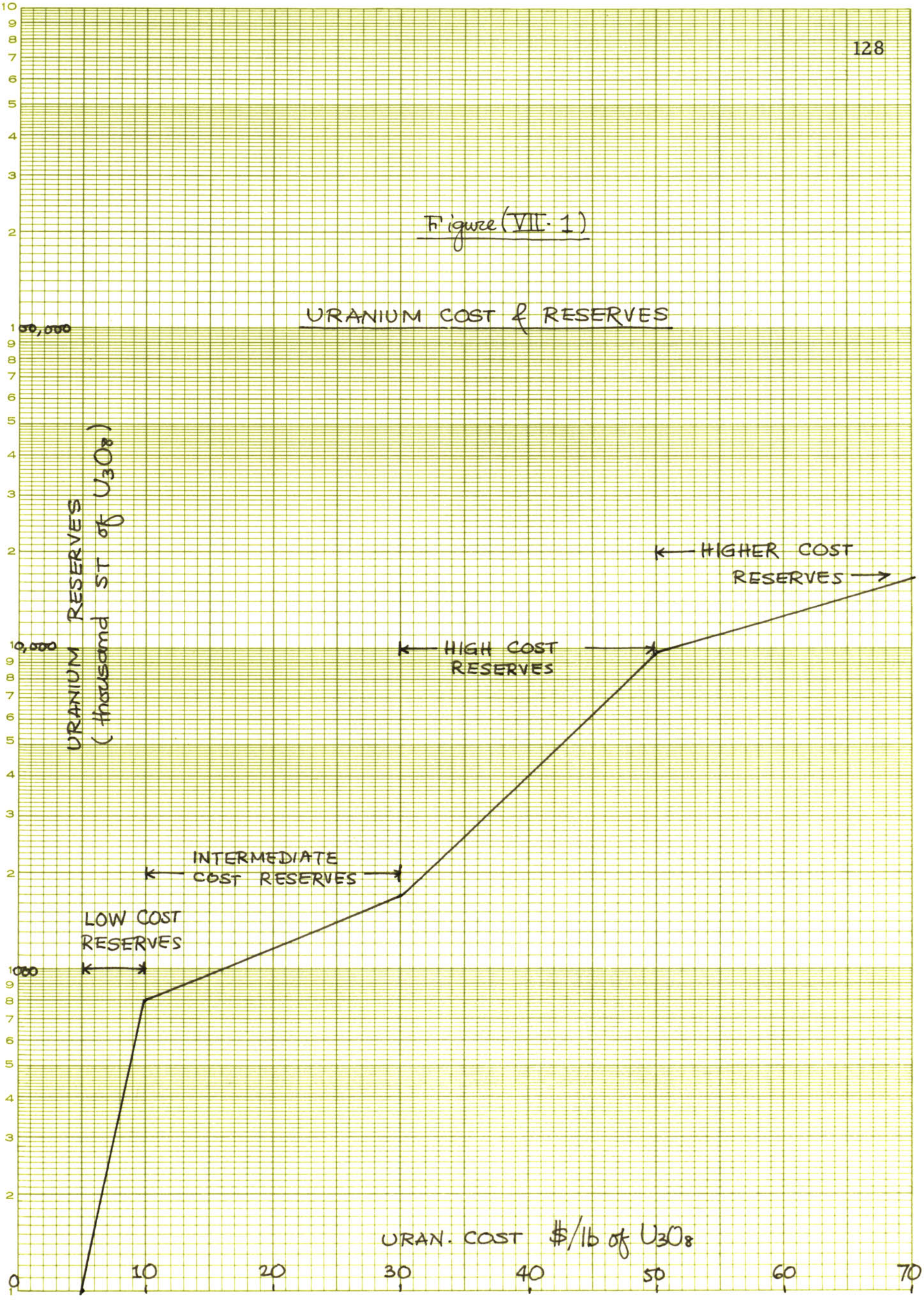
Rising U prices can be checked by (a) distributing the consumption of low cost and intermediate cost U resources over a longer period, (b) by sharing the burden of fuel consumption through the introduction of breeder reactors in the power complex. The former one depends on U consuming reactor installations and intermediate cost U reserves. The latter one depends on the timing of breeder reactor introduction and their percentage share in the entire nuclear power complex. U price is influenced by :

(1) Uranium Resources and Cost of Production :

Figure VII.1 (from Table I.2) shows the relation between the cost of U production per lb of U_3O_8 and the estimated U.S. reserves. The U price increases by $5/lb for the consumption of first 800,000 ST of low cost U_3O_8 (price range $5 to 10/lb), by $20/lb for the consumption of next 900,000 ST of intermediate cost

Figure (VII·1)

URANIUM COST & RESERVES



U_3O_8 (price range \$10 to \$30/lb) and by \$20/lb for the consumption of next 9000,000 ST of high cost U_3O_8 (price range \$30 to \$50/lb). Thus the rate of price increase of intermediate cost uranium with amount mined is almost four times the rate for low cost uranium and is almost nine times the rate for high cost uranium. In this respect, it will be much prudent to use intermediate cost uranium as cautiously as possible.

If a rise of \$1/lb in the uranium price raises its fuel cycle cost by 0.07 mills/kwhr in LWRs (Ref. 7), this rise will amount to about 1.75 mills/kwhr if high cost reserves (at a price of \$30/lb) were to be used instead of low cost reserves (at a price of \$ 5/lb). On this basis, it can be safely concluded that the nuclear power growth will be almost negligible if such high cost U reserves were to be used.

(2) Nuclear Power Complex Systems :

A properly designed nuclear complex, such as of case THETA comprised of LWRs, Fast U-235 reactors and Fast Breeders, can be developed to make the best use of available low cost U reserves. Fig VII. 2 and VII. 3 showing the cumulative uranium requirements for different nuclear power complexes illustrate this fact. The two cases of ALPHA (consisting of only LWRs) considered, with and without Pu recycling, have the highest demands for uranium. Although BETA, a case of transition between LWRs and Breeders does not require high cost U resources, it is of less merit than case DELTA having ACRs as an intermediate step between the transition. The uranium requirements of case GAMMA with all ACRs after 1975 are higher after the turn of the century. The uranium requirements of case KAPPA and SIGMA

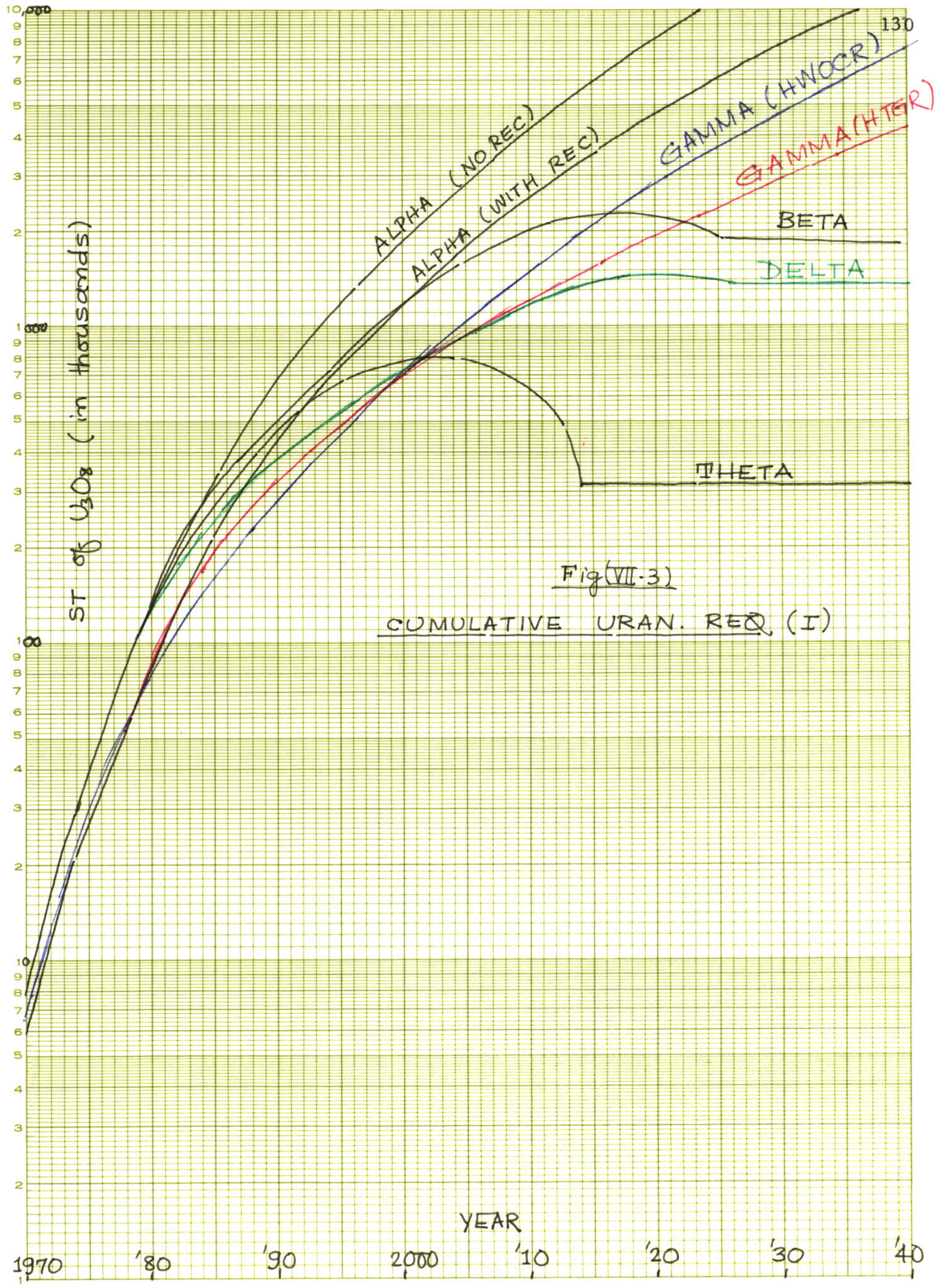


Fig (VII·3)

CUMULATIVE URAN. REQ (I)

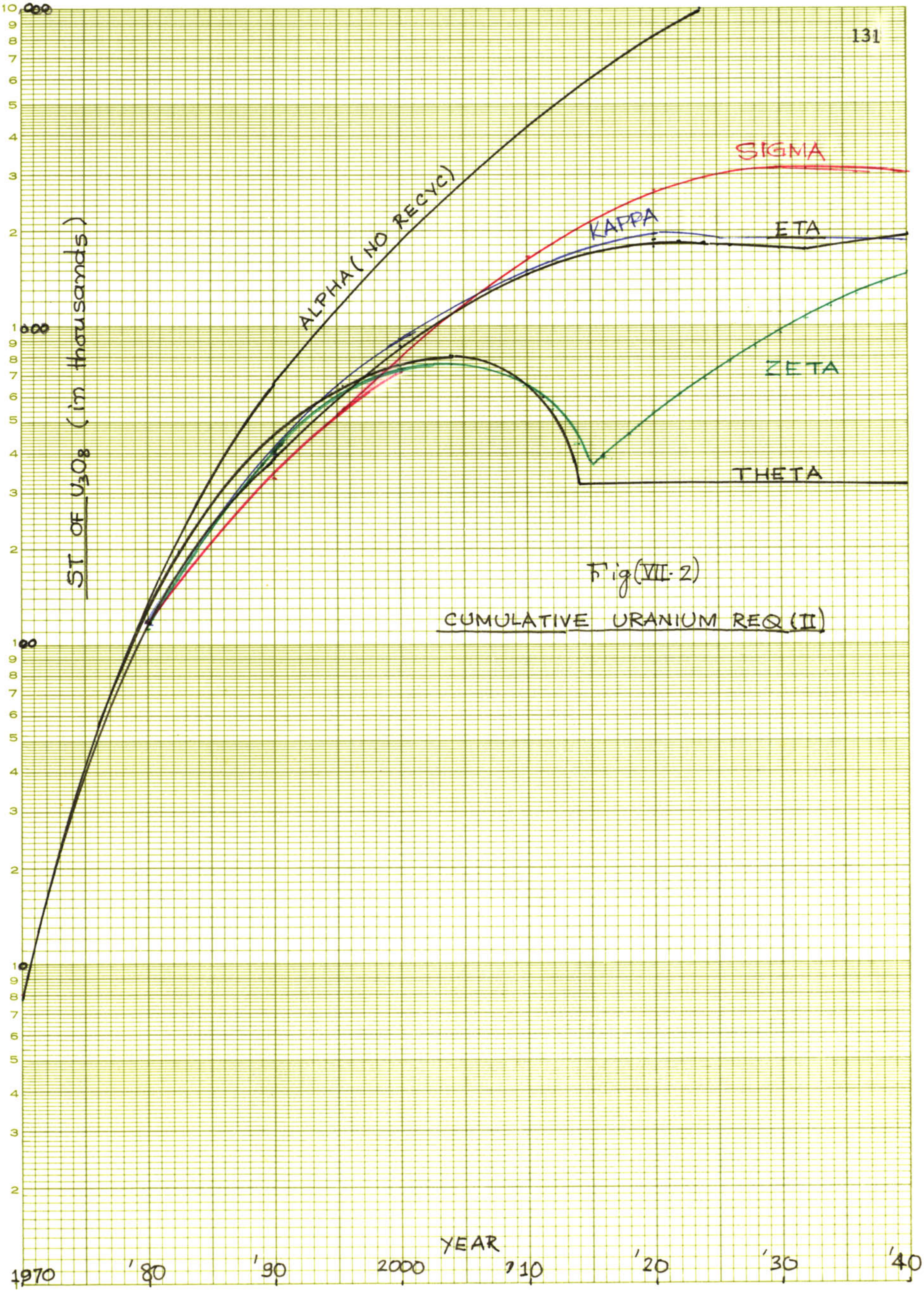


Fig (VII·2)

CUMULATIVE URANIUM REQ (II)

with late introduction of breeders (in 1990 and year 2000 respectively) would require high cost uranium reserves in the next century. Although a huge plutonium stockpile is available in these last two cases, and will reduce uranium requirements if it is used in ACR in association with uranium (as suggested in IBNE), it is not very certain whether such a practice would be practical.

The least amount of uranium is consumed in case THETA. As this case develops a plutonium stockpile after year 2015, a somewhat better case would be one in which some light water reactors or advanced converter reactors were kept in operation after this date, fueled with depleted uranium and excess plutonium from breeders. It will be better also to introduce breeders at a later date if commercial breeders were not available very soon.

The uranium prices in all these cases are as shown in Fig VII. 4 and Fig VII. 5. It can be seen from these figures that the uranium prices rise very steeply between $10-30/lb range. Uranium price is lowest in the case THETA.

Major factors influencing uranium requirements and prices in a nuclear power complex system are :

(a) the uranium reactor performance

(b) the percentage share of LWR, ACR and Breeders in the nuclear power complex

(c) the time of introduction of Breeders and ACR

(d) the available <u>excess</u> plutonium to be used in U reactors

(e) the use of BNE and IBNE in the complex.

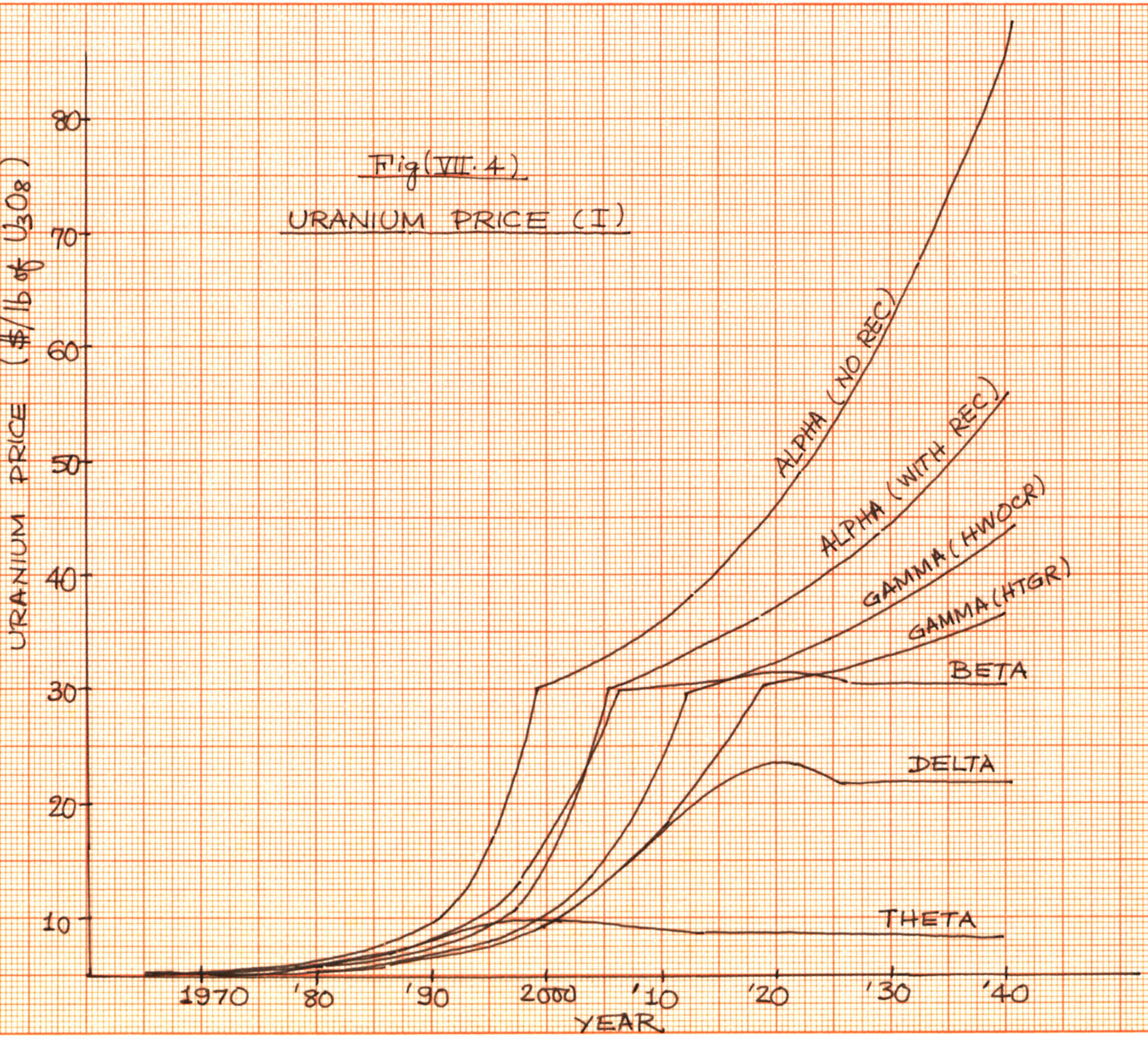
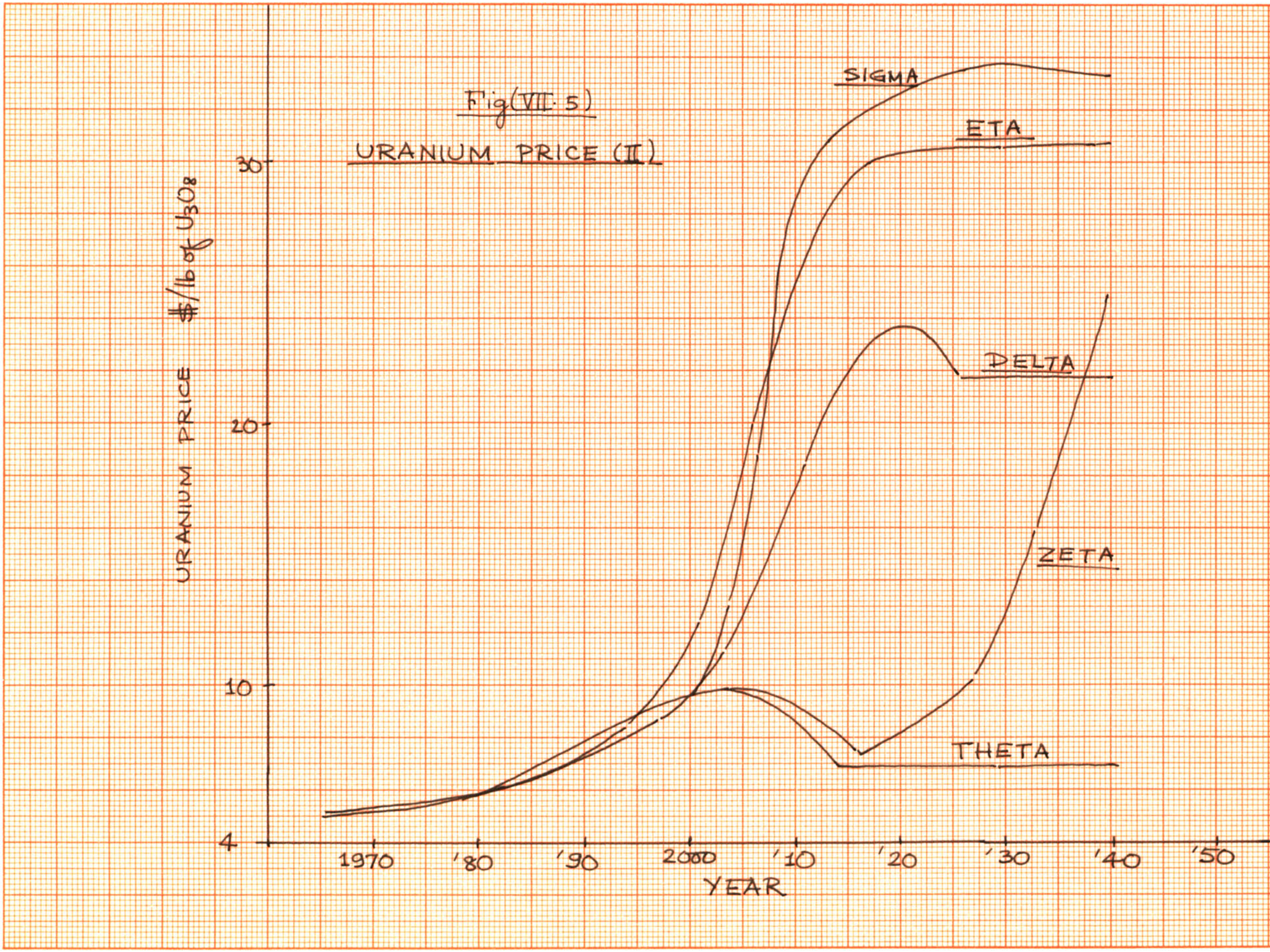


Fig (VII.4)

URANIUM PRICE (I)



Fig(VII·5)

URANIUM PRICE (II)

(3) Other Factors :

Other less important factors influencing the uranium price are :

(a) International market for uranium

(b) Uranium from sea water

(c) Cost performance of committed nuclear power plants

(d) Cost performance of fossil-fuel plants

(e) Tails assay in the diffusion plants

Conclusion :

It is possible to infer that, if at the start of 1965 the free market uranium price is $5/lb, with the present estimated low-cost uranium resources, the price of uranium will not exceed $10/lb by year 2000 and will remain stable thereafter for the reasons of lesser demand and excess available plutonium to be used in uranium reactors, provided fast breeders are developed by the end of the century.

CHAPTER VIII

CONCLUSIONS & SUGGESTIONS

VIII. A CONCLUSIONS :

This research is an attempt to investigate some of the guidelines in setting up a nuclear power complex system comprised of light water reactors, advanced converter reactors and fast breeder reactors over a period of seventy-five years. A nuclear power complex will be superior to another if it can (a) utilise its nuclear fuel resources more efficiently, (b) adjust itself to make full use of evolving technology in the choice of reactor type, and (c) produce power as cheaply as possible. In a dynamic system of moving targets, these questions become very complex and thus make the forecasting very difficult.

With the basic three assumptions of [1] exponential growth of nuclear power generating capacity, [2] the specific reactor performance characterstics of Ref (2) , and [3] trends in the development of nuclear power industries, and the preceding analysis, it is possible to derive the following conclusions :

[1] There exists a problem of nuclear fuel resources, largely depending on the growth of nuclear power industries and the utilization patterns of nuclear fuels. The two fissile nuclear fuels considered are naturally occuring U-235 and fissile Plutonium produced (although fertile Thorium also has some potential use). If the growth of nuclear power is very rapid, as has been assumed in this study, the uranium resources alone will not be able to meet the total fuel

requirements, thus requiring that sufficient amounts of plutonium be produced and utilised to meet the total demands. The implication is that by the turn of this century, the plutonium fueled fast breeder reactors must share a substantial demand for nuclear power.

[2] If only light water reactors (LWR) are built even with plutonium recycling and improvements in fuel utilization, extraordinary amounts of uranium will be required, as much as 12 million short tons of U_3O_8 (at a price of $56/lb) by year 2040. It is thus necessary to make use of advanced converter reactors (ACR) or other reactors making more efficient utilization of nuclear fuel.

[3] Commercial ACRs will not only improve U utilization but may also produce electrical power at lower rates and will produce enough plutonium for initial breeder inventory requirements.

[4] Commercial breeder reactors will not only utilise previously built plutonium stockpile but utilize it very efficiently, will reduce the total demand for uranium and will be self-sufficient in their fuel requirements in thirty to forty years.

[5] Plutonium recycling in LWRs and or in ACRs does not solve the long-term fuel problem, although it may appear to be attractive in short-term; but it will be much less favourable than its use to provide inventory for fast breeders even if the latter approach requires the storage of plutonium until commercial fast breeders are developed.

[6] A nuclear power complex system with a

gradual transition from LWRs to ACRs to Breeder reactors will be much superior to one operating with only one of them, because, only uranium reactors all the time demand extraordinary amounts of U and only breeder reactors all the time build up excessive plutonium stockpiles, increasing the unintended investments. A nuclear power complex system designed to use uranium and plutonium simultaneously and at a gradually increasing rate will be much superior to one making a complete transition from one type of reactor system to another type.

[7] There will be four stages of development in the growth of nuclear power generating industries :

(a) First Stage (short range) : The complex will consist of only LWRs , for a duration of about first ten years.

(b) Second Stage (intermediate range) : The complex consisting predominantly of ACRs, the rest being LWRs, lasting for a duration of about ten to fifteen years.

(c) Third Stage (long range) : This is the case of Balanced Nuclear Economy [BNE] , where the plutonium production rate and consumption rate will be equal, predominantly of fast breeder reactors, the rest being ACRs, lasting for a duration of about forty years.

(d) Fourth Stage (longer range) : This is the case of Integrated Balanced Nuclear Economy [IBNE] , (where excess of Pu will be fed into newly installed ACRs), predominantly of fast breeder reactors, is assumed to last for last twenty five years.

The time span and fraction of total power generated in each reactor type during these different stages will largely depend on the commercial attractiveness of these reactors, the fuel resource problem and the developed technology at that time.

[8] The use of ACRs in the power complex influences (a) total uranium requirements, (b) total plutonium production prior to and during BNE, (c) the time at which breeders need to be introduced and (d) the development of art of fast reactor technology. Although, commercially developed HWOCR or HTGR reactors seem to be the proper recommendation, Fast U-235 fueled reactors show a higher promise as a substitute for ACRs. This is because, (a) they require lesser amounts of cumulative uranium as they are required in smaller proportion in the entire nuclear power complex, (b) they produce almost two and half times more plutonium than other advanced converters thus helping the growth of breeders during and prior to BNE, (c) with less uranium consumed they can defer the time at which fast breeders need to be introduced, and last but not the least (d) they will help the development of the art of fast reactor technology, and thus reduce the research and development investments in the advanced converter reactors and fast breeder reactors as well. This implies that, only one type of reactor, namely Fast U-235 fueled reactors, need to be developed.

[9] Should it be impossible to develop commercial fast breeder reactors in future, the choice of ACR is more favourable in case of HTGR-Th than HWOCR-U, because in the long-run the total

uranium requirements are less in the former case than in latter, for the same amount of electricity generated and bred fissile fuel recycled. HTGR-Th reactors will also utilize available economic Thorium resources. However, if it is possible to develop fast breeder reactors in future and Fast U-235 reactors are not desired [because of highly enriched uranium feed required, which will have to be imported from the point of view of those countries who do not have diffusion plant], the choice of ACR will be in favour of HWOCR reactors for two reasons : (1) in short-run the uranium requirements of HWOCR-U are less than that of HTGR-Th reactors, and (2) bred fissile plutonium will be available, if desired, for breeder reactor inventory requirements.

[10] A nuclear power complex having Fast U-235 reactors as a substitute for ACRs prior to development of breeders will not only require very small amounts of uranium but will also produce substantial amount of plutonium in the fourth stage of complex [IBNE] . This excess Pu could be used in ACRs or could be exported to capture a foreign market in breeder reactors.

[11] The time at which breeders need to be introduced is determined by : (a) uranium requirements and availability, (b) the pressure to use already developed plutonium stockpile, and (c) the research and development investments required for successful commercial operation.

In general, the effect of late breeder introduction will be to (a) increase the total uranium requirements, (b) increase the proportion of ACRs in the nuclear power complex, and (c) produce less excess plutonium in the last stage of the complex.

With the introduction of fast U-235 reactors and fast breeders in the power complex, the uranium requirements are considerably reduced. Hence, even if they are introduced in late eighties or ninties, sharing a major fraction of total power generation, the fuel problem may not be serious. It may be even reasonable to recycle the bred fissile plutonium in LWRs for some time and thus reduce : (a) short term uranium requirements, (b) cost of power generation in LWRs and (c) the burden of unintended investments in plutonium. Fast U-235 reactors do not require plutonium and thus this practice of plutonium recycling will not be objectionable. Plutonium requirements of fast breeders can be met from the plutonium produced in Fast U-235 reactors. On this basis it is possible to recommend that :

Until 1990 there should be only LWRs, recycling their bred plutonium. [Notice that the price of uranium in such a case [see Table VI. 2] will not exceed $ 7. 50/lb]. In 1990, fast U-235 reactors be introduced at a rapidly increasing rate and from year 2000 onwards there be a Balanced Nuclear Economy between Fast U-235 reactors and fast breeders.

This recommendation in effect implies that, there will be no necessity of developing ACRs if fast reactors can be introduced on commercial basis by year 2000 or so. As a matter of fact, the research and development investments in ACRs can be diverted to the leisurely development of fast reactors.

[12] Balanced Nuclear Economy as the third stage of nuclear power complex, not only reduces the unintended plutonium investments but also reduces the cost of power generation and extends the nuclear fuel base. The time span of BNE (i. e. when the ACR capacity goes to zero) depends largely on the nuclear power growth rate constant (Lambda), plutonium production rate in converters and breeders and the delay δ , and changes considerably with change in each of them. This time span of BNE is almost forty years when HWOCR type of ACRs are installed in the complex but reduces to thirty years when Fast U-235 are substituted for them, because of latter's higher plutonium production rate.

The effect of delay δ on breeder growth in BNE is to reduce it by introducing a factor $e^{\lambda\delta}$ in the denominator for the expression for the ξ , the limiting value of share of breeder reactors in the complex. The fractional changes in λ affect the limiting fraction of breeder generating capacity more than in δ and the extent to which it will be affected by fractional changes in α and β will depend on their relative magnitudes. The effect of delay can also be interpreted to cause the condition that a BNE persist for all time to change from $\frac{\ell b}{I_b} < \lambda$ to $\frac{\ell b}{I_b} < \lambda e^{\lambda\delta}$.

The growth of advanced converter reactor capacity during BNE also depends largely on the above mentioned condition. The ACR capacity may grow initially under certain circumstances but decreases with time, eventually.

[13] Integrated Balanced Nuclear Economy (IBNE) as the last stage of power complex utilises the excess of plutonium by feeding it into newly installed advanced converter reactors. In IBNE with ACRs in the nuclear power complex the penalty on highly capital intensive breeders because of decreasing load factors will be lesser than without it. Such use of plutonium also ensures a competitive market for plutonium after BNE and also reduces external fuel requirements of the system.

[14] With a properly designed nuclear power complex it is safe to conclude that the free market price of uranium will not exceed $ 10/lb by the year 2000 and will remain stable around that value later on because of reduced demand for uranium and excess available plutonium during the last stage of the nuclear complex. This is true with the assumption that commercial breeders will be available by late eighties.

[15] The value of plutonium in a balanced nuclear economy, with certain assumptions regarding costs of breeder and converter reactors, increases with time. The plutonium value almost saturates at a level of $11/gm by the end of fortieth year in a case of BNE installing HWOCR as ACRs and saturates at about $ 13/gm by the end of thirtieth year in the case of a BNE installing Fast U-235 reactors. The plutonium value is higher in the latter case because of higher cost of power generation in Fast U-235 reactors.

VIII. B SUGGESTIONS FOR FURTHER STUDY :

[a] Following are suggested improvements :

(1) The nuclear power growth was assumed to be of exponential nature and was subdivided into a number of segments of five year interval each. The exponential growth rate constant being discontinuous, the growth of nuclear power during each segment became discontinuous. A regression analysis can be performed to improve on this. The suggested form of regression is :

$$P(t) = P_o \exp [1/(a' + b't)]$$

where a' and b' are constants and should be evaluated.

(2) The reactor plant life was neglected in this study, and this should be included to determine the installed reactor capacity of each type.

[b] Following are the suggested additions :

(1) This study has only two types of ACRs- namely HWOCR and HTGR. Additions of other types of ACRs will improve on the logic of choice of ACRs and time and share of breeder reactor introduction in the nuclear complex.

(2) The characterstics assumed for each nuclear power complex system considered are derived from personal judgments, sometimes quite arbitrarily for the sake of simplicity of analysis. Various refinements and additions may improve the particular cases considered although conclusions may be almost the same.

[c] Following is the suggested advanced analysis of this subject :

In a free-enterprise economy, only those types of reactors will be installed which show maximum economic advantage - i.e. minimum cost of power generation per kwhr of electricity generated. A nuclear power complex will be determined by first knowing the cost of power generation in each individual reactors and not the other way around.

The computer code developed in this study can be improved to take into account the following : (1) the cost of power generation in each type of reactor, (2) the reactor performance characteristics and their demand for nuclear fuels, (3) and the development trends of nuclear reactor industries.

Fig VIII.1 shows the suggested model of this situation which has the following exogeneous variables : (1) total installed nuclear power capacity, (2) total nuclear fuel resources and their availability, and (3) reactor performance characteristics.

The dynamic model shows five different sectors :

(I) Total installed nuclear power capacity P(t) is distributed amongst LWRs, ACRs and Breeders. Total growth GRP(t) is similarly distributed in each of them and is shown by GRC, GRA & GRB.

(II) Uranium requirements in LWRs and ACRs are shown by UC and UA, respectively, and are combined together to compare with total uranium reserves and their cost of production.

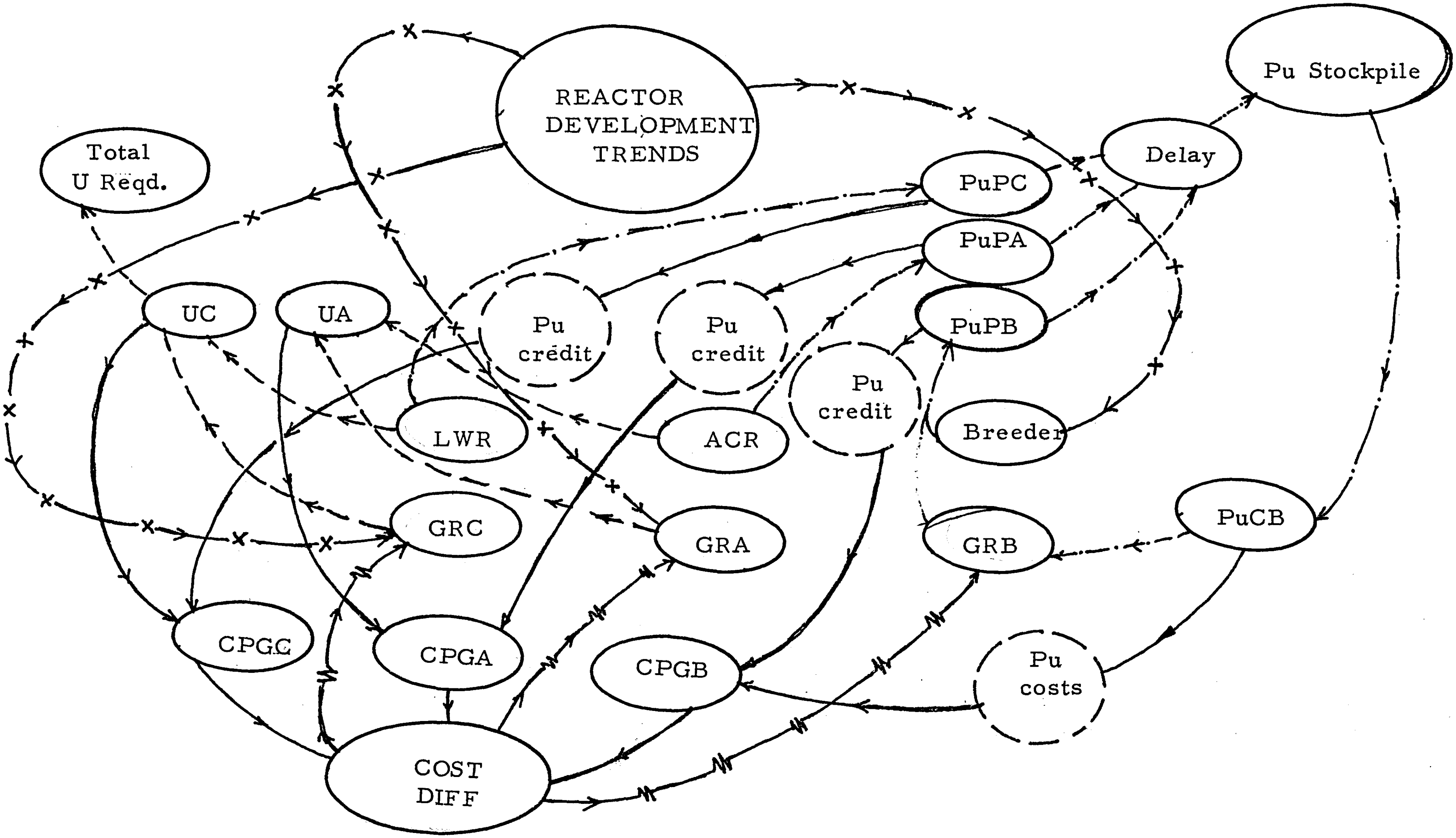


Fig. VIII. 1 THE DYNAMIC MODEL OF GROWTH OF NUCLEAR POWER

(III) Cost of power generation in each of them is shown by CPGC, CPGA and CPGB respectively. These costs are partly influenced by their uranium requirements and plutonium credits. The cost differential of these power generation costs (COST DIFF) influences the new reactor installations GRC, GRA and GRB, and only that type of reactor is installed which shows the minimum cost of power generation.

(IV) Plutonium production rate in each of them PuPC, PuPA and PuPB increases the plutonium stockpile after a delay of δ years. Plutonium consumption rate PuCB in breeders decreases the plutonium stockpile. (Pu recycling is not shown in the figure.)

(V) Reactor development trends influence directly the installed (new) capacities of these individual reactors, deciding the time at which each of them are introduced, the initial growth rate, the situation of BNE and the situation of IBNE.

[d] Following is the suggested method to determine an " Optimum Nuclear Power Complex " :

The aim is to have an optimum distribution of power output between A(t), B(t) and C(t) so that the present worth of all expenditures to install A(t), B(t) and C(t) is minimum possible.

The expenditures in each of the reactor type during the time interval dt is :

$$EXPC(t) = [\ C_c\,(dC/dt) + O_c\,C(t)\ ]\ e^{-it}\,dt$$

$$EXPA(t) = [\ C_a\,(dA/dt) + O_a\,A(t)\ ]\ e^{-it}\,dt \qquad \text{and,}$$

$$EXPB(t) = [\ C_b\,(dB/dt) + O_b\,B(t)\ ]\ e^{-it}\ dt$$

where, C_c, C_a, and C_b are Capital costs in C(t), A(t) and B(t) (dollars/ MWe capacity)

O_c, O_a, and O_b are operating costs in C(t), A(t) and B(t) (dollars / MWeyr of electricity produced)

i is interest rate (fraction/yr)

and, t is time at which they are installed.

The total expenditures at any time will be :

$$TEXP(t) = EXPC(t) + EXPA(t) + EXPB(t)$$

and for this to be minimum,

$$\partial \int [TEXP(t)]\ dt = 0$$

Since total nuclear power is given by :

$$P(t) = P_o \exp [\ 1/(\ a' + b't\ )]$$

and also, $= C(t) + A(t) + B(t)$

and for the case of BNE,

$$I_b\ d[\ B(t+\delta)]\ /dt = 1\,[\ a\ A(t) + b\ B(t) + c\ C(t)\ ]$$

it is possible to solve all these equations simultaneously to determine the optimum nuclear power complex. This can be best done with the help of linear programming or dynamic programming.

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Ref. (5) DYNAMO user's manual, Alexander Pugh, MIT Press, 1964.

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2. Development, Growth, and state of Atomic Energy Industry
Hearings before the joint committee on atomic energy, congress of the United States, Part I and II, 1963.

APPENDIX

DYNUCLEAR

```
printf sl madtrn
W 2010.6

00010 NOTE
00020 NOTE
00030 NOTE              COMPUTER PROGRAM  DYNUCLEAR
00040 NOTE
00050 NOTE
00060 NOTE  THIS PROGRAM WRITTEN FOR THESIS ENTITLED, 'THE DYNAMICS
00070 NOTE  OF GROWTH AND ECONOMIC ANALYSIS OF EXPANDING NUCLEAR
00080 NOTE  POWER GENERATING INDUSTRIES BASED ON PLUTONIUM CONVERTER
00090 NOTE  AND BREEDER REACTORS' (JANUARY 1966,M.I.T.) CALCULATES
00100 NOTE  FOR EVERY QUARTER OF A YEAR FROM 1965 TO YEAR 2040 :
00110 NOTE  THE TOAL NUCLEAR POWER INSTALLED CAPACITY,THE TOTAL
00120 NOTE  POWER GENERATED,THE SHARE OF POWER CAPACITIES OF LIGHT
00130 NOTE  WATER REACTORS,ADVANCED CONVERTER REACTORS AND BREEDER
00140 NOTE  REACTORS UNDER ASSUMED NUCLEAR POWER COMPLEX. THIS PROGRAM
00150 NOTE  ALSO CALCULATES THE TOTAL URANIUM REQUIREMENTS,THE TOTAL
00160 NOTE  PLUTONIUM PRODUCED AND CONSUMED,THE PRICE OF URANIUM
00170 NOTE  AND THE PLUTONIUM IN THE CASE OF BALANCED NUCLEAR ECONOMY.
00180 NOTE
00190 NOTE              THE GROWTH OF NUCLEAR POWER
00200 NOTE
00210 51A   P1.K=CLIP(0,PX1.K#TIME.K,T6)
00220 51A   P2.K=CLIP(0,PX2.K#TIME.K,T11)
00230 51A   P3.K=CLIP(0,PX3.K,TIME.K,T16)
00240 51A   P4.K=CLIP(0,PX4.K,TIME.K,T21)
00250 51A   P5.K=CLIP(0,PX5.K,TIME.K,T26)
00260 51A   P6.K=CLIP(0,PX6.K,TIME.K,T31)
00270 51A   P7.K=CLIP(0,PX7.K,TIME.K,T36)
00280 51A   P8.K=CLIP(0,PX8.K,TIME.K,T41)
00290 51A   P9.K=CLIP(0,PX9.K,TIME.K,T46)
00300 51A   P10.K=CLIP(0,PX10.K,TIME.K,T51)
00310 51A   P11.K=CLIP(0,PX11.K,TIME.K,T56)
00320 7A    P12.K=P12A.K+P12B.K
00330 28A   P12AZ.K=(M55)EXP(ARG12.K)
00340 28A   P12BZ.K=(M60)EXP(ARG13.K)
00350 45A   P12AY.K=STEP(P12AZ.K,T56)
00360 45A   P12BY.K=STEP(P12BZ.K,T61)
00370 28A   P12AT.K=(P12A.K)EXP(LD12A.K)
00380 28A   P12BT.K=(P12B.K)EXP(LD13.K)
00390 51A   P12A.K=CLIP(0,P12AY.K,TIME.K,T61)
00400 51A   P12B.K=CLIP(0,P12BY.K,TIME.K,77)
00410 45A   PX1.K=STEP(PY1.K,1)
00420 45A   PX2.K=STEP(PY2.K#T6)
00430 45A   PX3.K=STEP(PY3.K,T11)
00440 45A   PX4.K=STEP(PY4.K,T16)
00450 45A   PX5.K=STEP(PY5.K,T21)
00460 45A   PX6.K=STEP(PY6.K,T26)
00470 45A   PX7.K=STEP(PY7.K,T31)
00480 45A   PX8.K=STEP(PY8.K,T36)
00490 45A   PX9.K=STEP(PY9.K,T41)
00500 45A   PX10.K=STEP(PY10.K,T46)
R 1.400+.466
```

```
printf s2 madtrn
W 2045.5
00510 45A    PX11.K=STEP(PY11.K,T51)
00520 28A    PY1.K=(M0)EXP(ARG1.K)
00530 28A    PY2.K=(M5)EXP(ARG2.K)
00540 28A    PY3.K=(M10)EXP(ARG3.K)
00550 28A    PY4.K=(M15)EXP(ARG4.K)
00560 28A    PY5.K=(M20)EXP(ARG5.K)
00570 28A    PY6.K=(M25)EXP(ARG6.K)
00580 28A    PY7.K=(M30)EXP(ARG7.K)
00590 28A    PY8.K=(M35)EXP(ARG8.K)
00600 28A    PY9.K=(M40)EXP(ARG9.K)
00610 28A    PY10.K=(M45)EXP(ARG10.K)
00620 28A    PY11.K=(M50)EXP(ARG11.K)
00630 18A    ARG1.K=(LAMD1)(TIME.K-T0)
00640 18A    ARG2.K=(LAMD2)(TIME.K-T5)
00650 18A    ARG3.K=(LAMD3)(TIME.K-T10)
00660 18A    ARG4.K=(LAMD4)(TIME.K-T15)
00670 18A    ARG5.K=(LAMD5)(TIME.K-T20)
00680 18A    ARG6.K=(LAMD6)(TIME.K-T25)
00690 18A    ARG7.K=(LAMD7)(TIME.K-T30)
00700 18A    ARG8.K=(LAMD8)(TIME.K-T35)
00710 18A    ARG9.K=(LAMD9)(TIME.K-T40)
00720 18A    ARG10.K=(LMD10)(TIME.K-T45)
00730 18A    ARG11.K=(LMD11)(TIME.K-T50)
00740 18A    ARG12.K=(LMDZ2.K)(TIME.K-T55)
00750 18A    ARG13.K=(LMDZ3.K)(TIME.K-T60)
00760 51A    LAMD1.K=CLIP(0,LMDX1.K,TIME.K,T6)
00770 51A    LAMD2.K=CLIP(0,LMDX2.K,TIME.K,T11)
00780 51A    LAMD3.K=CLIP(0,LMDX3.K,TIME.K,T16)
00790 51A    LAMD4.K=CLIP(0,LMDX4.K,TIME.K,T21)
00800 51A    LAMD5.K=CLIP(0,LMDX5.K,TIME.K,T26)
00810 51A    LAMD6.K=CLIP(0,LMDX6.K,TIME.K,T31)
00820 51A    LAMD7.K=CLIP(0,LMDX7.K,TIME.K,T36)
00830 51A    LAMD8.K=CLIP(0,LMDX8.K,TIME.K#T41)
00840 51A    LAMD9.K=CLIP(0,LMDX9.K,TIME.K,T46)
00850 51A    LMD10.K=CLIP(0,LDX10.K,TIME.K,T51)
00860 51A    LMD11.K=CLIP(0,LDX11.K,TIME.K,T56)
00870 51A    LD12A.K=CLIP(0,LMDZ2.K,TIME.K,T61)
00880 51A    LD13.K=CLIP(0,LMDZ3.K,TIME.K,77)
00890 45A    LMDX1.K=STEP(LMDY1.K,1)
00900 45A    LMDX2.K=STEP(LMDY2.K,T6)
00910 45A    LMDX3.K=STEP(LMDY3.K,T11)
00920 45A    LMDX4.K=STEP(LMDY4.K,T16)
00930 45A    LMDX5.K=STEP(LMDY5.K,T21)
00940 45A    LMDX6.K=STEP(LMDY6.K,T26)
00950 45A    LMDX7.K=STEP(LMDY7.K,T31)
00960 45A    LMDX8.K=STEP(LMDY8.K,T36)
00970 45A    LMDX9.K=STEP(LMDY9.K#T41)
00980 45A    LDX10.K=STEP(LDY10.K,T46)
00990 45A    LDX11.K=STEP(LDY11.K,T51)
01000 45A    LMDZ2.K=STEP(LMD12,T56)
R 1.533+.550
```

```
printf s3 madtrn

W 2128.5
01010 45A    LMDZ3.K=STEP(LMD13,T61)
01020 29A    LMDY1.K=(K)LOGN(R1.K)
01030 29A    LMDY2.K=(K)LOGN(R2.K)
01040 29A    LMDY3.K=(K)LOGN(R3.K)
01050 29A    LMDY4.K=(K)LOGN(R4.K)
01060 29A    LMDY5.K=(K)LOGN(R5.K)
01070 29A    LMDY6.K=(K)LOGN(R6.K)
01080 29A    LMDY7.K=(K)LOGN(R7.K)
01090 29A    LMDY8.K=(K)LOGN(R8.K)
01100 29A    LMDY9.K=(K)LOGN(R9.K)
01110 29A    LDY10.K=(K)LOGN(R10.K)
01120 29A    LDY11.K=(K)LOGN(R11.K)
01130 20A    R1.K=M5/M0
01140 20A    R2.K=M10/M5
01150 20A    R3.K=M15/M10
01160 20A    R4.K=M20/M15
01170 20A    R5.K=M25/M20
01180 20A    R6.K=M30/M25
01190 20A    R7.K=M35/M30
01200 20A    R8.K=M40/M35
01210 20A    R9.K=M45/M40
01220 20A    R10.K=M50/M45
01230 20A    R11.K=M55/M50
01240 37B    CAR=BOXLIN(2,1)
01250 6A     CAR*1.K=POWER.K
01260 6A     POWT.K=CAR*2.K
01270 C      CAR*=0/1500
01280 7A     GROTH.K=POWER.K-POWT.K
01290 37B    LOCAL=BOXLIN(2,1)
01300 6A     LOCAL*1.K=POWER.K
01310 C      LOCAL*=0/0
01320 6A     TMWE.K=LOCAL*2.K
01330 20A    ALPHA.K=PLPAD/BRDIN
01340 21A    BETA.K=(1/BRDIN)(PLPAD-PLPBR)
01350 21A    GAMMA.K=(1/BRDIN)(PLPLW-PLPAD)
01360 20A    GAMM1.K=PLPLW/BRDIN
01370 20A    BETA1.K=PLPBR/BRDIN
01380 7A     BETA2.K=BETA1.K-GAMM1.K
01390 7A     POWER.K=POW1.K+POW2.K
01400 10A    POW1.K=P1.K+P2.K+P3.K+P4.K+P5.K+P6.K
01410 10A    POW2.K=P7.K+P8.K+P9.K+P10.K+P11.K+P12.K
01420 9A     LAMDA.K=LMDA.K+LMDB.K+LD12A.K+LD13.K
01430 10A    LMDA.K=LAMD1.K+LAMD2.K+LAMD3.K+LAMD4.K+LAMD5.K+LAMD6.K
01440 10A    LMDB.K=LAMD7.K+LAMD8.K+LAMD9.K+LMD10.K+LMD11.K+0
01450 NOTE           INITIAL  CONDITIONS
01460 6N     LMDX1=LMDY1
01470 6N     PX1=M0
01480 NOTE           DATA FOR THE COMPUTATIONS OF TMWE,GROTH ETC.
01490 C      T0=0/T5=5/T6=6/T10=10/T11=11/T15=15/T16=16/T20=20
01500 C      T25=25/T26=26/T30=30/T31=31/T35=35/T36=36/T40=40
01510 C      T41=41/T45=45
R 1.233+.350
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printf s4 madtrn
W 2232.6
01510 C      T46=46/T50=50/T51=51/T56=56/T55=55/T60=60/T61=61/K=0.20
01520 C      M0=1500/M5=6500/M10=27500/M15=75000/M20=165000/M25=295000
01530 C      M30=475000/M35=730000/M40=1050000/M45=1380000/M50=1750000
01540 C      M55=2200000/M60=2687000/LMD12=0.040/LMD13=0.0360
01550 58A    ILWRC.K=TABHL(INV1,TIME.K,0,35,35)
01560 C      INV1*=1.0/0.7
01570 6A     IHWRC.K=0.2
01580 58A    IHTRC.K=TABHL(INV2,TIME.K,0,35,35)
01590 C      INV2*=0.9/0.6
01600 C      ILWWR=1.0/IHWWR=0.33/BLWWR=0.25/BHWWR=0.15
01610 C      INFUR=1.44/BNFUR=0.23
01620 58A    BLWRC.K=TABHL(BURN1,TIME.K,0,35,35)
01630 C      BURN1*=0.16/0.13
01640 C      BHWRC=0.09
01650 58A    BHTRC.K=TABHL(BURN2.K,TIME.K,0,35,35)
01660 C      BURN2*=0.04/0.025
01670 C      BRDIN=4.20/PLPLW=0.32/PLPAD=0.35/PLPBR=0.43/DELTA=3
01680 C      DATA1*=5/10
01690 C      DATA2*=0/20
01700 C      DATA3*=0/20
01710 C      DATA4*=0/50
01720 58A    L.K=TABHL(LOADF,TIME.K,15,35,10)
01730 C      LOADF*=0.8/0.75/0.7
01740 7A     YEAR.K=TIME.K+1964
01750 SPEC   DT=.25/LENGTH=76/PRTPER=2/PLTPER=2
01760 NOTE   2)YEAR/4)TMWE/6)GROTH/8)LAMDA
01770 NOTE   1)YEAR/2)ILWRC/3)ILWWR/4)IHWRC/5)IHWWR/6)IHTRC/7)INFUR
R 1.000+.366
printf a21 madtrn
W 2234.5
00010 NOTE          NUCLEAR POWER COMPLEX 'ALPHA'
00020 NOTE   POLICY A ONLY LWR AND PLUTONIUM RECYCLED.
00030 NOTE   POLICY A1 ONLY LWR AND PLUTONIUM NOT RECYCLED.
00040 NOTE          POWER GENERATION
00050 17A    PGA.K=(L.K)(TMWE.K)(1)+(0.5)(L.K)(GROTH.K)+(0)(0)(0)
00060 1L     TPGA.K=TPGA.J+(DT)(PGA.JK-0)
00070 6N     TPGA=PGA
00080 NOTE   URANIUM REQUIREMENTS,POLICY A AND A1
00090 15A    UNRA1.K=(ILWWR.K)(GROTH.K)+(BLWWR.K)(PGA.K)
00100 1L     TUNA1.K=TUNA1.J+(DT)(UNRA1.JK-0)
00110 6N     TUNA1=UNRA1
00120 15A    URNRA.K=(ILWRC.K)(GROTH.K)+(BLWRC.K)(PGA.K)
00130 1L     TURNA.K=TURNA.J+(DT)(URNRA.JK-0)
00140 6N     TURNA=URNRA
00150 NOTE        PLUTONIUM  STOCKPILE
00160 13A    PLPR.K=(L.K)(PLPLW)(TMWE.K)
00170 6A     PLPRA.K=TRNA*4.K
00180 6A     TRNA*1.K=PLPR.K
00190 C      TRNA*=0/0/0/0
00200 37B    TRNA=BOXLIN(4,1)
00210 45A    PLSPA.K=STEP(PLAT.K,3)
00220 1L     PLAT.K=PLAT.J+(DT)(PLPRA.JK+0)
R .783+.150
```

```
printf a22 madtrn
W 2320.7
00230 13N    PLAT=(.8)(MO)(PLPLW)
00240 NOTE          URANIUM  PRICE
00250 9A     UPRA.K=PRA1.K+PRA2.K+PRA3.K+PRA4.K
00260 51A    PRA1.K=CLIP(10,PRAT1.K,TURNA.K,800000)
00270 51A    PRA2.K=CLIP(20,PRAT2.K,TURNA.K,1700000)
00280 51A    PRA3.K=CLIP(20,PRAT3.K,TURNA.K,9700000)
00290 51A    PRA4.K=CLIP(50,PRAT4.K,TURNA.K,24700000)
00300 58A    PRAT1.K=TABHL(DATA1,TURNA.K,0,800000,800000)
00310 58A    PRAT2.K=TABHL(DATA2,TURNA.K,800000,1700000,900000)
00320 58A    PRAT3.K=TABHL(DATA3,TURNA.K,1700000,9700000,8000000)
00330 58A    PRAT4.K=TABHL(DATA4,TURNA.K,9700000,24700000,15000000)
00340 9A     UPRA1.K=PRAX1.K+PRAX2.K+PRAX3.K+PRAX4.K
00350 51A    PRAX1.K=CLIP(10,PRAY1.K,TUNA1.K,800000)
00360 51A    PRAX2.K=CLIP(20,PRAY2.K,TUNA1.K,1700000)
00370 51A    PRAX3.K=CLIP(20,PRAY3.K#TUNA1.K,9700000)
00380 51A    PRAX4.K=CLIP(50,PRAY4.K,TUNA1.K,24700000)
00390 58A    PRAY1.K=TABHL(DATA1,TUNA1.K,0,800000,800000)
00400 58A    PRAY2.K=TABHL(DATA2,TUNA1.K,800000,1700000,900000)
00410 58A    PRAY3.K=TABHL(DATA3,TUNA1.K,1700000,9700000,8000000)
00420 58A    PRAY4.K=TABHL(DATA4,TUNA1.K,9700000,24700000,15000000)
00430 PRINT  1)YEAR/2)TMWE/3)TPGA/4)TUNA1/5)TURNA/6)UPRA1/7)UPRA/8)PLSPA
R .650+.333
printf b21 madtrn
W 2322.8
00010 NOTE          NUCLEAR POWER COMPLEX  'BETA'
00020 NOTE   LWR UPTO 1980.BREEDERS INTRODUCED IN 1980,INITIALLY
00030 NOTE   AT A SLOWER RATE,LATER DETERMINED BY BNE(FROM 1985).
00040 NOTE   PLUTONIUM IN LWR NOT RECYCLED BUT STOCKPILED.
00050 NOTE            POWER  COMPLEX
00060 51A    BB.K=CLIP(TMWE.K,BBX.K,TIME.K,62)
00070 1L     BBX.K=BBX.J+(DT)(GRBB.JK+0)
00080 6N     BBX=0
00090 51A    GRBB.K=CLIP(GROTH.K,GRTT.K,TIME.K,62)
00100 8A     GRTT.K=GRBB1.K+GRBB2.K+GRBB3.K
00110 58A    GRBB1.K=TABHL(INGBR,TIME.K,15,21,1)
00120 C      INGBR*=0/1000/3000/5000/8000/10000/0
00130 6A     GRBB2.K=TRNB*4.K
00140 6A     TRNB*1.K=SUM1.K
00150 C      TRNB*=0/0/0/0
00160 37B    TRNB=BOXLIN(4,1)
00170 17A    SUM1.K=(L.K)(GAMM1)(P(.K)+(L.K)(BETA2)(BZ.K)+(0)(0)(0)
00180 45A    PZ.K=STEP(TMW1.K,18)
00190 51A    TMW1.K=CLIP(0,TMWE.K,TIME.K,21)
00200 58A    BZ.K=TABHL(BEX,TIME.K,17,21,1)
00210 C      BEX*=0/4000/9000/17000/0
00220 6A     GRBB3.K=TRNC*4.K
00230 6A     TRNC*1.K=SM2.K
00240 C      TRNC*=0/0/0/0
00250 37B    TRNC=BOXLIN(4,1)
00260 17A    SM2.K=(L.K)(PB.K)(GAMM1)+(L.K)(BETA2)(BB1.K)+(0)(0)(0)
00270 45A    BB1.K=STEP(BB.K,21)
00280 45A    PB.K=STEP(TMWE.K,21)
00290 56A    CB.K=MAX(CB1.K,0)
00300 7A     CB1.K=TMWE.K-BB.K
00310 51A    GRCB.K=CLIP(0,GRCBX.K,TIME.K,62)
00320 7A     GRCBX.K=GROTH.K-GRBB.K
R 1.050+.216
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```
printf b22 madtrn
W 2351.0
00330 NOTE        POWER GENERATION
00340 7A     PGB.K=PGCB.K+PGBB.K
00350 17A    PGCB.K=(L.K)(CB.K)(1)+(0.5)(L.K)(GRCB.K)+(0)(0)(0)
00360 17A    PGBB.K=(L.K)(BB.K)(1)+(0.5)(L.K)(GRBB.K)+(0)(0)(0)
00370 1L     TPGCB.K=TPGCB.J+(DT)(PGCB.JK+0)
00380 6N     TPGCB=PGCB
00390 1L     TPGBB.K=TPGBB.J+(DT)(PGBB.JK+0)
00400 6N     TPGBB=PGBB
00410 NOTE         URANIUM  REQUIREMENTS
00420 15A    URNB.K=(ILWWR.K)(GRCB.K)+(BLWWR.K)(PGCB.K)
00430 1L     TURNB.K=TURNB.J+(DT)(URNB.JK+0)
00440 6N     TURNB=URNB
00450 NOTE        PLUTONIUM  STOCKPILE
00460 17A    PLPRB.K=(L.K)(CB.K)(PLPLW)+(L.K)(BB.K)(PLPBR)+(0)(0)(0)
00470 12A    PLCNB.K=(BRDIN)(GRBB.K)
00480 37B    TRBB=BOXLIN(4,1)
00490 6A     TRBB*1.K=PLPRB.K
00500 6A     PLPRX.K=TRBB*4.K
00510 C      TRBB*=0/0/0/0
00520 45A    PLSPB.K=STEP(PSTP.K,3)
00530 52L    PSTP.K=PSTP.J+(DT)(PLPRX.JK-PLCNB.JK+0+0)
00540 13N    PSTP=(0.8)(M0)(PLPLW)
00550 NOTE        URANIUM  PRICE
00560 9A     UPRB.K=PRB1.K+PRB2.K+PRB3.K+PRB4.K
00570 51A    PRB1.K=CLIP(10,PRBT1.K,TURNB.K,800000)
00580 51A    PRB2.K=CLIP(20,PRBT2.K,TURNB.K,1700000)
00590 51A    PRB3.K=CLIP(20,PRBT3.K,TURNB.K,9700000)
00600 51A    PRB4.K=CLIP(50,PRBT4.K,TURNB.K,24700000)
00610 58A    PRBT1.K=TABHL(DATA1,TURNB.K,0,800000,800000)
00620 58A    PRBT2.K=TABHL(DATA2,TURNB.K,800000,1700000,900000)
00630 58A    PRBT3.K=TABHL(DATA3,TURNB.K,1700000,9700000,8000000)
00640 58A    PRBT4.K=TABHL(DATA4,TURNB.K,9700000,24700000,15000000)
00650 PRINT 1)YEAR/2)TMWE/3)CB/4)BB/5)GRBB/6)TURNB/7)UPRB/8)PLSPB
R 1.033+.183
printf g21 madtrn
W 2353.7
00010 NOTE        NUCLEAR POWER COMPLEX 'GAMMA'
00020 NOTE   LWR UPTO 1975. HWOCR INTRODUCED IN 1976.NO BREEDERS
00030 NOTE   PLUTONIUM PRODUCED IN HWOCR IS RECYCLED.
00050 NOTE        NUCLEAR COMPLEX
00060 51A    AC.K=CLIP(AC2.K,AC1.K,TIME.K,T21)
00070 1L     AC1.K=AC1.J+(DT)(GRAC1.JK+0)
00080 6N     AC1=0
00090 12A    GRAC1.K=(GRRAT.K)(GROX.K)
00100 45A    GROX.K=STEP(GROY.K,T11)
00110 51A    GROY.K=CLIP(0,GROTH.K,TIME.K,T21)
00120 58A    GRRAT.K=TABHL(RATIO,TIME.K,10,20,1)
00130 C      RATIO*=0/.1/.2/.3/.4/.5/.6/.7/.8/.9/1
00140 45A    TMWW.K=STEP(TMWE.K,T21)
00150 7A     AC2.K=TMWW.K-CC2.K
00160 51A    CC.K=CLIP(CC2.K,CC1.K,TIME.K,T21)
00170 7A     CC1.K=TMWE.K-AC1.K
00180 45A    CC2.K=STEP(90000,T21)
00190 51A    GRAC.K=CLIP(GROTH.K,GRAC1.K,TIME.K,T21)
00200 7A     GRCC.K=GROTH.K-GRAC.K
R .750+.250
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printf g22 madtrn
W 1044.5
00210 NOTE          POWER GENERATION
00220 17A     PGCC.K=(L.K)(CC.K)(1)+(L.K)(GRCC.K)(.5)+(0)(0)(0)
00230 17A     PGAC.K=(L.K)(AC.K)(1)+(0.5)(GRAC.K)(L.K)+(0)(0)(0)
00240 1L      TPGCC.K=TPGCC.J+(DT)(PGCC.JK-0)
00250 6N      TPGCC=PGCC
00260 1L      TPGAC.K=TPGAC.J+(DT)(PGAC.JK-0)
00270 6N      TPGAC=PGAC
00280 NOTE          URANIUM  REQUIREMENTS
00290 15A     URNCC.K=(ILWRC.K)(GRCC.K)+(BLWRC.K)(PGCC.K)
00300 15A     URNAC.K=(IHWRC.K)(GRAC.K)+(BHWRC.K)(PGAC.K)
00310 7A      URNC.K=URNCC.K+URNAC.K
00320 1L      TURNC.K=TURNC.J+(DT)(URNC.JK-0)
00330 6N      TURNC=URNC
00340 NOTE          NO PLUTONIUM IS STOCKPILED
00350 NOTE    SECOND CAS HTGR REACTORS IN PLACE OF HWOCR
00360 NOTE    OTHERWISE IT IS SAME AS ABOVE.
00370 NOTE           URANIUM  REQUIREMENTS
00380 15A     URNCD.K=(ILWRC.K)(GRCC.K)+(BLWRC.K)(PGCC.K)
00390 15A     URNAD.K=(IHTRC.K)(GRAC.K)+(BHTRC.K)(PGAC.K)
00400 7A      URND.K=URNCD.K+URNAD.K
00410 1L      TURND.K=TURND.J+(DT)(URND.JK-0)
00420 6N      TURND=URND
00430 NOTE       URANIUM  PRICE
00440 9A      UPRC.K=PRC1.K+PRC2.K+PRC3.K+PRC4.K
00450 51A     PRC1.K=CLIP(10,PRCT1.K,TURNC.K,800000)
00460 51A     PRC2.K=CLIP(20,PRCT2.K,TURNC.K,1700000)
00470 51A     PRC3.K=CLIP(20,PRCT3.K,TURNC.K,9700000)
00480 51A     PRC4.K=CLIP(50,PRCT4.K,TURNC.K,24700000)
00490 58A     PRCT1.K=TABHL(DATA1,TURNC.K,0,800000,800000)
00500 58A     PRCT2.K=TABHL(DATA2,TURNC.K,800000,1700000,900000)
00510 58A     PRCT3.K=TABHL(DATA3,TURNC.K,1700000,9700000,8000000)
00520 58A     PRCT4.K=TABHL(DATA4,TURNC.K,9700000,24700000,15000000)
00530 9A      UPRD.K=PRD1.K+PRD2.K+PRD3.K+PRD4.K
00540 51A     PRD1.K=CLIP(10,PRDT1.K,TURND.K,800000)
00550 51A     PRD2.K=CLIP(20,PRDT2.K,TURND.K#1700000)
00560 51A     PRD3.K=CLIP(20,PRDT3.K,TURND.K,9700000)
00570 51A     PRD4.K=CLIP(50,PRDT4.K,TURND.K,24700000)
00580 58A     PRDT1.K=TABHL(DATA1,TURND.K,0,800000,800000)
00590 58A     PRDT2.K=TABHL(DATA2,TURND.K#800000,1700000,900000)
00600 58A     PRDT3.K=TABHL(DATA3,TURND.K,1700000,9700000,8000000)
00610 58A     PRDT4.K=TABHL(DATA4,TURND.K,9700000,24700000,15000000)
00620 PRINT 1)YEAR/2)TMWE/3)CC/4)AC/5)TURNC/6)TURND/7)UPRC/8)UPRD
00630 NOTE
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printf d21 madtrn
W 1204.3
00010 NOTE       NUCLEAR POWER COMPLEX 'DELTA'
00020 NOTE  UPTO 1975 ONLY LWR,THEN HWOCR INTRODUCED GRADUALLY
00030 NOTE  UPTO 1985. BREEDERS INTRODUCED IN 1980.FROM 1985
00040 NOTE  BNE STARTS. NO PLUTONIUM RECYCLING IN LWR + HWOCR
00060 NOTE      NUCLEAR  COMPLEX
00070 51A   BE.K=CLIP(TMWE.K,BBX.K,TIME.K,61)
00080 1L    BBX.K=BBX.J+(DT)(GRBE.JK+0)
00090 6N    BBX=0
00100 56A   AE.K=MAX(AEC.K,0)
00110 51A   AEC.K=CLIP(AEY.K,AEX.K,TIME.K,T21)
00120 1L    AEX.K=AEX.J+(DT)(GRAEX.JK+0)
00130 6N    AEX=0
00140 7A    GRAEX.K=GRAE1.K+GRAE2.K
00150 56A   CE.K=MAX(CEX.K,0)
00160 51A   CEX.K=CLIP(CET.K,CES.K,TIME.K,T21)
00170 1L    CET.K=CET.J+(DT)(GRCEX.JK+0)
00180 6N    CET=91497
00190 8A    CES.K=TMWT.K-AEX.K-BEX.K
00200 51A   BEX.K=CLIP(0,BE.K,TIME.K,T21)
00210 45A   AEY.K=STEP(AEZ.K,T21)
00220 8A    AEZ.K=TMWE.K-CE.K-BE.K
00230 45A   GRCEX.K=STEP(CONST.K,T21)
00240 51A   CONST.K=CLIP(0,-5000,TIME.K,T40)
00250 8A    GRAE.K=GROTH.K-GRBE.K-GRCE.K
00260 51A   GRCE.K=CLIP(GRCEX.K,GRCEY.K,TIME.K,T21)
00270 9A    GRCEY.K=GROTH.K-GRAE1.K-GRAE2.K-GRBE1.K
00280 51A   GRBE.K=CLIP(GROTH.K,GRBEX.K,TIME.K,61)
00290 8A    GRBEX.K=GRBE1.K+GRBE2.K+GRBE3.K
00300 12A   GRAE1.K=(MULT1.K)(GRP3.K)
00310 45A   GRP3.K=STEP(GROTH.K,T11)
00320 18A   GRAE2.K=(MULT2.K)(GRP4.K-GRBE1.K)
00330 45A   GRP4.K=STEP(GROTH.K,T16)
00340 58A   MULT1.K=TABHL(RATA,TIME.K,10,16,1)
00350 C     RATA*=0/.1/.2/.3/.4/.5/0
00360 58A   MULT2.K=TABHL(RATB,TIME.K,15,21,1)
00370 C     RATB*=0/.6/.7/.8/.9/1/0
00380 58A   GRBE1.K=TABHL(BRGR,TIME.K,15,21,1)
00390 C     BRGR*=0/1000/3000/5000/8000/10000/0
00400 6A    GRBE2.K=TRNE*4.K
00410 6A    TRNE*1.K=SX.K
00420 C     TRNE*=0/0/0/0
00430 37B   TRNE=BOXLIN(4,1)
00440 17A   SX.K=(L.K)(ALPHA)(PX.K)+(L.K)(-BETA)(BX.K)+(L.K)(GAMMA)(CX.K)
00450 45A   PX.K=STEP(TMWT.K,18)
00460 51A   TMWT.K=CLIP(0,TMWE.K,TIME.K,T21)
00470 58A   BX.K=TABHL(BOX,TIME.K,17,21,1)
00480 C     BOX*=0/4000/9000/17000/0
00490 45A   CX1.K=STEP(CE.K,18)
00500 51A   CX.K=CLIP(0,CX1.K,TIME.K,21)
R 1.483+.600
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printf d22mad"""" madtrn
W 1309.4
00010 6A    GRBE3.K=TRNF*4.K
00020 6A    TRNF*1.K=SY.K
00030 C     TRNF*=0/0/0/0
00040 37B   TRNF=BOXLIN(4,1)
00050 17A   SY.K=(L.K)(ALPHA)(PY.K)+(L.K)(-BETA)(BY.K)+(L.K)(GAMMA)(CY.K)
00060 45A   PY.K=STEP(TMWE.K,T21)
00070 45A   BY.K=STEP(BE.K,21)
00080 45A   CY.K=STEP(CE.K,21)
00090 NOTE        POWER  GENERATION
00100 17A   PGCE.K=(L.K)(CE.K)(1)+(L.K)(.5)(GRCE.K)+(0)(0)(0)
00110 17A   PGBE.K=(L.K)(BE.K)(1)+(L.K)(.5)(GRBE.K)+(0)(0)(0)
00120 17A   PGAE.K=(L.K)(AE.K)(1)+(L.K)(.5)(GRAE.K)+(0)(0)(0)
00130 NOTE        URANIUM  REQUIREMENTS
00140 15A   URNCE.K=(ILWWR.K)(GRCE.K)+(BLWWR.K)(PGCE.K)
00150 15A   URNAE.K=(IHWWR.K)(GRAE.K)+(BHWWR.K)(PGAE.K)
00160 7A    URNE.K=URNCE.K+URNAE.K
00170 1L    TURNE.K=TURNE.J+(DT)(URNE.JK+0)
00180 6N    TURNE=URNE
00190 NOTE          PLUTONIUM  STOCKPILE
00200 17A   PLPRE.K=(L.K)(PLPLW)(CE.K)+(L.K)(PLPBR)(BE.K)+(L.K)(PLPAD)(AE.K)
00210 12A   PLCNE.K=(BRDIN)(GRBE.K)
00220 37B   TRBE=BOXLIN(4,1)
00230 6A    TRBE*1.K=PLPRE.K
00240 6A    PLPRY.K=TRBE*4.K
00250 C     TRBE*=0/0/0/0
00260 45A   PLSPE.K=STEP(PSTE.K,3)
00270 52L   PSTE.K=PSTE.J+(DT)(PLPRY.JK-PLCNE.JK+0+0)
00280 13N   PSTE=(.8)(M0)(PLPLW)
00290 NOTE        URANIUM  PRICE
00300 9A    UPRE.K=PRE1.K+PRE2.K+PRE3.K+PRE4.K
00310 51A   PRE1.K=CLIP(10,PRET1.K,TURNE.K,800000)
00320 51A   PRE2.K=CLIP(20,PRET2.K,TURNE.K,1700000)
00330 51A   PRE3.K=CLIP(20,PRET3.K,TURNE.K#9700000)
00340 51A   PRE4.K=CLIP(50,PRET4.K,TURNE.K,24700000)
00350 58A   PRET1.K=TABHL(DATA1,TURNE.K,0,800000,800000)
00360 58A   PRET2.K=TABHL(DATA2,TURNE.K,800000,1700000,900000)
00370 58A   PRET3.K=TABHL(DATA3,TURNE.K,1700000,9700000,8000000)
00380 58A   PRET4.K=TABHL(DATA4,TURNE.K,9700000,24700000,15000000)
00390 NOTE  1)YEAR/2)TMWE/3)CE/4)AE/5)BE/6)GRCE/7)GRAE/8)GRBE
00400 PRINT 2)YEAR/4)TURNE/6)UPRE/8)PLSPE
R 1.300+.716
printf e21 madtrn
W 1314.6
00010 NOTE        NUCLEAR POWER COMPLEX  'ETA'
00020 NOTE  THIS IS A SIMILAR CASE OF BNE OF CASE DELTA BUT
00030 NOTE  NOW THE ADVANCED CONVERTER ARE OF HTGR(TH) TYPE AND
00040 NOTE  RECYCLE THE BRED U-233.HTGR(TH) ARE INTRODUCED IN 1975
00050 NOTE  AND BREEDERS IN 1980. BNE STARTS FROM 1985.
00060 NOTE         NUCLEAR POWER COMPLEX
00070 51A   BEX.K=CLIP(BEM.K,BET.K#TIME.K,61)
00080 1L    BET.K=BET.J+(DT)(GRBEX.JK+0)
00090 6N    BET=0
00100 7A    BEM.K=TMWE.K-AEX.K
00110 1L    AEX.K=AEX.J+(DT)(GRAEX.JK+0)
00120 6N    AEX=0
R .933+.516
```

```
printf e22 madtrn
W 1320.8
00130 51A    GRAEX.K=CLIP(0,GRAEL.K,TIME.K,61)
00140 12A    GRAEL.K=(MULTX.K)(GROTH.K)
00150 58A    MULTX.K=TABHL(FACTR,TIME.K,10,16,1)
00160 C      FACTR*=0/.1/.2/.3/.4/.5/.5
00170 56A    CEX.K=MAX(CET.K,0)
00180 8A     CET.K=TMWE.K-AEX.K-BEX.K
00190 8A     GRCEX.K=GROTH.K-GRBEX.K-GRAEX.K
00200 51A    GRBEX.K=CLIP(GROTH.K,GRBEL.K,TIME.K,61)
00210 8A     GRBEL.K=GRBE1.K+GRBE2.K+GRBE3.K
00220 45A    GRP4.K=STEP(GROTH.K,T16)
00230 58A    GRBE1.K=TABHL(BRGR,TIME.K,15,21,1)
00240 C      BRGR*=0/1000/3000/5000/8000/10000/0
00250 6A     GRBE2.K=TRNE*4.K
00260 6A     TRNE*1.K=SX.K
00270 C      TRNE*=0/0/0/0
00280 37B    TRNE=BOXLIN(4,1)
00290 17A    SX.K=(L.K)(ALPHA)(PX.K)+(L.K)(-BETA)(BX.K)+(L.K)(GAMMA)(CX.K)
00300 45A    PX.K=STEP(TMWT.K,18)
00310 51A    TMWT.K=CLIP(0,TMWE.K,TIME.K,T21)
00320 58A    BX.K=TABHL(BOX,TIME.K,17,21,1)
00330 C      BOX*=0/4000/9000/17000/0
00340 51A    CX.K=CLIP(0,CX1.K,TIME.K,21)
00350 45A    CX1.K=STEP(CEX.K,18)
00360 6A     GRBE3.K=TRNF*4.K
00370 6A     TRNF*1.K=SY.K
00380 C      TRNF*=0/0/0/0
00390 37B    TRNF=BOXLIN(4,1)
00400 17A    SY.K=(L.K)(ALPHA)(PY.K)+(L.K)(-BETA)(BY.K)+(L.K)(GAMMA)(CY.K)
00410 45A    PY.K=STEP(TMWE.K,T21)
00420 45A    BY.K=STEP(BEX.K,T21)
00430 45A    CY.K=STEP(CEX.K,T21)
00440 NOTE          POWER  GENERATION
00450 17A    PGCEX.K=(L.K)(CEX.K)(1)+(L.K)(.5)(GRCEX.K)+(0)(0)(0)
00460 17A    PGBEX.K=(L.K)(BEX.K)(1)+(L.K)(.5)(GRBEX.K)+(0)(0)(0)
00470 17A    PGAEX.K=(L.K)(AEX.K)(1)+(L.K)(.5)(GRAEX.K)+(0)(0)(0)
00480 NOTE          URANIUM  REQUIREMENTS
00490 15A    URNCE.K=(ILWWR.K)(GRCEX.K)+(BLWWR.K)(PGCEX.K)
00500 15A    URNAE.K=(IHTRC.K)(GRAEX.K)+(BHTRC.K)(PGAEX.K)
00510 7A     URNE.K=URNCE.K+URNAE.K
00520 1L     TURNX.K=TURNX.J+(DT)(URNE.JK+0)
00530 6N     TURNX=URNE
00540 NOTE            PLUTONIUM  STOCKPILE
00550 17A    PRE.K=(L.K)(PLPLW)(CEX.K)+(L.K)(PLPBR)(BEX.K)+(L.K)(PLPAD)(AEX
00560 12A    PLCNE.K=(BRDIN)(GRBEX.K)
00570 37B    TRBE=BOXLIN(4,1)
00580 6A     TRBE*1.K=PRE.K
00590 6A     PLPRY.K=TRBE*4.K
00600 C      TRBE*=0/0/0/0
00610 45A    PSPEX.K=STEP(PSTE.K,3)
00620 52L    PSTE.K=PSTE.J+(DT)(PLPRY.JK-PLCNE.JK+0+0)
R 1.466+.633
```

```
printf e23 madtrn
W 1442.7
00640 NOTE        URANIUM  PRICE
00650 9A     UPREX.K=PRE1.K+PRE2.K+PRE3.K+PRE4.K
00660 51A    PRE1.K=CLIP(10,PRET1.K,TURNX.K,800000)
00670 51A    PRE2.K=CLIP(20,PRET2.K,TURNX.K,1700000)
00680 51A    PRE3.K=CLIP(20,PRET3.K,TURNX.K,9700000)
00690 51A    PRE4.K=CLIP(50,PRET4.K,TURNX.K,24700000)
00700 58A    PRET1.K=TABHL(DATA1,TURNX.K,0,800000,800000)
00710 58A    PRET2.K=TABHL(DATA2,TURNX.K,800000,1700000,900000)
00720 58A    PRET3.K=TABHL(DATA3,TURNX.K,1700000,9700000,8000000)
00730 58A    PRET4.K=TABHL(DATA4,TURNX.K,9700000,24700000,15000000)
00740 NOTE   1)YEAR/2)TMWE/3)CEX/4)AEX/5)BEX/6)GRCEX/7)GRAEX/8)GRBEX
00750 PRINT  2)YEAR/4)TURNX/6)UPREX/8)PSPEX
R .700+.333
printf k21 madtrn
W 1444.0
00010 NOTE        NUCLEAR POWER COMPLEX 'KAPPA'
00020 NOTE   UPTO 1975 ONLY LWR.IN 1976 ADVANCED CONVERTERS OF
00030 NOTE   TYPE HWOCR ARE INTRODUCED. THE BREEDERS ARE NOW
00040 NOTE   INTRODUCED IN 1990 AS COMPARED TO 1980 IN PREVIOUS
00050 NOTE   CASE. BNE STARTS IN 1995.NO PLUTONIUM RECYCLING.
00060 NOTE        NUCLEAR COMPLEX
00070 51A    BF.K=CLIP(TMWE.K,BFX.K,TIME.K,64)
00080 1L     BFX.K=BFX.J+(DT)(GRBFX.JK+0)
00090 6N     BFX=0
00100 56A    AF.K=MAX(AFC.K,0)
00110 51A    AFC.K=CLIP(AFY.K,AFX.K,TIME.K,T26)
00120 1L     AFX.K=AFX.J+(DT)(GRAFX.JK+0)
00130 6N     AFX=0
00140 56A    CF.K=MAX(CFX.K,0)
00150 51A    CFX.K=CLIP(CFT.K,CFS.K,TIME.K,T21)
00160 1L     CFT.K=CFT.J+(DT)(GRCFX.JK+0)
00170 6N     CFT=91500
00180 8A     CFS.K=TMWT.K-AFX.K+0
00190 45A    AFY.K=STEP(AFZ.K,T26)
00200 8A     AFZ.K=TMWE.K-CF.K-BF.K
00210 45A    GRCFX.K=STEP(CONST.K,T21)
00220 51A    CONST.K=CLIP(0,-5000,TIME.K,T40)
00230 51A    GRCF.K=CLIP(GRCFX.K,GRCFY.K,TIME.K,T21)
00240 7A     GRCFY.K=GROTH.K-GRAFT.K
00250 51A    GRAFT.K=CLIP(0,GRAFX.K,TIME.K,T40)
00260 8A     GRAF.K=GROTH.K-GRBF.K-GRCF.K
00270 12A    GRAFX.K=(MULTF.K)(GROTH.K)
00280 58A    MULTF.K=TABHL(GUNA,TIME.K,10,26,1)
00290 C      GUNA*=0/.1/.2/.3/.4/.5/.6/.7/.8/.9/1/1/1/1/1/1/0
00300 51A    GRBF.K=CLIP(GROTH.K,GRBFX.K,TIME.K,64)
00310 8A     GRBFX.K=GRBF1.K+GRBF2.K+GRBF3.K
00320 58A    GRBF1.K=TABHL(BRGRF,TIME.K,25,31,1)
00330 C      BRGRF*=0/1000/3000/5000/8000/10000/0
00340 6A     GRBF2.K=TRNF*4.K
00350 6A     TRNF*1.K=SF.K
00360 C      TRNF*=0/0/0/0
00370 37B    TRNF=BOXLIN(4,1)
00380 17A    SF.K=(L.K)(ALPHA)(PM.K)+(L.K)(-BETA)(BM.K)+(L.K)(GAMMA)(CM.K)
00390 45A    PM.K=STEP(TMWT.K,28)
00400 51A    TMWT.K=CLIP(0,TMWE.K,TIME.K,31)
R 1.333+.666
```

```
printf k22 madtrn
W 1532.6
00410 58A    BM.K=TABHL(BOM,TIME.K,27,31,1)
00420 C      BOM*=0/4000/9000/17000/0
00430 45A    CM1.K=STEP(CF.K,28)
00440 51A    CM.K=CLIP(0,CM1.K,TIME.K,31)
00450 6A     GRBF3.K=TRNG*4.K
00460 6A     TRNG*1.K=ST.K
00470 C      TRNG*=0/0/0/0
00480 37B    TRNG=BOXLIN(4,1)
00490 17A    ST.K=(L.K)(PN.K)(ALPHA)+(L.K)(-BETA)(BN.K)+(L.K)(GAMMA)(CN.K)
00500 45A    PN.K=STEP(TMWE.K,T31)
00510 45A    BN.K=STEP(BF.K,31)
00520 45A    CN.K=STEP(CF.K,31)
00530 NOTE        POWER  GENERATION
00540 17A    PGCF.K=(L.K)(CF.K)(1)+(L.K)(.5)(GRCF)+(0)(0)(0)
00550 17A    PGBF.K=(L.K)(BF.K)(1)+(L.K)(.5)(GRBF.K)+(0)(0)(0)
00560 17A    PGAF.K=(L.K)(AF.K)(1)+(L.K)(.5)(GRAF.K)+(0)(0)(0)
00570 NOTE          URANIUM  REQUIREMENTS
00580 15A    URNCF.K=(ILWWR.K)(GRCF.K)+(BLWWR.K)(PGCF.K)
00590 15A    URNAF.K=(IHWWR.K)(GRAF.K)+(BHWWR.K)(PGAF.K)
00600 7A     URNF.K=URNCF.K+URNAF.K
00610 1L     TURNF.K=TURNF.J+(DT)(URNF.JK+0)
00620 6N     TURNF=URNF
00630 NOTE       PLUTONIUM  STOCKPILE
00640 17A    PLPRF.K=(L.K)(PLPLW)(CF.K)+(L.K)(PLPBR)(BF.K)+(L.K)(PLPAD)(AF.K
00650 12A    PLCNF.K=(BRDIN)(GRBF.K)
00660 37B    TRBF=BOXLIN(4,1)
00670 6A     TRBF*1.K=PLPRF.K
00680 6A     PLPDF.K=TRBF*4.K
00690 C      TRBF*=0/0/0/0
00700 45A    PLSPF.K=STEP(PSTF.K,3)
00710 52L    PSTF.K=PSTF.J+(DT)(PLPDF.JK-PLCNF.JK+0+0)
00720 13N    PSTF=(.8)(M0)(PLPLW)
00730 NOTE          URANIUM  PRICE
00740 9A     UPRF.K=PRF1.K+PRF2.K+PRF3.K+PRF4.K
00750 51A    PRF1.K=CLIP(10,PRFT1.K,TURNF.K,800000)
00760 51A    PRF2.K=CLIP(20,PRFT2.K,TURNF.K,1700000)
00770 51A    PRF3.K=CLIP(20,PRFT3.K,TURNF.K,9700000)
00780 51A    PRF4.K=CLIP(50,PRFT4.K,TURNF.K,24700000)
00790 58A    PRFT1.K=TABHL(DATA1,TURNF.K,0,800000,800000)
00800 58A    PRFT2.K=TABHL(DATA2,TURNF.K,800000,1700000,900000)
00810 58A    PRFT3.K=TABHL(DATA3,TURNF.K,1700000,9700000,8000000)
00820 58A    PRFT4.K=TABHL(DATA4,TURNF.K,9700000,24700000,15000000)
00830 NOTE   1)YEAR/2)TMWE/3)CF/4)AF/5)BF/6)GRCF/7)GRAF/8)GRBF
00840 PRINT  2)YEAR/4)TURNF/6)UPRF/8)PLSPF
R 1.916+.766
printf s21 madtrn
W 1535.8
00010 NOTE        NUCLEAR POWER COMPLEX  'SIGMA'
00020 NOTE   IN THIS CASE THERE ARE ONLY LWR UPTO 1980 WHICH THEN
00030 NOTE   DECREASE LINEARLY BY YR 2000. HWOCR ARE INSTALLED BETWEEN 1980
00040 NOTE   AND YR 2000 AT THE BALANCED RATE BETWEEN TMWE AND LWR. THE
00050 NOTE   PLUTONIUM PRODUCED BY LWR IS NOT RECYCLED BUT IS RECYCLED
00060 NOTE   IN HWOCR UPTO 2005. THE BREEDERS ARE INTRODUCED AT A
00070 NOTE   SLOWER RATE FROM 2000.THE BNE STARTS FROM 2005.
R .800+.333
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prints"f s22 madtrn
W 1748.4
00080 NOTE        NUCLEAR POWER COMPLEX
00090 6A     BS.K=BF.K
00100 6A     AS.K=AF.K
00110 6A     CS.K=CF.K
00120 6A     GRCS.K=GRCF.K
00130 6A     GRBS.K=GRBF.K
00140 6A     GRAS.K=GRAF.K
00150 6A     TURNS.K=TURNF.K
00160 6A     PLSPS.K=PLSPF.K
00170 6A     UPRFS.K=UPRF.K
00180 51A    BF.K=CLIP(TMWE.K#BFX.K,TIME.K,71)
00190 1L     BFX.K=BFX.J+(DT)(GRBFX.JK+0)
00200 6N     BFX=0
00210 51A    CF.K=CLIP(CS2.K,TMWE.K,TIME.K,17)
00220 58A    CS2.K=TABHL(CSCAP,TIME.K,16,36,20)
00230 C      CSCAP*=75000/0
00240 51A    AF.K=CLIP(AS2.K,AS1.K,TIME.K,36)
00250 7A     AS1.K=TMWE.K-CS.K
00260 56A    AS2.K=MAX(ASXT.K,0)
00270 45A    ASS.K=STEP(AS2.K,41)
00280 7A     ASXT.K=TMWE.K-BS.K
00290 51A    GRCF.K=CLIP(GRCF2.K,GROTH.K,TIME.K,17)
00300 51A    GRCF2.K=CLIP(0,-3571,TIME.K,36)
00310 51A    GRAF.K=CLIP(GRAF2.K,GRAF1.K,TIME.K#36)
00320 7A     GRAF1.K=GROTH.K-GRCF.K
00330 7A     GRAF2.K=GROTH.K-GRBF.K
00340 51A    GRBF.K=CLIP(GROTH.K,GRBFX.K,TIME.K,71)
00350 8A     GRBFX.K=GRBF1.K+GRBF2.K+GRBF3.K
00360 58A    GRBF1.K=TABHL(BRGRF,TIME.K,35,41,1)
00370 C      BRGRF*=0/1000/3000/5000/8000/10000/0
00380 6A     GRBF2.K=TRNF*4.K
00390 6A     TRNF*1.K=SF.K
00400 C      TRNF*=0/0/0/0
00410 37B    TRNF=BOXLIN(4,1)
00420 13A    SF.K=(L.K)(PLPBR.K)(BM.K)
00430 58A    BM.K=TABHL(BOM,TIME.K,37,41,1)
00440 C      BOM*=0/4000/9000/17000/0
00450 6A     GRBF3.K=TRNG*4.K
00460 6A     TRNG*1.K=ST.K
00470 C      TRNG*=0/0/0/0
00480 37B    TRNG=BOXLIN(4,1)
00490 17A    ST.K=(L.K)(PN.K)(ALPHA)+(L.K)(-BETA)(BN.K)+(L.K)(GAMMA)(CN.K)
00500 45A    PN.K=STEP(TMWE.K,T41)
00510 45A    BN.K=STEP(BS.K,41)
00520 6A     CN.K=0
00530 NOTE        POWER  GENERATION
00540 17A    PGCF.K=(L.K)(CF.K)(1)+(L.K)(.5)(GRCF)+(0)(0)(0)
00550 17A    PGBF.K=(L.K)(BF.K)(1)+(L.K)(.5)(GRBF.K)+(0)(0)(0)
00560 17A    PGAF.K=(L.K)(AF.K)(1)+(L.K)(.5)(GRAF.K)+(0)(0)(0)
00570 NOTE          URANIUM  REQUIREMENTS
R 2.066+.633
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printf s23 madtrn
W 1809.5
00580 15A   URNCF.K=(ILWWR.K)(GRCF.K)+(BLWWR.K)(PGCF.K)
00590 15A   URNAF.K=(INVEN.K)(GRAF.K)+(BURNP.K)(PGAF.K)
00600 51A   INVEN.K=CLIP(IHWWR.K,IHWRC.K,TIME.K,41)
00610 51A   BURNP.K=CLIP(BHWWR.K,BHWRC.K,TIME.K,41)
00620 8A    URNF.K=URNCF.K+URNAF.K+0
00630 1L    TURNF.K=TURNF.J+(DT)(URNF.JK+0)
00640 6N    TURNF=URNF
00650 NOTE      PLUTONIUM  STOCKPILE
00660 17A   PLPRF.K=(L.K)(PLPLW)(CF.K)+(L.K)(PLPBR)(BF.K)+(L.K)(PLPAD)(ASS
00670 12A   PLCNF.K=(BRDIN)(GRBF.K)
00680 37B   TRBF=BOXLIN(4,1)
00690 6A    TRBF*1.K=PLPRF.K
00700 6A    PLPDF.K=TRBF*4.K
00710 C     TRBF*=0/0/0/0
00720 45A   PLSPF.K=STEP(PSTF.K,3)
00730 52L   PSTF.K=PSTF.J+(DT)(PLPDF.JK-PLCNF.JK+0+0)
00740 13N   PSTF=(.8)(M0)(PLPLW)
00750 NOTE         URANIUM  PRICE
00760 9A    UPRF.K=PRF1.K+PRF2.K+PRF3.K+PRF4.K
00770 51A   PRF1.K=CLIP(10,PRFT1.K,TURNF.K,800000)
00780 51A   PRF2.K=CLIP(20,PRFT2.K,TURNF.K,1700000)
00790 51A   PRF3.K=CLIP(20,PRFT3.K,TURNF.K,9700000)
00800 51A   PRF4.K=CLIP(50,PRFT4.K,TURNF.K,24700000)
00810 58A   PRFT1.K=TABHL(DATA1,TURNF.K,0,800000,800000)
00820 58A   PRFT2.K=TABHL(DATA2,TURNF.K,800000,1700000,900000)
00830 58A   PRFT3.K=TABHL(DATA3,TURNF.K,1700000,9700000,8000000)
00840 58A   PRFT4.K=TABHL(DATA4,TURNF.K,9700000,24700000,15000000)
00850 PRINT 1)YEAR/2)TMWE/3)CS/4)AS/5)BS/6)GRCS/7)GRAS/8)GRBS
00860 NOTE  2)YEAR/4)TURNS/6)UPRFS/8)PLSPS
R 1.433+.533
printf t21 madtrn
W 1811.8
00010 NOTE       NUCLEAR POWER COMPLEX  'THETA'
00020 NOTE  THE ADVANCED CONVERTERS ARE NOW FAST U-235 FUELED REACTORS
00030 NOTE  RATHER THAN HWOCR AS IN CASE DELTA. THEY ARE INTRODUCED IN
00040 NOTE  1976.THE BREEDERS ARE INTRODUCED IN 1980AS BEFORE.
00050 NOTE  THE BNE STARTS FROM 1985. NO PLUTONIUM RECYCLING.
00060 NOTE                NUCLEAR POWER COMPLEX
00070 6A    BEY.K=BE.K
00080 6A    AEY.K=AE.K
00090 6A    CEY.K=CE.K
00100 6A    GRBY.K=GRBE.K
00110 6A    GRAY.K=GRAE.K
00120 6A    GRCY.K=GRCE.K
00130 6A    TRNEY.K=TURNE.K
00140 6A    PSPEY.K=PLSPE.K
00150 6A    UPREY.K=UPRE.K
00160 51A   BE.K=CLIP(TMWE.K,BBX.K,TIME.K,T50)
00170 1L    BBX.K=BBX.J+(DT)(GRBE.JK+0)
00180 6N    BBX=0
R .950+.500
```

```
printf t22 madtrn
W 1845.2
00190 56A    AE.K=MAX(AEC.K,0)
00200 51A    AEC.K=CLIP(AET.K,AEX.K,TIME.K,T21)
00210 1L     AEX.K=AEX.J+(DT)(GRAEX.JK+0)
00220 6N     AEX=0
00230 7A     GRAEX.K=GRAE1.K+GRAE2.K
00240 56A    CE.K=MAX(CEX.K,0)
00250 51A    CEX.K=CLIP(CET.K,CES.K,TIME.K,T21)
00260 1L     CET.K=CET.J+(DT)(GRCEX.JK+0)
00270 6N     CET=91497
00280 8A     CES.K=TMWT.K-AEX.K-BEX.K
00290 51A    BEX.K=CLIP(0,BE.K,TIME.K,T21)
00300 45A    AET.K=STEP(AEZ.K,T21)
00310 8A     AEZ.K=TMWE.K-CE.K-BE.K
00320 45A    GRCEX.K=STEP(CONST.K,T21)
00330 51A    CONST.K=CLIP(0,-5000,TIME.K,T40)
00340 8A     GRAE.K=GROTH.K-GRBE.K-GRCE.K
00350 51A    GRCE.K=CLIP(GRCEX.K,GRCEY.K,TIME.K,T21)
00360 9A     GRCEY.K=GROTH.K-GRAE1.K-GRAE2.K-GRBE1.K
00370 51A    GRBE.K=CLIP(GROTH.K,GRBEX.K,TIME.K,T50)
00380 8A     GRBEX.K=GRBE1.K+GRBE2.K+GRBE3.K
00390 12A    GRAE1.K=(MULT1.K)(GRP3.K)
00400 45A    GRP3.K=STEP(GROTH.K,T11)
00410 18A    GRAE2.K=(MULT2.K)(GRP4.K-GRBE1.K)
00420 45A    GRP4.K=STEP(GROTH.K,T16)
00430 58A    MULT1.K=TABHL(RATA,TIME.K,10,16,1)
00440 C      RATA*=0/.1/.2/.3/.4/.5/0
00450 58A    MULT2.K=TABHL(RATB,TIME.K,15,21,1)
00460 C      RATB*=0/.6/.7/.8/.9/1/0
00470 58A    GRBE1.K=TABHL(BRGR,TIME.K,15,21,1)
00480 C      BRGR*=0/1000/3000/5000/8000/10000/0
00490 6A     GRBE2.K=TRNE*4.K
00500 6A     TRNE*1.K=SX.K
00510 C      TRNE*=0/0/0/0
00520 37B    TRNE=BOXLIN(4,1)
00530 17A    SX.K=(L.K)(ALPHA)(PX.K)+(L.K)(-BETA)(BX.K)+(L.K)(GAMMA)(CX.K)
00540 45A    PX.K=STEP(TMWT.K,18)
00550 51A    TMWT.K=CLIP(0,TMWE.K,TIME.K,T21)
00560 58A    BX.K=TABHL(BOX,TIME.K,17,21,1)
00570 C      BOX*=0/4000/9000/17000/0
00580 45A    CX1.K=STEP(CE.K,18)
00590 51A    CX.K=CLIP(0,CX1.K,TIME.K,21)
00600 6A     GRBE3.K=TRNF*4.K
00610 6A     TRNF*1.K=SY.K
00620 C      TRNF*=0/0/0/0
00630 37B    TRNF=BOXLIN(4,1)
00640 17A    SY.K=(L.K)(ALPHA)(PY.K)+(L.K)(-BETA)(BY.K)+(L.K)(GAMMA)(CY.K)
00650 45A    PY.K=STEP(TMWE.K,T21)
00660 45A    BY.K=STEP(BE.K,21)
00670 45A    CY.K=STEP(CE.K,21)
R 1.933+.650
```

```
printf t23 madtrn
W 1937.4
00680 NOTE        POWER  GENERATION
00690 17A    PGCE.K=(L.K)(CE.K)(1)+(L.K)(.5)(GRCE.K)+(0)(0)(0)
00700 17A    PGBE.K=(L.K)(BE.K)(1)+(L.K)(.5)(GRBE.K)+(0)(0)(0)
00710 17A    PGAE.K=(L.K)(AE.K)(1)+(L.K)(.5)(GRAE.K)+(0)(0)(0)
00720 NOTE        URANIUM  REQUIREMENTS
00730 15A    URNCE.K=(ILWWR.K)(GRCE.K)+(BLWWR.K)(PGCE.K)
00740 15A    URNAE.K=(INFUR.K)(GRAE.K)+(BNFUR.K)(PGAE.K)
00750 7A     URNE.K=URNCE.K+URNAE.K
00760 1L     TURNE.K=TURNE.J+(DT)(URNE.JK+0)
00770 6N     TURNE=URNE
00780 NOTE         PLUTONIUM  STOCKPILE
00790 17A    PLPRE.K=(L.K)(PLPLW)(CE.K)+(L.K)(PLPBR)(BE.K)+(L.K)(PLPAD)(AE.
00800 12A    PLCNE.K=(BRDIN)(GRBE.K)
00810 37B    TRBE=BOXLIN(4,1)
00820 6A     TRBE*1.K=PLPRE.K
00830 6A     PLPRY.K=TRBE*4.K
00840 C      TRBE*=0/0/0/0
00850 45A    PLSPE.K=STEP(PSTE.K,3)
00860 52L    PSTE.K=PSTE.J+(DT)(PLPRY.JK-PLCNE.JK+0+0)
00870 13N    PSTE=(.8)(M0)(PLPLW)
00880 NOTE        URANIUM  PRICE
00890 9A     UPRE.K=PRE1.K+PRE2.K+PRE3.K+PRE4.K
00900 51A    PRE1.K=CLIP(10,PRET1.K,TURNE.K,800000)
00910 51A    PRE2.K=CLIP(20,PRET2.K,TURNE.K,1700000)
00920 51A    PRE3.K=CLIP(20,PRET3.K,TURNE.K,9700000)
00930 51A    PRE4.K=CLIP(50,PRET4.K,TURNE.K,24700000)
00940 58A    PRET1.K=TABHL(DATA1,TURNE.K,0,800000,800000)
00950 58A    PRET2.K=TABHL(DATA2,TURNE.K,800000,1700000,900000)
00960 58A    PRET3.K=TABHL(DATA3,TURNE.K,1700000,9700000,8000000)
00970 58A    PRET4.K=TABHL(DATA4,TURNE.K,9700000,24700000,15000000)
00980 NOTE   1)YEAR/2)TMWE/3)CEY/4)AEY/5)BEY/6)GRCY/7)GRAY/8)GRBY
00990 PRINT 2)YEAR/4)TRNEY/6)UPREY/8)PSPEY
R 1.166+.533
printf z21 madtrn
W 1939.9
00010 NOTE        NUCLEAR POWER COMPLEX  'ZETA'
00020 NOTE   IN THIS CASE THERE ARE TWO KINDS OF ADVANCED CONVERTER
00030 NOTE   REACTORS: HTGR AND FASR U-235 FUELED REACTORS. HTGR ARE FOR
00040 NOTE   URANIUM UTILISATION AND FAST U-235 FUELED REACTORS FOR THE
00050 NOTE   PLUTONIUM PRODUCTION REQUIRED FOR INITIAL GROWTH OF BREEDERS.
00060 NOTE   HTGR ARE INTRODUCED IN 1975 AT A CONSTANT GROWTH RATE AND FAS
00070 NOTE   U-235 REACTORS IN 1975 .BNE STARTS FROM 1985.
00080 NOTE                NUCLEAR POWER COMPLEX
00090 6A     BEZ.K=BE.K
00100 6A     AEZ.K=AE.K
00110 6A     CEZ.K=CE.K
00120 6A     GRBZ.K=GRBE.K
00130 6A     GRAZ.K=GRAE.K
00140 6A     GRCZ.K=GRCE.K
00150 6A     TURNZ.K=TURNE.K
00160 6A     PSPEZ.K=PLSPE.K
00170 6A     UPREZ.K=UPRE.K
00180 51A    BE.K=CLIP(TMWQ.K,BBX.K,TIME.K,T51)
R .750+.333
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printf z22 madtrn
W 2037.1
00190 1L     BBX.K=BBX.J+(DT)(GRBE.JK+0)
00200 6N     BBX=0
00210 56A    AE.K=MAX(AEC.K,0)
00220 51A    AEC.K=CLIP(AET.K,AEX.K,TIME.K,T21)
00230 1L     AEX.K=AEX.J+(DT)(GRAEX.JK+0)
00240 6N     AEX=0
00250 1L     HTGR.K=HTGR.J+(DT)(GRHT.JK+0)
00260 6N     HTGR=0
00270 56A    CE.K=MAX(CEX.K,0)
00280 51A    CEX.K=CLIP(CET.K,CES.K,TIME.K,T21)
00290 1L     CET.K=CET.J+(DT)(GRCEX.JK+0)
00300 6N     CET=74000
00310 8A     CES.K=TMWT.K-AEX.K-BEX.K
00320 51A    BEX.K=CLIP(0,BE.K,TIME.K,T21)
00330 45A    AET.K=STEP(AEST.K,T21)
00340 9A     AEST.K=TMWE.K-HTGR.K-CE.K-BE.K
00350 7A     GRAEX.K=GRAE1.K+GRAE2.K
00360 45A    GRCEX.K=STEP(CONST.K,T21)
00370 51A    CONST.K=CLIP(0,-5000,TIME.K,36)
00380 9A     GRAE.K=GROTH.K-GRHT.K-GRCE.K-GRBE.K
00390 45A    GRHT.K=STEP(ABCD.K,T11)
00400 51A    ABCD.K=CLIP(TOM.K,4000,TIME.K,T36)
00410 51A    TOM.K=CLIP(50000,5000,TIME.K,T51)
00420 51A    GRCE.K=CLIP(GRCEX.K,GRCEY.K,TIME.K,T21)
00430 10A    GRCEY.K=GROTH.K-GRHT.K-GRAE1.K-GRAE2.K-GRBE1.K+0
00440 51A    GRBE.K=CLIP(GROQL.K,GRBEX.K,TIME.K,T51)
00450 8A     GRBEX.K=GRBE1.K+GRBE2.K+GRBE3.K
00460 12A    GRAE1.K=(MULT1.K)(GRP3.K)
00470 45A    GRP3.K=STEP(GROQL.K,T11)
00480 7A     GROQL.K=GROTH.K-GRHT.K
00490 18A    GRAE2.K=(MULT2.K)(GRP4.K-GRBE1.K)
00500 45A    GRP4.K=STEP(GROQL.K,T16)
00510 58A    MULT1.K=TABHL(RATA,TIME.K,10,16,1)
00520 C      RATA*=0/.1/.2/.3/.4/.5/0
00530 58A    MULT2.K=TABHL(RATB,TIME.K,15,21,1)
00540 C      RATB*=0/.6/.7/.8/.9/1/0
00550 58A    GRBE1.K=TABHL(BRGR,TIME.K,15,21,1)
00560 C      BRGR*=0/1000/3000/5000/6000/8000/0
00570 6A     GRBE2.K=TRNE*4.K
00580 6A     TRNE*1.K=SX.K
00590 C      TRNE*=0/0/0/0
00600 37B    TRNE=BOXLIN(4,1)
00610 17A    SX.K=(L.K)(ALPHA)(PX.K)+(L.K)(-BETA)(BX.K)+(L.K)(GAMMA)(CX.K)
00620 45A    PX.K=STEP(TMWT.K,18)
00630 51A    TMWT.K=CLIP(0,TMWQ.K,TIME.K,T21)
00640 7A     TMWQ.K=TMWE.K-HTGR.K
00650 58A    BX.K=TABHL(BOX,TIME.K,17,21,1)
00660 C      BOX*=0/4000/9000/15000/0
00670 45A    CX1.K=STEP(CE.K,18)
00680 51A    CX.K=CLIP(0,CX1.K,TIME.K,21)
R 1.400+.366
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printf z23 madtrn
W 2051.9
00690 6A      GRBE3.K=TRNF*4.K
00700 6A      TRNF*1.K=SY.K
00710 C       TRNF*=0/0/0/0
00720 37B     TRNF=BOXLIN(4,1)
00730 17A     SY.K=(L.K)(ALPHA)(PY.K)+(L.K)(-BETA)(BY.K)+(L.K)(GAMMA)(CY.K)
00740 45A     PY.K=STEP(TMWQ.K,T21)
00750 45A     BY.K=STEP(BE.K,21)
00760 45A     CY.K=STEP(CE.K,21)
00770 NOTE        POWER  GENERATION
00780 17A     PGCE.K=(L.K)(CE.K)(1)+(L.K)(.5)(GRCE.K)+(0)(0)(0)
00790 17A     PGBE.K=(L.K)(BE.K)(1)+(L.K)(.5)(GRBE.K)+(0)(0)(0)
00800 17A     PGAE.K=(L.K)(AE.K)(1)+(L.K)(.5)(GRAE.K)+(0)(0)(0)
00810 17A     PGHT.K=(L.K)(HTGR.K)(1)+(L.K)(.5)(GRHT.K)+(0)(0)(0)
00820 NOTE        URANIUM  REQUIREMENTS
00830 15A     URNCE.K=(ILWWR.K)(GRCE.K)+(BLWWR.K)(PGCE.K)
00840 15A     URNAE.K=(INFUR.K)(GRAE.K)+(BNFUR.K)(PGAE.K)
00850 15A     URNHT.K=(IHTRC.K)(GRHT.K)+(BHTRC.K)(PGHT.K)
00860 8A      URNE.K=URNCE.K+URNAE.K+URNHT.K
00870 1L      TURNE.K=TURNE.J+(DT)(URNE.JK+0)
00880 6N      TURNE=URNE
00890 NOTE          PLUTONIUM  STOCKPILE
00900 17A     PLPRE.K=(L.K)(PLPLW)(CE.K)+(L.K)(PLPBR)(BE.K)+(L.K)(PLPAD)(AE.K
00910 12A     PLCNE.K=(BRDIN)(GRBE.K)
00920 37B     TRBE=BOXLIN(4,1)
00930 6A      TRBE*1.K=PLPRE.K
00940 6A      PLPRY.K=TRBE*4.K
00950 C       TRBE*=0/0/0/0
00960 45A     PLSPE.K=STEP(PSTE.K,3)
00970 52L     PSTE.K=PSTE.J+(DT)(PLPRY.JK-PLCNE.JK+0+0)
00980 13N     PSTE=(.8)(MO)(PLPLW)
00990 NOTE        URANIUM  PRICE
01000 9A      UPRE.K=PRE1.K+PRE2.K+PRE3.K+PRE4.K
01010 51A     PRE1.K=CLIP(10,PRET1.K,TURNE.K,800000)
01020 51A     PRE2.K=CLIP(20,PRET2.K,TURNE.K,1700000)
01030 51A     PRE3.K=CLIP(20,PRET3.K,TURNE.K,9700000)
01040 51A     PRE4.K=CLIP(50,PRET4.K,TURNE.K,24700000)
01050 58A     PRET1.K=TABHL(DATA1,TURNE.K,0,800000,800000)
01060 58A     PRET2.K=TABHL(DATA2,TURNE.K,800000,1700000,900000)
01070 58A     PRET3.K=TABHL(DATA3,TURNE.K,1700000,9700000,8000000)
01080 58A     PRET4.K=TABHL(DATA4,TURNE.K,9700000,24700000,15000000)
01090 PRINT  1)YEAR/2)TMWE/3)CEZ/4)HTGR/5)AEZ/6)BEZ/7)GRCZ/8)GRHT
01100 NOTE   1)YEAR/2)GROTH/3)GRAZ/4)GRBZ/5)TURNZ/6)UPREZ/7)PSPEZ
R 1.400+.616
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printf plutm madtrn
W 1231.5
00010 NOTE  PLUTONIUM VALUE IN BNE
00020 NOTE  THIS PROGRAMME CALCULATES THE VALUE OF PLUTONIUM IN
00030 NOTE  A CASE OF BALANCED NUCLEAR ECONOMY FOR TWO DIFFERENT
00040 NOTE  CASES OF ACR NAMELY HWOCR AND FAST-U235.THE FORMULA
00050 NOTE  USED IS :
00060 NOTE        PLUTONIUM VALUE=(CPGA-CPGB)(1-EXP(MU)(TIME))/
00070 NOTE                        A-B+I.IB(1-EXP(MU)(TIME)/L
00080 12A   ARG1.K=(-MU1)(TIME.K)
00090 28A   ARG2.K=(1)EXP(ARG1.K)
00100 7A    ARG3.K=1-ARG2.K
00110 12A   NUM1.K=(ARG3.K)(X1)
00120 13A   ARG4.K=(IB)(RI)(ARG3.K)
00130 8A    DEN1.K=A1-B1+ARG4.K
00140 20A   PLVHW.K=NUM1.K/DEN1.K
00150 12A   ARGX.K=(-MU2)(TIME.K)
00160 28A   ARGY.K=(1)EXP(ARGX.K)
00170 7A    ARGZ.K=1-ARGY.K
00180 12A   NUM2.K=(ARGZ.K)(X2)
00190 13A   ARGT.K=(IB)(RI)(ARGZ.K)
00200 8A    DEN2.K=A2-B1+ARGT.K
00210 20A   PLVFU.K=NUM2.K/DEN2.K
00220 C     X1=7625/X2=12826/A1=350/A2=830/B1=430/IB=4200
00230 C     RI=0.143/MU1=-0.0180/MU2=0.1495
00240 SPEC  DT=1/LENGTH=40/PRTPER=1/PLTPER=1
00250 PRINT 3)PLVHW/6)PLVFU
R .800+.666
```

END