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TECHNICAL AND ECONOMIC PARAMETERS AFFECTING FAST BREEDER REACTOR DEPLOYMENT

ABSTRACT

The effects of various technical and economic parameters on LMFBR deployment plans have been studied to assess the best future "mix" of light water reactors and fast breeder reactors which will result in minimum cumulative nuclear generating costs discounted to the year 1985. Projected growth in domestic nuclear generating capacity was taken from various predictions [19, 20, 21], and the future domestic nuclear generating capacity was assumed to consist only of light water reactors and liquid metal cooled fast breeder reactors. Technical characteristics representing the two reactor types were taken as fixed, typical values for this study. The light water reactor characteristics represent a composite between PWRs and BWRs, whereas the most recent follow-on design was used as the reference for LMFBRs. Annual domestic power generation costs are calculated as a function of the installed capacity of both light water and fast breeder reactors in each particular year, the unit costs of each reactor type, the load factor, plutonium requirements, plutonium price

and discount rate, and other factors. The cumulative nuclear generating costs are then computed as the sum of the discounted annual costs.

Future variations in plant capital costs and incremental changes in fuel cycle costs for the two respective reactor types govern the ideal time scale for introduction of LMFBRs. Using published predictions concerning future variations in these unit charges [41, 42, 43] and assuming unlimited supplies of plutonium, the economically desirable, most rapid growth rate of breeder capacity can be determined. When other economic factors are held constant, the price of plutonium then dominates both the economically ideal introduction date for breeders and the rate growth of installed FBR capacity.

It may not be possible to achieve this economically ideal FBR deployment plan for various practical reasons including a scarcity of plutonium. This necessitates formulation of workable strategies so that the breeder deployment may approach, as nearly as possible, the ideal minimum cumulative nuclear generating costs.

These strategies are obviously dependent on the technical parameters of breeding ratio and in-core and ex-core specific inventory of the reference breeder design. However, equally important are the economic parameters of discount rate and "pay-off" period examined together with the influence of whatever policy for plutonium utilization that is adopted. The economic difference between a thirty and a fifty year "pay-off" period, for example, may be greater than $10 billion present-worthed to the year of breeder introduction. More important, however, the results indicated in these two may be the reverse.

Contrary to some expressed views [30, 58], this analysis indicates that it may not necessarily be uneconomical to stockpile plutonium from LWRs for subsequent LMFBR use instead of recycling in LWRs. A method to achieve storage with little impact on present light water reactors is described. In addition, the existence of a breeder reactor fraction which yields system generating costs insensitive to plutonium price has been found. Although the particular fraction results from the model considered, the principle can be extended to a more complex nuclear system. Thus it is possible for a reactor user, through the proper combination of reactor types, to hedge the plutonium market and be protected from all price fluctuations.

Whether it is more desirable to realize short-term or long-range minimization of energy, costs must be determined first. Once this decision has been made, the appropriate policy for utilization or stockpiling of plutonium will follow. Conversely, since practical strategy for LMFBR deployment may be substantially limited by the quantity of plutonium available and its price, the nature of the plutonium market and its resulting price structure will determine whether the objectives are short or long-range in character.

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INTRODUCTION

The Problem

The advent of the fast breeder reactor has long been heralded as the potential salvation for the ills that plague mankind in its attempt to find adequate energy resources. In fact, the fast breeder reactor appears to be precisely what man has been forever seeking - something for nothing. It has been suggested that in a fast breeder reactor man will use "cheap" and plentiful potential fuel in the form of natural uranium, along with some plutonium, to produce energy while at the same time increasing the quantity of valuable plutonium. All this might be accomplished in an economic structure such that the net fuel cycle costs could be negative, and the overall energy generation costs would be so low that abundant power would be affordable by all. Not only may it be possible to produce enough electrical power to satisfy contemporary needs; but because of the unique "breeding" characteristic of this form of power generation, the amount of plutonium will increase ultimately doubling at a faster rate than the demand for electricity and, thereby, assuring sufficient supplies of energy for all man's needs.

This optimistic expectation is contingent upon only two factors: the development, introduction and use of nuclear reactions which will operate in such a manner; and the availability of sufficient plutonium in order to initially charge these reactors and to refuel them. The development of such reactors is being pursued through the United States Atomic Energy Commission's Liquid Metal Fast Breeder Reactor (LMFBR) Program. The second factor, assurance of sufficient plutonium to fuel these reactors, is examined in this dissertation. Plutonium availability is affected by the technological (non-nuclear as well as nuclear) and the economic climate, both of which contribute certain parameters which influence the availability of this relatively new element.

The object of this work is to determine, for a nuclear electrical generating system consisting solely of light water reactors and fast breeder reactors, the discounted minimum nuclear generating costs over the next several decades. In order to determine this, it will be necessary to identify the parameters which influence these costs, as well as the values which these parameters must assume, in order to combine to produce a minimum. The method that has been employed to define this minimum involved the development of a model of the domestic nuclear generating system in order to ascertain the total nuclear generating costs. The costs for each combination of parameters were calculated and compared to one another by determining the additional costs incurred above an ideal. The ideal is defined solely on the basis of parameters which give the minimum costs each year even though the parameters may not be compatible from year to year (i.e., ideal capacity may switch from all light water reactors one year to all breeders the next) and, therefore, would not be realistic. Once the most desirable parameter combination (having attainable costs nearest the ideal) has been identified, policies may be formulated which contribute to the development of this parameter combination and ultimately to the achievement of minimum generating costs.

Some may regard it as premature to consider potential problems which may not arise for 15-25 years. One must realize, however, that: (1) Experience has shown that approximately 20 years is required for new nuclear reactor concepts to become commercially viable; (2) The anticipated lives of present and foreseen nuclear systems is thirty years or more; (3) Utility planning must be forecast long in advance (For utility planning, it is already the year 1978); and (4) The interval between the present and the LMFBR introduction date provides sufficient time to implement any schemes that may be required to approach the desirable minimum nuclear generating cost. Therefore, it is not only reasonable to conduct such a study at the present time, it is necessary to do so.

Background and Previous Work

Breeder reactors are of fundamental importance because they will utilize precious natural resources much more efficiently than presently installed burner (or consumer) reactors. The raw material which is required as feed for a breeder reactor consists of plentiful natural or depleted uranium as opposed to the costly enriched uranium required in today's reactors. The use of fast breeder reactors makes possible energy production per unit weight of mined uranium about 50 times greater than that achievable in present types of reactors [1].

The real key to low cost power and sufficient power lies not in the extent of our fuel deposits, but rather in how well the resources are utilized. The reserves of coal, oil, and gas in this country will be more precious in the long term as sources of organic molecules than as sources of heat [2]. As for nuclear energy sources, as long as the fission process is utilized, ultimate depletion of our uranium deposits is inevitable without the breeder [3].

There has been, in the past, considerable interest in the analysis of a nuclear power program consisting of a variety of reactor types [4, 5, 6]. Iliffe [7] and others [8] have even made analyses of reactors as portions of a total electrical generating system. Many of these investigations have considered the effect of economics but have been primarily oriented toward a specific task such as Eschbach's determination of the value of plutonium in specific reactors [9] or to project the future value which it might assume under different circumstances [10, 11].

In this country, when considerations of different reactor types have been appraised, any savings have generally been expressed in terms of energy or resources such as less uranium ore consumed or fewer units of separative work required [12, 13, 14]. This type of expression is understandable and, for a comparison of similar technologies, good in that a better physical description can be obtained. However, expressing savings in such terms is useless when comparisons to dissimilar technologies or even different fields of endeavor (social priorities, for instance) are desired.

Two domestic studies which have considered the economics of breeder reactors have done so on the basis of cost-benefit analysis [15, 16]. While cost-benefit analyses are useful for deciding between projects which have the same end, this type of treatment will not produce results which can be compared to other unrelated topics. It, therefore, seems imperative that an analysis be made of a mixed reactor program that yields results in terms of net dollars saved and, by so doing, is able to determine the time-dependence of the parameters necessary to approach, as nearly as possible, the most desirable economic consequence.

Nuclear Growth Rate

Since 1900, the demand for electrical energy has increased by a factor of two every ten years (ten year doubling time) in the United States [17]. This same rate of increase is projected for the near future, at least (cf. Figure 1). This requires the installation of new electrical generation capacity sufficient to satisfy the projected demand plus provisions for some degree of reserve power. The kinds and amounts of generating capabilities that satisfy the electrical demand are also shown in Figure 1. Today nuclear power has become an accepted means of power generation. As the most prominent fuel of the near future, it will capture an increasingly greater proportion of the installed electric generating capacity for economic reasons.

The extent to which nuclear power will be utilized was projected by the AEC in its 1962 Report to the President [18] (see Curve A of Figure 2). This estimate was updated in the 1967 Supplement of this report [19] as shown in Curve B of Figure 2. Since that date, more optimistic predictions of the fraction of installed generating capacity that will be nuclear have appeared based on the burgeoning number of nuclear generating

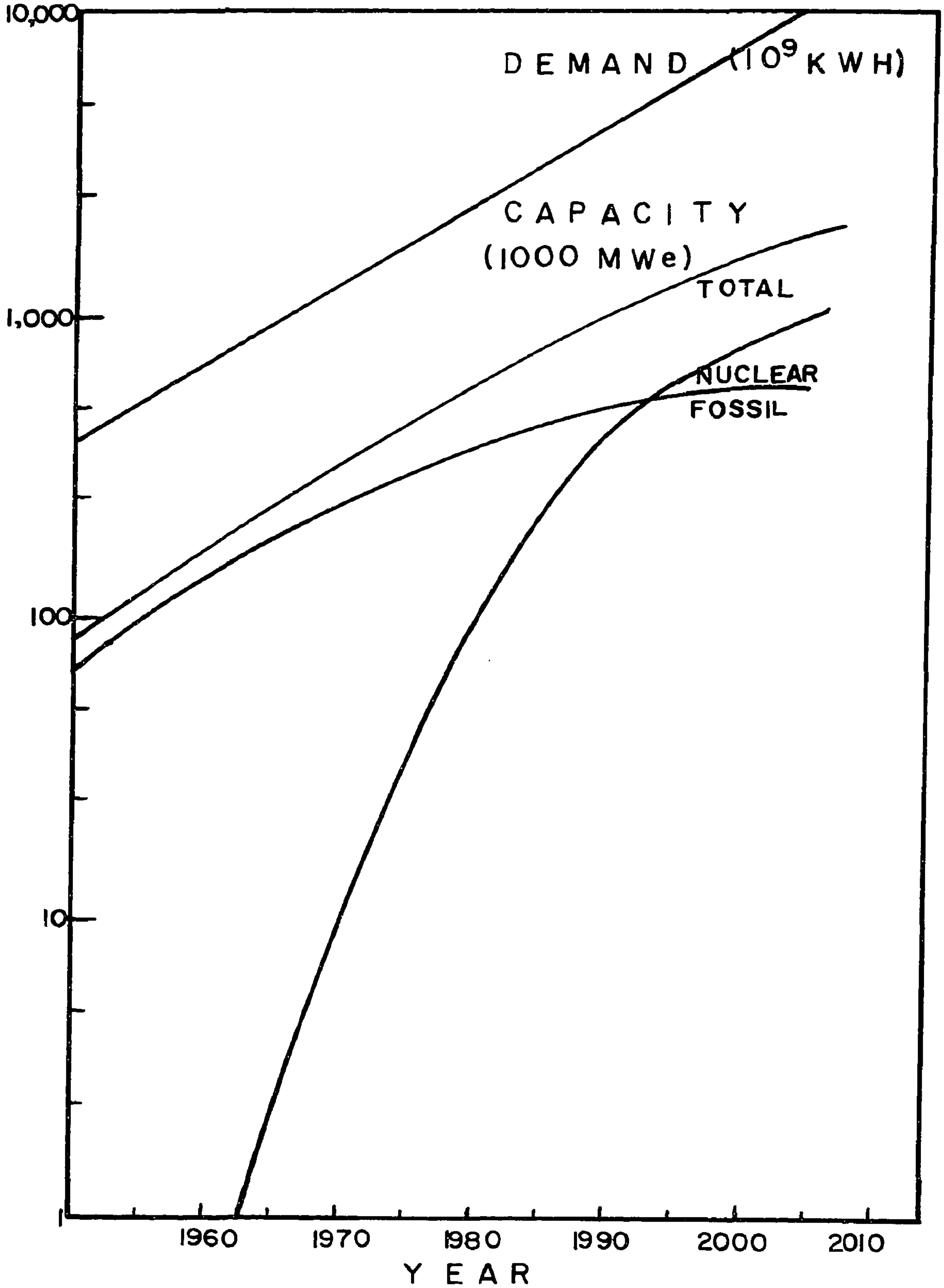

Figure 1: Projection of Domestic Electrical Generating Demand and Capacity

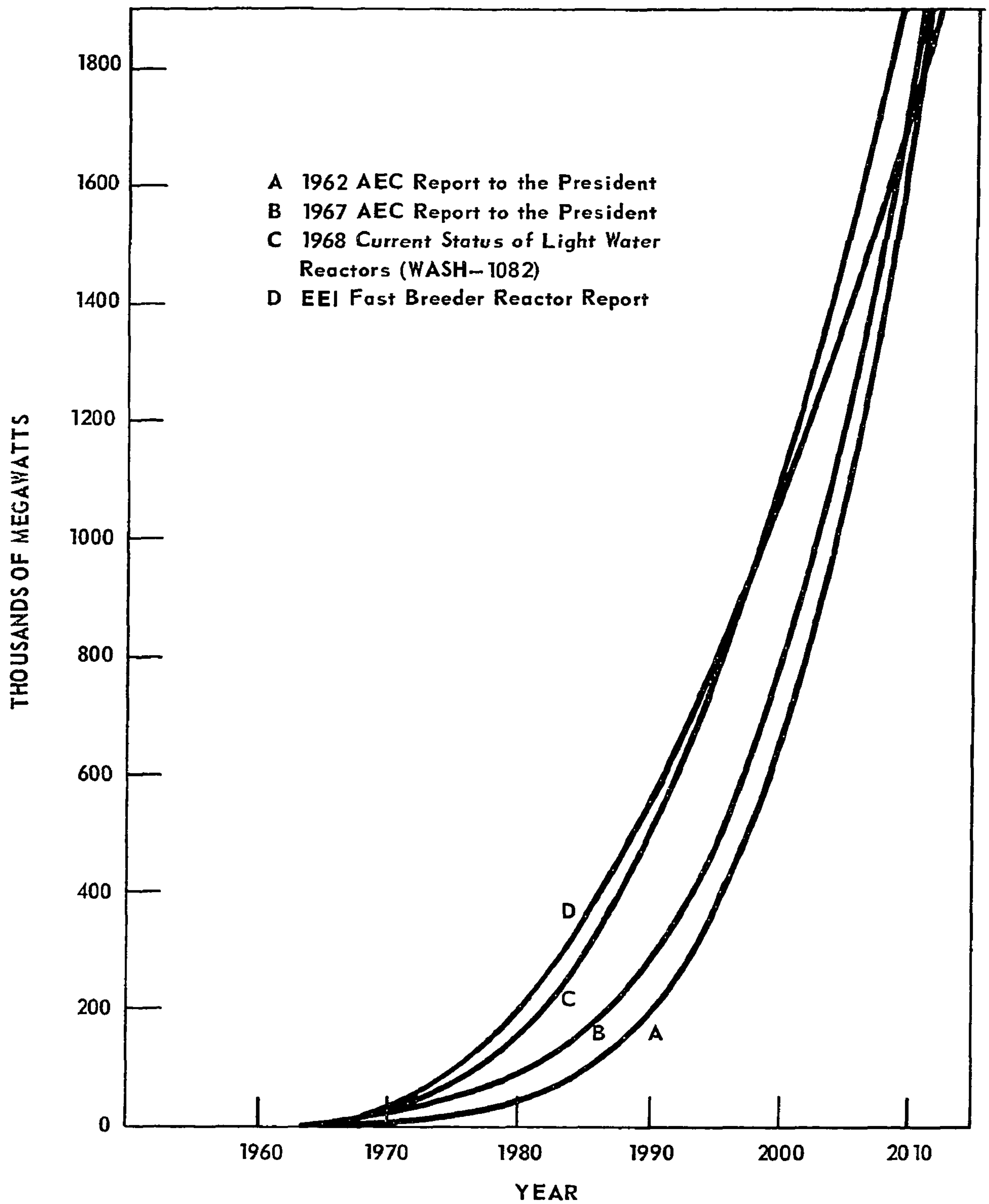

Figure 2: Estimated Installed Nuclear Capacity

plants that were ordered during the years 1967 and 1968 [20, 21]. The rate of increase of these estimates indicates an installed nuclear capacity of 150,000 Mw(e) in 1980 and suggests the nuclear capacity will approach 2,000,000 Mw(e) by the year 2010 (see Curves C, D of Figure 2). The rate of nuclear plant sales in the intervening three years have not borne out such optimistic estimates due mainly to increasing nuclear plant costs, a veritable saturation of the manufacturers' facilities, nuclear plant licensing delays and frequent and more heightened attacks on nuclear power by environmentalists urging a slowdown in power production in general, and nuclear plant construction in particular. Nevertheless, some industry sources, arguing on the basis of pure economics, hold fast to the 1980 projection [22] while others take a more conservative viewpoint based on the factors mentioned which tend to support the earlier estimates [23]. In light of these factors, it appears reasonable to assume that the installed nuclear capacity until 1985 will be in the region bounded by the 1967 AEC Report and later projections. Should the economic, technical, and political factors combine to achieve the more recent 1980 projections, the current estimates for the year 2000 could certainly be considered reasonable.

For the purposes of this study, it will be assumed that the nuclear generating capacity is composed solely of light water reactors and fast breeder reactors. Although there is presently minor support for other reactor concepts, the bulk of the commercial and AEC funding and interest seems to lie with these two reactor types.

Plutonium

Whenever a quantity of natural or slightly enriched uranium is fissioned, some plutonium is produced by neutron absorption in ^{238}U. The net amount of plutonium produced is dependent upon a great many factors. The most fundamental factor is the average energy of the neutron energy distribution (spectrum) in the reactor which governs the relative magnitude of the rates of production and consumption of plutonium. Since most materials have a lower cross section (probability of interaction) at higher neutron energies (a "fast" neutron energy distribution) than at "thermal" energies (neutrons in thermal equilibrium with surrounding media), the absorption tends to be a smaller portion of the total neutron interactions in a fast breeder. Also the number of neutrons produced per neutron absorbed (η) tends to be higher at higher energies. A higher energy neutron spectrum, as well as the degree of fuel burnup, tends to produce a more desirable isotopic composition of the product plutonium. These factors all contribute to the fast reactor being preferred for the production and utilization of plutonium. Table I indicates some of the important parameters associated with plutonium production and consumption for various average neutron energies.

The plutonium produced may be utilized or "burned" in the reactor in which it has been produced or in some other reactor. If in the same reactor, the plutonium may be burned *in situ* which has the economic benefit of not requiring reprocessing. However, the amount of material that can be efficiently burned *in situ* is limited, so that it may be preferable to recycle the plutonium in new fuel elements. If the recycled plutonium is to be used in a different reactor, this may be or may not be of the same type as the original.

Fast Breeder Reactors and Plutonium

Fast reactors are fueled with plutonium mixed with natural uranium in the ratio 1:3 or 1:4. Since they produce more plutonium than they consume, such reactors are known as "breeders". A useful figure of merit of a breeder is the amount of time required for a given reactor

TABLE I

NEUTRONIC PROPERTIES OF MIXED OXIDE FUEL

	Average Neutron Energy	U-238 σ_a[i] (b)	Pu-239 σ_a[i] (b)	Pu-239 σ_f[i] (b)	Pu-239 α[i] $\left(\frac{\sigma_a - \sigma_f}{\sigma_f}\right)$	Pu-239 η[i,ii]	Typical Plutonium Isotopic Composition (w/o) 239	240	241
Thermal:	.025 eV	2.73	1014.5	740.6	0.370	2.116	57	24	14[iii]
	1 eV			15		2			
	100 eV		20	12	0.6				
	10 keV	0.80	2.7	1.92	0.4	2			
	50 keV	0.35	2.4	1.88	0.272	2.15			
Fast:	100 keV	0.21	2.2	1.80	0.208	2.4	86	11	2

i BNL-325 (1965)
ii J. Lamarsh, Nuclear Reactor Theory, p. 112 (1966)
iii J. B. Roll, "Commercial Plutonium Recycle", Power Engineering, p. 34, (November, 1970)

to produce sufficient plutonium to yield excess plutonium in an amount equal to its initial plutonium inventory, thus permitting a doubling of the installed capacity. The "doubling time" is directly proportional to the specific inventory requirements of the reactor and inversely a function of the breeding ratio.

Specific inventory (the reciprocal of specific power) is defined as the ratio: Quantity of fissile inventory per unit electrical or thermal power (kg/Mw or g/kW). The specific inventory, although usually considered as a whole, can be divided into in-core specific inventory (amount in the reactor at any time) and ex-core specific inventory (amount cooling, in reprocessing, fabrication, shipment or storage at any time). Generally, ex-core inventories can increase the total specific inventory by 50% or greater [24]. The decrease in cross section with neutron energy requires that in order to produce a given amount of power, the fissile specific inventory be much greater in a fast reactor than in a thermal reactor. This also makes the inventory charges a greater component of the total power cost in a fast reactor.

There are a variety of ways to define breeding ratio [25]. The only one which is strictly correct for a "closed" fuel cycle is the ratio of fuel atoms extracted from the reactor to fuel atoms inserted into the reactor, if these are of the same kind [3, 25].

$$BR = \frac{\text{Fissile atoms extracted}}{\text{Fissile atoms inserted}} \tag{1}$$

This quantity may be computed over the total life of the entire reactor (fissile core plus blankets of fertile uranium), the life of each core (quantity of plutonium discharged from core and blanket during one complete irradiation cycle), or taken on an instantaneous basis for a continuous feed reactor at equilibrium.

Breeding ratios for fast reactors can be in excess of 1.6 (a so-called high-gain breeder), but normally for LMFBRs the value is in the range 1.2 to 1.4. A high breeding ratio is not necessarily conducive to conservation of fuel resources, particularly not if it is obtained at the expense of a high specific inventory [26].

Simple or straight-line doubling time (SDT), which is applicable to a single reactor operating alone, is given by

$$SDT = k \frac{SI_{TOT}}{BR-1} \qquad (2)$$

where k is a constant whose value depends on load factor, α (the neutron capture-to-fission ratio for plutonium) and frequency of refueling. The simple doubling time gives some indication of the potential rate of growth of breeder capacity starting from zero.

Compound doubling time, on the other hand, reflects the gain that occurs if the plutonium "dividends" are immediately reinvested in other breeders that have the same rate of return as the original reactor [27].

$$CDT = \frac{\ln 2}{\ln\left(1 + \frac{1}{SDT}\right)} \qquad (3)$$

This expression can actually be meaningful only when a large number of similar reactors are operating simultaneously. Then the term "doubling time" can be thought of as the time required for a generation of breeders to provide sufficient plutonium inventory for a doubled population of reactors.

Typical doubling times of first generation LMFBRs range from 7 to 19 years [28]. In order to satisfy the requirements of a power industry doubling time of approximately ten years, the most desirable breeder would have a doubling time somewhat less than this. Since short doubling times result from high breeding ratios and low specific inventories for a given breeding ratio, a reactor with a shorter doubling time has an additional economic attraction as the inventory charges amount to a very large investment of capital and a large percentage of the fuel cycle costs.

Even though breeders produce more plutonium than they consume, changes in plutonium price can affect the fuel costs of fast reactors adversely (i.e., fuel cycle costs increase with plutonium price) for the range of breeding ratios mentioned above for LMFBRs [29]. At a breeding ratio of approximately 1.5, this trend reverses. Even for a breeding ratio of 1.6, a reduction of 0.1 mils/KWH requires an increase in plutonium cost of $10-$11/g.

Light Water Reactors and Plutonium

Plutonium is also produced in light water reactors. The quantity of plutonium generated in this instance is considerably less per unit power than that produced in a fast breeder reactor. This can be seen from Table I. In order that the power level ($\phi N_f \sigma_f$) is the same in both reactors, the flux in the fast reactor must be some hundreds of times that of the thermal reactor. Although the ^{238}U thermal absorption cross section is a factor of 10 greater, the larger fast neutron flux results in a higher plutonium conversion ratio. Typical light water reactor conversion ratios are only 0.4 - 0.6.

The higher α value at thermal energies (cf. Table I) results in plutonium produced in light water reactor being composed of the higher plutonium isotopes. Consequently, this means that the fissile plutonium ratio is lower in this kind of material. With a greater quantity of the ^{241}Pu isotope, there exists the additional problem of decay when the material is stored for long periods of time. All these factors contribute to the preference for plutonium produced in a fast spectrum.

There are some differences in the amounts of plutonium produced in various types of light water reactors. Under optimum fuel cycle management, pressurized water reactors generally produce about a 20% greater yield of plutonium than do boiling water reactors [30]. If desired, the quantity of plutonium produced in a light water reactor may be increased by adjusting the hydrogen-to-metal ratio [31]. However, such changes are accomplished at the expense of fuel cycle economy.

As well as producing the plutonium, light water reactors may also be fueled with it. This concept is presently being advocated throughout the nuclear industry through the program known as "light water recycle". There are many reasons for the current interest in the recycle of plutonium in light water reactors. Primarily, these stem from a desire to ease the tension on uranium ore and enrichment requirements as well as to utilize fissile material which is on hand. However, as can be seen again from Table I, light water reactors do not employ plutonium as efficiently as do fast breeder reactors.

It is undoubtedly true that plutonium will and should <u>eventually</u> be burned in light water reactors. It will be shown later that this course is not advisable in the near future if the goal of minimizing long-term nuclear power costs is to be achieved.

Choice Purely on the Basis of Economics

Other studies [15, 16] have clearly shown that the benefits to be realized by breeder reactors outweigh the costs which will be incurred in their development. These analyses have been based on detailed estimates of the required development costs as well as on overall appraisals of the savings breeders will provide as energy sources. Such analyses assume that once breeders have been developed, all the elements are attendant to their full-scale utilization. All of the absolute costs in these analyses are synchronized around some specific year of breeder introduction. In this study, costs of producing energy are all considered to be relative to the date of commercial introduction of breeder reactors by the technique of present-worth accounting or discounting*. The present study will not be concerned with justifying the costs expended for breeder reactor research, but will assume that the technology for both light water reactors and fast breeders is available after the "introduction date".

Whether additional nuclear generating capacity for future installation should be of the light water reactor type or the fast breeder type would be an elementary decision if only economic considerations were involved. The correct choice would be that for which the discounted generating costs for the quantity of capacity being added is least when considered over the desired period of time. If it is assumed that the useful plant lives of the two type reactors are the same, the present worth

*Discounting, or present-worth accounting, involves the assignment of a present value to some future expense or revenue. The vehicle for such a consideration is referred to as the present-worth factor. This expression is a function both of the length of time between the future transaction and the present as well as the discount rate which the evaluator deems appropriate. (More will be said concerning the "appropriate" discount rate later.) The selected discount rate, i, (generally in percent) is applied to the time span, n, (generally in years) in a compounded manner to determine the present-worth factor:

$$\text{PWF} = \frac{1}{(1 + i)^n}$$

Past costs may be considered in the same manner; however in this case, the sign on the time span, n, is negative.

factors in the future would be identical since the addition in either case is planned for the same point in time. Thus the proper decision purely on an economic basis could be made by comparing the annual generating costs of the two systems. Further, if the average load factors over the lives of the two types of plants could be assumed identical, then the unit generating costs (mil/KWH) would be a valid basis of comparison. Since the more general case enables one to permit different or even time-varying load factors for the two plant types in this study, the basis for the economic decision has been the annual generating costs.

Technological Limitations to Economic Choice

The economic choice of nuclear capacity addition that is preferred may not be realizable due to limitations imposed by technological considerations. It will be assumed that there will be reactor manufacturers who will always be capable of furnishing sufficient plants to satisfy the nuclear demand. Further, it will be assumed that the possibility always exists of commissioning light water reactors to meet the nuclear demand since this type plant is currently being built.

The two most important constraints on fast breeder reactor additions are the date of commercial introduction of the breeder and a sufficient quantity of plutonium to initially fuel new breeders as well as to refuel those already producing power. Target date of the LMFBR Program for a commercially acceptable plant is 1985 [32].

A method has been devised to assure that only those fast reactors that can be fueled may be built. This entails keeping a running total of the quantity of plutonium available for use through a plutonium "profit-and-loss" account. This statement includes entries for production and the possible use of plutonium in light water reactors in addition to the plutonium production and requirements of the fast breeders. The sum of all these is accumulated on an annual basis in a "plutonium balance". The permissible new additions to fast breeder reactor capacity are then determined from this balance.

Objective

The primary objective of this study is to determine that combination of light water reactors and fast breeder reactors which, while satisfying the nuclear generating demand, will result in minimum nuclear generating costs discounted to the year 1985.

The annual discounted costs are a function of (among others) the installed capacity of both the light water reactors and the fast breeder reactors in that year, the load factors and unit costs of each, the quantity of plutonium held in stockpile, the plutonium price and the discount rate.

$$DNGC = f(CAP_{LWR},\ CAP_{FBR},\ LF_{LWR},\ LF_{FBR},\ UC_{LWR},\ UC_{FBR},\ PuBal,\ PuPr,\ Disrat) \qquad (4)$$

The total generating costs are the sum of the annual discounted costs. The objective function is therefore:

$$TNGC = \sum_{i=1}^{n} DNGC_i \qquad (5)$$

In this study, the variables which influence this objective function are adjusted until that realizable combination of parameters is established which yields accumulated generating costs as close to the economically ideal generating costs as possible. The measure of this proximity is the added cost (ADCOST) above the economic ideal associated with each particular case.

From the rate of change of the additional costs with respect to each variable, the extent of cost dependence can be determined. This determination enables an identification of the more important variables to be controlled. Thereafter, formulation of policies to achieve minimum future generating costs of a mixed fast breeder-light water reactor economy will be possible.

It is recognized that the extent of future generating costs depends on the rate of growth of nuclear capacity. For this reason different growth rates, including those projections that have been widely proclaimed, have been considered. It is also acknowledged that the development of fusion or other innovative energy sources is a definite possibility. However, the fusion eventuality presently appears sufficiently uncertain that no allowance has been made for it in this investigation. This has been justified on the assumption that, should a controlled thermonuclear reaction be achieved in the laboratory within 10 years, an additional 20 years would be required to transform laboratory curiosity into commercial realization. Such intervals of time approach the horizon used in this study. Other unforseen or inestimable breakthroughs have similarly been neglected. In any analysis of this sort, projections into the future are fraught with such unpredictabilities.

MODEL OF THE NUCLEAR GENERATING INDUSTRY

The model which has been formulated to represent the future nuclear power generation system consists of various potential mixes of light water reactors and fast breeder reactors. The light water reactors are represented by a pressurized water reactor whose design has been initiated by Westinghouse and modified by Oak Ridge National Laboratory [32]. The first-generation liquid metal cooled fast breeder reactor is that designed by Atomics International [33].

All future additions to the nuclear capacity are assumed to be 1000 MW(e) in size. There does appear to be some, though not appreciable, motivation for single plants of greater capacity than this. Although the unit costs ($/KWe) are somewhat less for larger sized plants, the forced-outage rates are considerably greater (as much as 20-30%) as well [34]. Such a forced-outage rate has the effect of reducing overall system reliability. Secondly, thousand megawatt plants are a convenient number with which to make additions to the nuclear capacity. This is especially true since most estimated projections of future generating capacity are rounded to the nearest thousand megawatts. Finally, 1000 MWe is the size of the specific reactor designs which are being utilized here. This makes possible the direct application of the relevant design parameters.

TYPICAL LIGHT WATER REACTOR*

The typical light water reactor is fueled with slightly enriched UO_2 and both moderated and cooled by means of pressurized H_2O. Pertinent design characteristics are presented in Table II. A more complete description of the light water reactor may be found in Appendix I. The active core is 11 feet high and 12.8 feet in diameter. The reactor contains 264 fuel assemblies and 109 control rods. Chemical poison control in the form of a boric acid solution is used for shim control to reduce the control rod requirements [35].

*The basic design of the LWR is taken from a Westinghouse Study: 1000 MW(e) Closed Cycle Water Reactor Study, Report WCAP 2385, March, 1963.

TABLE II

PARTIAL DESCRIPTION OF TYPICAL LIGHT WATER REACTOR

<u>Reactor Power</u>	
Core nuclear power, MW(th)	3220
Net electrical power, MW(e)	1002
Net thermodynamic efficiency, %	31.1
<u>Core and Fuel</u>	
Moderator and coolant material	H_2O
Fuel material	UO_2
Fuel fabrication	pelletized
Cladding material	Zircaloy-4
Full life, yr	3
Equivalent diameter of core, ft	12.8
Active height of core, ft	11.0
Number of fuel assemblies	264
Peak-to-average power ratio	3.3
Average core power density, KW/liter	80.7
Average specific power, KW/kg of fertile material	31.7
<u>Fuel Cycle</u>	
Fuel management scheme	Three batches, scatter reloading
In-core residence time, yr (at 0.8 load factor)	2.3
Average fuel exposure, MWD/MT	25,000
Average exposure in maximum rod, MWD/MT	30,000

The typical light water reactor has a maximum-to-average heat flux ratio of 3.3, a core power density of 80.7 $\frac{KW}{liter}$, and a coolant outlet temperature of 598°F. Short control rod followers that extend 3.7 feet into the 11 foot core and other mixing devices force the interchange of coolant between and within assemblies [36].

The fuel elements are designed to operate for three years at a linear heat rating of 16 $\frac{KW}{ft}$ and a maximum heat flux of 544,000 BTU/hr·ft^2 to a maximum burnup of 30,000 MWD/MT of uranium. The peak cladding temperature is 640°F; coolant pressure is 2050 psi [37].

Physics calculations of the 1000 MW(e) pressurized water reactor were performed by Oak Ridge National Laboratory [38]. Initial excess reactivity (i.e., feed fuel enrichment) was treated as a parameter in these calculations in order to optimize fuel costs. The feed and discharge enrichment for the equilibrium cycle are shown in Figure 3 as a function of average exposure of discharged fuel. Also shown is the feed enrichment that would be required if the neutron leakage were 1% smaller (i.e., a larger core size).

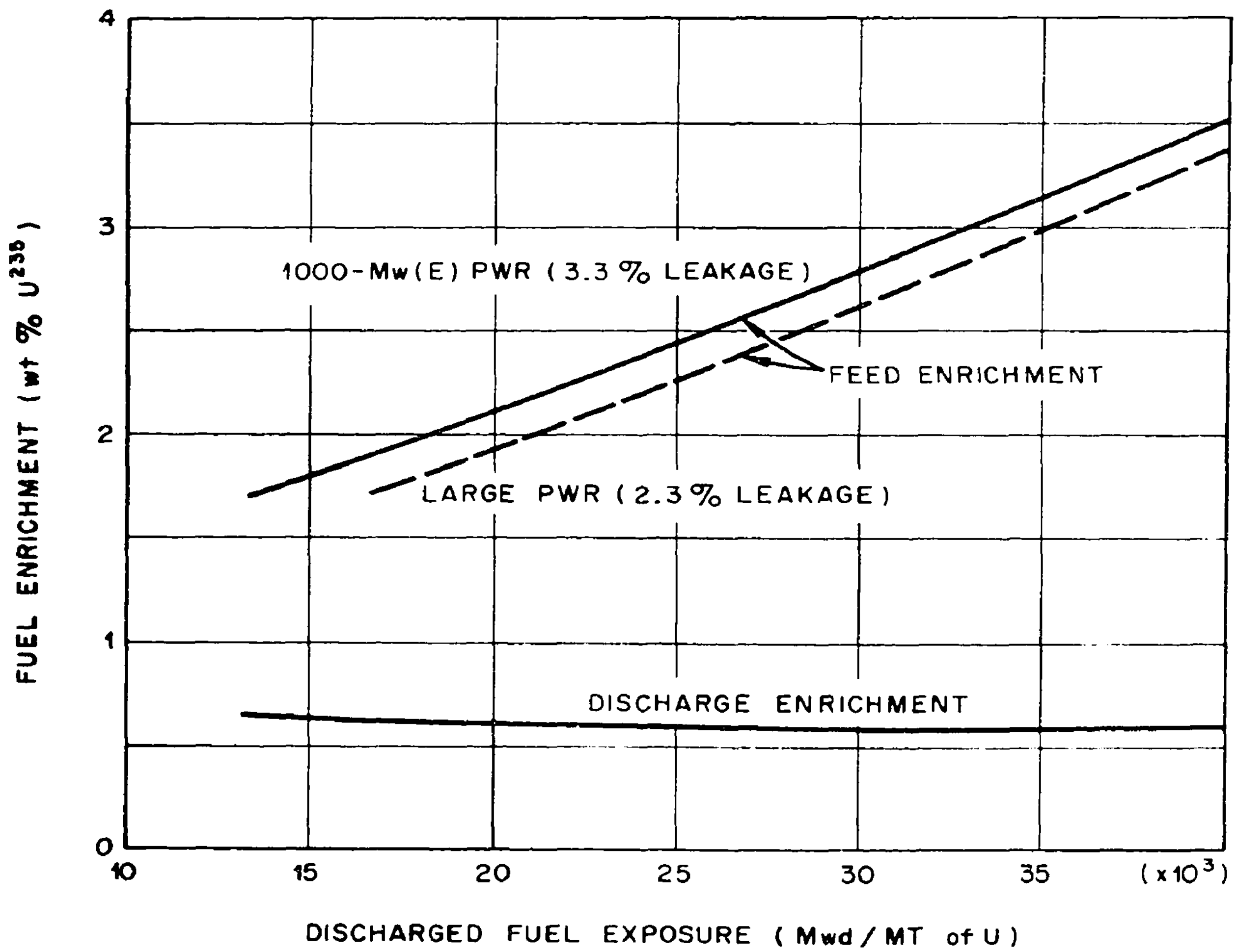

Figure 3: Light Water Reactor Feed and Discharge Uranium Enrichment Versus Fuel Exposure (after ORNL-3686)

The reference fuel management scheme is the "3-batch roundelay" or "scatter-reload" program in which one-third of the core loading is discharged at each annual shutdown. Discharge plutonium concentrations are shown in Figure 4.

In the present analysis, the initial enrichment was allowed to vary from 1.70% to 3.66% which yielded corresponding burnups that ranged from 10,000 to 40,000 MWD/MTU.

TYPICAL FAST BREEDER REACTOR

The typical first generation LMFBR consists of a core of mixed (uranium and plutonium) oxide fuel, suitably contained and subdivided to assure adequate heat removed by the circulating liquid-sodium coolant. At full load, sodium enters the vessel at the lower end at 760°F, flows up through the core and exits from the vessel at 1060°F [39].

Pertinent design characteristics of the reference LMFBR are given in Table III. A more complete description may be found in Appendix II.

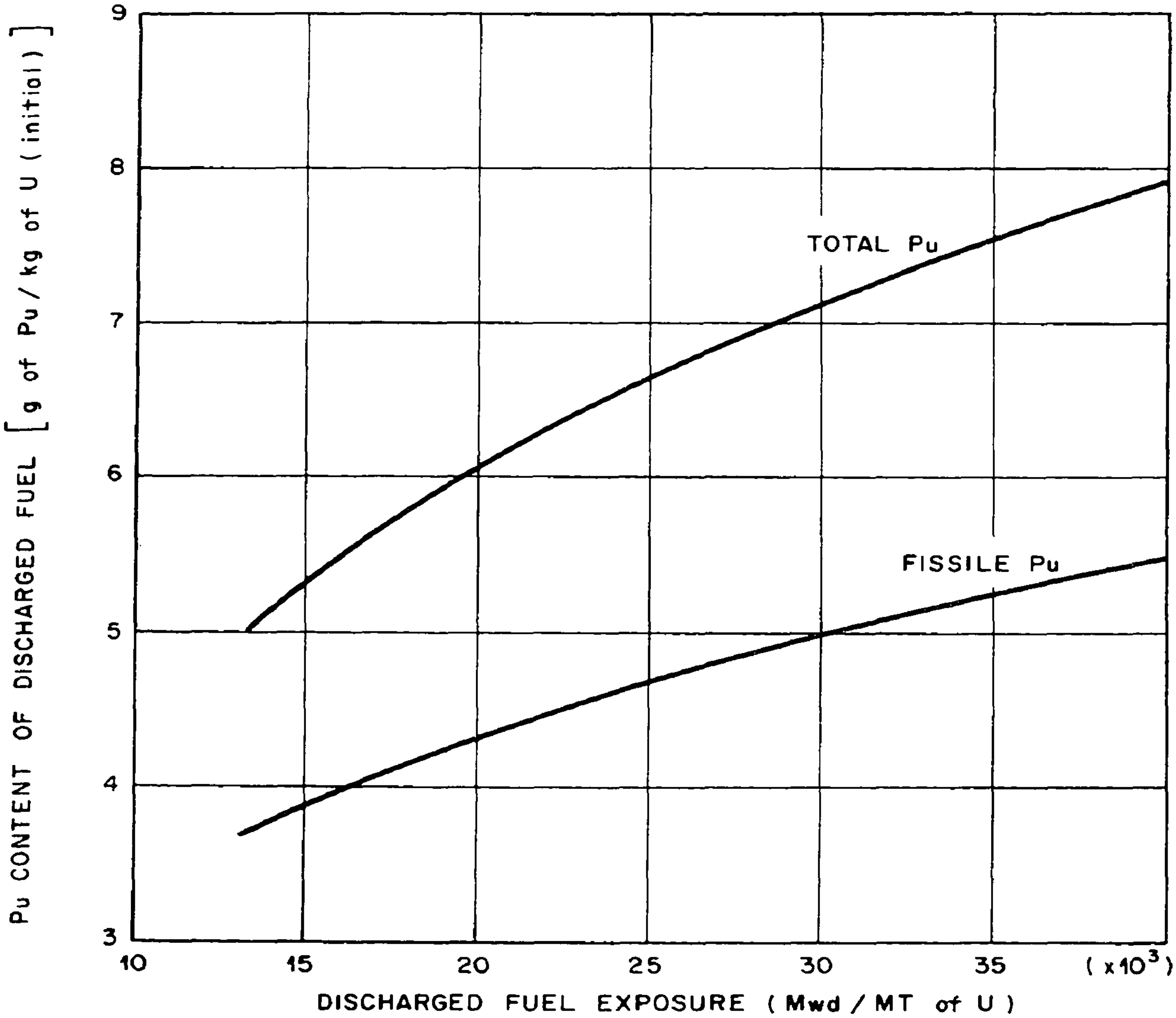

Figure 4: Plutonium Concentration in Light Water Reactor Discharged Fuel as a Function of Discharge Fuel Exposure (after ORNL-3686)

TABLE III

PARTIAL DESCRIPTION OF ASSUMED FIRST GENERATION LMFBR

Reactor Power	
Total reactor power, MW(th)	2500
Core power fraction (mid-cycle)	0.899
Radial blanket power fraction	0.069
Axial blanket power fraction	0.032
Net electrical power, MW(e)	1004
Net thermodynamic efficiency, %	40.7
Core and Fuel (mid-equilibrium cycle)	
Core fissile enrichment, at %	
inner zone	11.4
outer zone	15.4
Fissile mass (Pu + U-235), kg	
Core	1780
Axial blanket	116
Radial blanket	368
Fuel material	mixed PuO_2 , UO_2
Blanket material	depleted UO_2
Cladding material	304 or 316 SS
Peak-to-average power ratio	1.605
Average core power density, KW/liter	390
Average specific power of fuel material, KW/kg	190
Average breeding ratio	1.29
Doubling time, yr	~10
Fuel Cycle	
Fuel management scheme	scatter reload
In-core residence time, yr (at 0.8 load factor)	1.5
Average fuel burnup, MWD/MTH	75,000
Average exposure in maximum rod, MWD/MTH	100,000

The reactor core operates in a fast neutron flux, and power is regulated by moving neutron-absorbing control elements into or out of the core. The core is surrounded radially by two rows of depleted uranium blanket elements and a single row of stainless steel reflector elements. Depleted uranium is also used above and below the fuel as an axial blanket. Fifteen control and safety rods are provided for reactivity control. Tantalum has been selected as the reference absorber material. Nine control rods are used as combined shim and safety rods, and six are used strictly for safety.

The reactor will be refueled on a six month cycle with 1/3 of the core, 1/6 of the inner blanket, and 1/9 of the outer blanket being replaced each cycle. This corresponds to 144 days of fuel power (1000 MWe) operation. Refueling is performed during scheduled plant shutdown. Spent fuel is removed from the core and placed in one of the in-vessel storage positions for decay during the subsequent power cycle. The average exposure of the spent core fuel is 74,000 MWD/MT. The fast core elements have an average reactor residence time of 1.5 years, the inner radial blanket 3 years, the outer radial blanket 4.5 years, and the shim control rods 8 years. Additionally at each refueling, 1/9 of the outer blanket elements are rotated 180° to permit uniformity of the Pu buildup at the edge of the core where there is a sharp flux gradient. The downtime per refueling is estimated at about ten days [39].

The fuel burnup calculations for the reference LMFBR were performed by Atomics International [40]. The calculations were made in one-dimensional geometry using neutron-diffusion theory. Two core enrichment regions were employed to facilitate control of the peak-to-average power ratio. Each enrichment region was subdivided into three burnup zones to provide greater detail in the calculations. Each of the burnup zones was divided into three equal-volume fuel batches to simulate the fuel-management scheme. The time history of the changes in isotopic composition of each batch was calculated on a cycle-by-cycle basis. At each refueling, one fuel batch from each burnup zone was discharged and replaced with fresh fuel.

The radial blanket was similarly treated with six fuel batches in the inner-ring blanket and nine fuel batches in the outer-ring blanket. A uniformly distributed tantalum poison was used in the outer-core enrichment region to simulate the control rods. Equilibrium operation had been achieved by the tenth refueling cycle.

The isotopic composition for the initial loading is assumed to be 60% ^{239}Pu, 24% ^{240}Pu, 12% ^{241}Pu, and 4% ^{242}Pu. This is felt to be representative of early LWR discharge compositions. The startup core employs three different enrichments in each of the two core zones to minimize the swing in reactivity during the approach to equilibrium. The lower-enrichment batches are replaced first to provide a smooth transition to high-burnup, high-enrichment fuel.

The results of their analysis consist of the mass balances describing the isotopes charged to and discharged from the reactor. These balances are shown in Table IV for the isotopes of interest. As can be seen, during equilibrium operation 610 kg of fissile plutonium are charged to the reactor and 721 kg are discharged at each refueling shutdown. AI calculates a total breeding ratio of 1.29; and from their assumption of the ex-core fuel inventory and processing losses, they conclude the simple doubling time (cf. Equation 2) is 8.7 years.

TABLE IV

FBR ISOTOPIC MASS BALANCES (kg)

Feed Fuel to Equilibrium	^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	>^{242}Pu	Total
Core	10	3565	567	232	43	17	0	4434
Axial Blanket	7	2468	0	0	0	0	0	2475
Inner Radial Blanket	4	1345	0	0	0	0	0	1349
Outer Radial Blanket	2	796	0	0	0	0	0	798
Total	23	8174	567	232	43	17	0	9056

Total Fissile Pu 610
Total Fissile 633

Discharge End of Equilibrium Cycle	^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	>^{242}Pu	Total
Core	5	3243	533	244	37	18	2	4082
Axial Blanket	5	2394	63	2	0	0	0	2464
Inner Radial Blanket	3	1268	56	3	0	0	0	1330
Outer Radial Blanket	1	755	32	2	0	0	0	790
Total	14	7660	684	251	37	18	2	8666

Total Fissile Pu 721
Total Fissile 735

ASSUMPTIONS FOR ECONOMIC ANALYSIS

The analysis for each year under consideration follows the flow diagram shown in Figure 5. The range of total nuclear generating capacity noted above is spanned in separate sets of calculations. All presently installed nuclear capacity is assumed to be composed entirely of light water reactors. Further, additions to capacity are determined on the basis of: (1) technological capabilities (i.e., breeder cannot be constructed before the introduction date); (2) technological limitation (breeders are not constructed if there will be insufficient plutonium to fuel them); and (3) economic criteria (costs associated with each alternative). When both reactor types are technologically possible, the choice as to addition is made solely on the basis of economics. This results in the most economic, technically achievable units being installed at all times.

The extent of the added increment to nuclear capacity in any year, n, is determined from the difference between the estimate and the previous year's installed capacity.

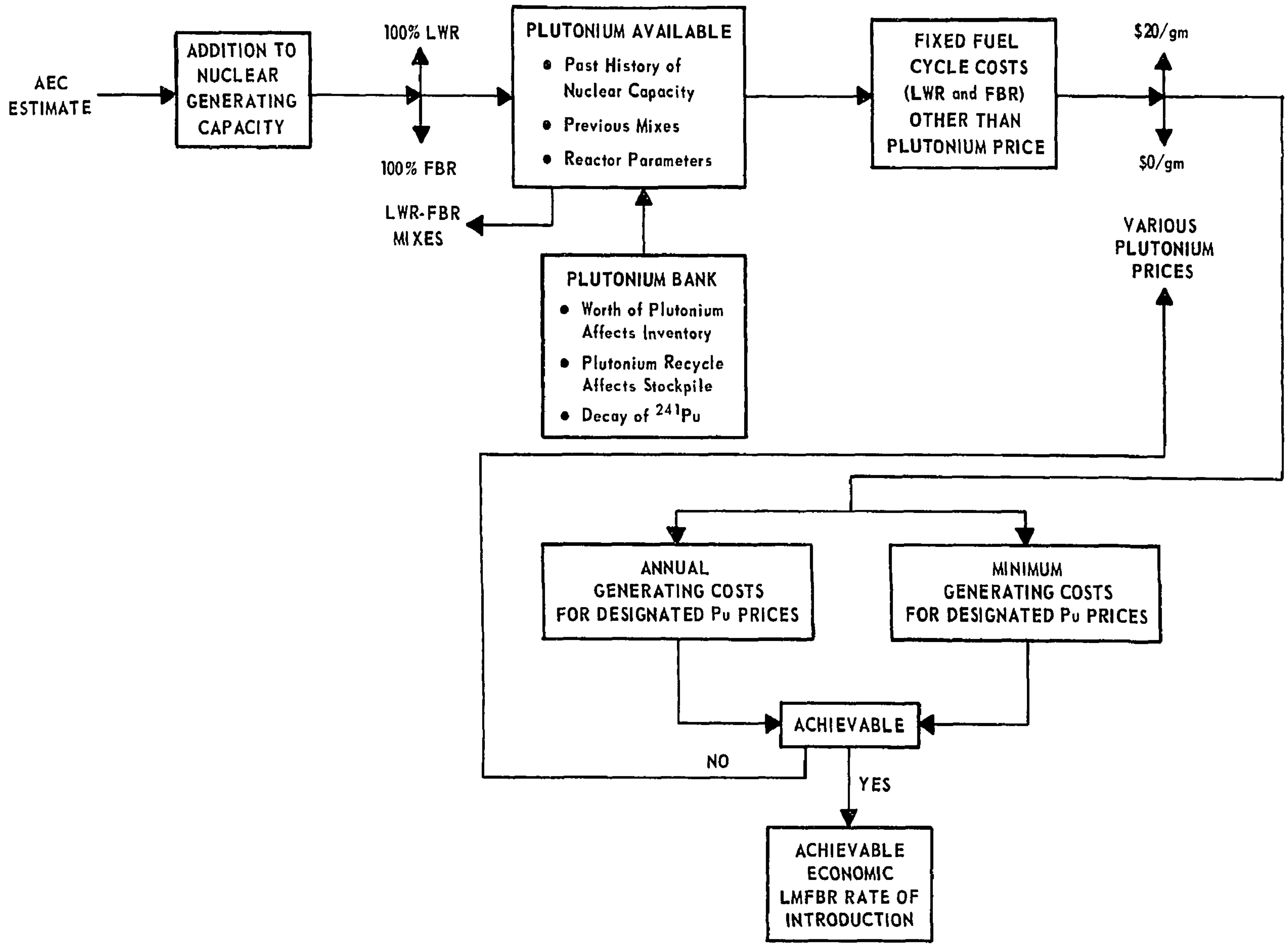

Figure 5: Flow Diagram of Annual Calculations to Determine Preferred Achievable Breeder Mix and Costs

$$I_n = E_n - K_{n-1} \quad (6)$$

where: I_n is the incremental nuclear generating capacity in the nth year, MWe
E_n is the estimate of nuclear generating capacity in the nth year, MWe
K_{n-1} is the installed nuclear capacity in the preceeding year, MWe

Once this has been established, an approximation to the permissible LWR-FBR "mix" of the incremental capacity is made from the balance of the previous year's plutonium reserve and the total (in-core and ex-core) specific inventory of the breeder. If the date of fast breeder introduction has not yet been reached, all of the new addition is considered to be light water reactor. However, some specific fast reactor capacity may be specified before being economically justified to simulate the commissioning of demonstration plants.

All additions to fast reactor capacity are rounded to the next lowest 1000 MWe so as to assure a positive residual plutonium balance. If the allowed increment of fast breeder reactor capacity is not as great as the added nuclear capacity in the particular year (I_n in Equation 6), the balance is added as LWR capacity. The following relation must always be satisfied however:

$$I_n = I_{F\,n} + I_{L\,n}^{*} \qquad (7)$$

where: $I_{F\,n}$ is the incremental FBR capacity in the nth year, MWe
$I_{L\,n}$ is the incremental LWR capacity in the nth year, MWe

Determination of Plutonium Requirements

Once the allowable mix has been determined, the plutonium supply and demand for that situation is calculated. These are obtained from the prior installed capacity of light water reactors ($K_{L\,n-1}$) and fast breeder reactors ($K_{F\,n-1}$) and the quantities of plutonium produced and required by each reactor type. These parameters are presented in the previous reactor descriptions. The production and supply are also influenced by fabrication and reprocessing losses which are considered fixed for the duration of a calculation though they are varied in subsequent calculations from 0% to 10 and 5%, respectively.

No material holdup time is considered; that is, plutonium is assumed to be immediately available for further use upon discharge from the reactors. This is a very generous approach since normally there would be some definite time

*Single capital subscripts are used hereafter to denote the reactor type associated with fuel cooling, processing, and fabrication. Other analyses of this type have considered holdup times of one year or greater [7]. The effect of no holdup time is that the availability of plutonium for fueling reactors is increased and thus this analysis represents the most optimistic expectation for the growth rate of fast breeder reactor capacity.

The net total of yearly plutonium production less the requirements, called the plutonium balance,

$$B'_n = B_{n-1} + L_R [K_{L_{n-1}} P_L + K_{F_{n-1}} P_F] \tag{8}$$
$$- L_F [R_L (K_{L_{n-1}} + I_{L_n}) + R_F (2/3\, K_{F_{n-1}} + I_{F_n})]$$

and $R_F = SI\ (1+X)$

$P_L = U\ H^a$

where: B'_n is the plutonium balance in the nth year, kg
B_{n-1} is the previous year's plutonium balance corrected for decay, kg
L_R is the reprocessing loss term, 1 - losses
L_F is the fabrication loss term, 1 + losses
P_L is the plutonium production in LWR, kg/MWe
P_F is the plutonium production in FBR, kg/MWe
R_L is the plutonium requirement in LWR, kg/MWe
R_F is the plutonium requirement in FBR, kg/MWe
SI is the in-core specific inventory, kg/MWe
X is the ex-core inventory fraction
U is the initial LWR uranium loading, kg
H is an expression giving plutonium production as a function of burnup, gPu/kgU initial

must always be positive. If the incremental breeder capacity initially chosen is so great as to result in a negative balance, a portion of the incremental FBR capacity must be substituted by light water reactors so as to achieve a positive plutonium balance. Similarly if the plutonium balance is greater than the total specific inventory, a larger fast breeder capacity could be supported. Finally, the plutonium balance must be corrected for use in the next period by accounting for the decay of the fissile plutonium fraction which is the short-lived 241 isotope.

$$B_n = [F + (1-F)\ e^{-\lambda\tau}]\ B_n' \qquad (9)$$

where: F is the ratio of ^{239}Pu/total fissile Pu
λ is the decay constant of ^{241}Pu, sec^{-1}
τ is the time in one year, sec

<u>Determination of Energy Costs</u>

The cost of producing the required amount of electrical power utilizing the above determined LWR-FBR mix must be ascertained. The costs, which vary in time, are based on the estimates of others [41, 42, 43]. Light water reactor capital cases ranging from $175/KWe to $250 KWe (in 1970 dollars) are considered. The LMFBR plants are assumed to suffer a 25% penalty over the light water reactors on both capital and operating expenses. Resulting capital costs are discussed in the next chapter. These agree fairly well with others that have been presented [44]. Future operating, maintenance, and insurance costs are also described in the next chapter.

The future fuel costs estimates, taken from the same above-mentioned reports, allow for changes in technology (fabrication, reprocessing, and cooling) at approximately five year intervals. The fuel costs have been broken down into two components. The first is calculated at zero plutonium price (no plutonium credit for light water reactor); a second term has been added to these costs to reveal the effect of the plutonium price variation.

$$C_{FC} = Z + bV \tag{10}$$

where: C_{FC} is the fuel cycle costs for each reactor type, mils/kWH

Z is the fuel cycle cost at zero Pu price, mils/kWH

V is the plutonium price, $/g

b is the rate of change of fuel costs with plutonium price

The resulting fuel cycle costs agree well with another analysis of fuel cycle cost variation due to changes in plutonium price [29]. All these costs are totaled to yield unit costs (mils/kWH) for each type of reactor.

$$C = C_C + C_O + C_I + C_{FC} \qquad (11)$$

where: C is the total unit costs for each reactor type, mils/kWH
C_C is the unit capital costs, mils/kWH
C_O is the unit operating and maintenance costs, mils/kWH
C_I is the unit insurance costs, mils/kWH

The annual costs per unit of electrical capacity, in dollars, for the two reactors are obtained from the product of the unit costs and the respective capacity factors (which could be time varying but have been taken as a constant 80% over plant life).

$$A = 0.001\, C\, \ell\, M \qquad (12)$$

where: A is the annual cost of generation, \$/kW-yr
ℓ is the load factor, %
M is the number of hours per year

Such an assumption has been shown to be valid for a single reactor over a thirty year lifetime [45] and, therefore, should certainly be reasonable when considering a large number of similar reactors in various stages of life. The annual nuclear generating costs (billions of dollars) are determined from products of the installed nuclear capacity for the year, the installed fraction of each reactor type, and its annual costs.

$$G = [K_{F_n} A_F + K_{L_n} A_L] \times 10^6 \tag{13}$$

where: G is the nuclear generating cost, $\$10^9$

Charges for plutonium inventory, determined from the plutonium balance, plutonium price, and prevailing discount rate, must be added to the annual nuclear generating costs. The total annual generating costs

$$T_n = [G + V\ B_n\ D] \frac{1}{(1+D)^n} \tag{14}$$

where: T_n is the total discounted nuclear generating cost in year n, $\$10^9$
D is the discount rate, %

are discounted to the year 1985 through the use of the present-worth factor (see page 21). The discounted nuclear generating costs are then added to the previous year's total to produce the cumulative nuclear generating costs to that year.

$$S_N = \sum_{i=1}^{N} T_i \tag{15}$$

where: S_N is the cumulative discounted generating costs, $\$10^9$
N is the full extent of the study, years

Determination of Economic Ideal

For the purpose of comparison, an "economic ideal" case is calculated. This is used as a base or reference for determining the additional costs of the realizable cases. The calculation of an ideal considers as the criteria for additions to nuclear capacity only the annual costs associated with each plant type. If the costs associated with the LWR for a given year (and plutonium price) are less than those for the FBR, all added capacity for that year is taken to be light water reactor. The converse is also true, of course. Additionally, if the year is after 1995 (30 years after the assumed start up of the first nuclear plant), the obsolete nuclear generating capacity is replaced with the most economical type of plant (not necessarily the same as the type replaced).

The economic generating capacity of the two reactor types are calculated along with their associated fraction of installed nuclear generating capacity. The economic annual nuclear generating costs are calculated similar to Equation 12.

The overall minimum generating costs for all plutonium prices, every reactor mix and each year are ascertained. These are accumulated as optimum economic nuclear generating costs for every year, O_n, similar to Equation 15. It is this economically determined minimum which is tabulated and used as the base for determining the added cost.

$$Y_N = S_N - O_N \tag{16}$$

where: Y_N is the added cost for the years in the study, $\$10^9$
S_N is the actual discounted generating cost, $\$10^9$
O_N is the optimum economic generating cost, $\$10^9$

The definition of economic optimum ignores the consequences of plutonium inventory. This always permits the imaginary construction of the most economic unit. For example, even if sufficient plutonium is not available, the breeder is always able to be added. Plutonium inventory charges need not be considered in the ideal economic case because the demand for plutonium would (nearly) equal its supply.

These charges (cf. Equation 14) may be ignored if: 1) The plutonium balance is very nearly zero; 2) The plutonium price is equal to zero; or 3) The discount rate equal to zero. While none of these options are realistic, it will be found that the inventory charges may effectively be minimized by approaching these limits.

For greater speed, a digital computer program, MIN-E-COST, has been formulated to perform the above series of calculations for the time period 1965 to 2010. It is known that in taking as the horizon a year which is too near there is a risk of making an error which can lead to economic losses. The choice of this horizon also corresponds to the degree of uncertainty in the future [46]. Another study [44] has shown that such an analysis is not greatly affected by end effects, provided the calculations range over 40 to 50 years.

The output of the MIN-E-COST program is displayed both in the form of tables and graphs of annual costs for the range of plutonium values desired. Most parameters affecting these results may be internally varied. The results of this program have been found to be in exact agreement with manual calculations utilizing the same parameters.

DISCUSSION OF VARIABLES AFFECTING MINIMUM GENERATING COSTS

The principal parameters affecting the minimization of nuclear generating costs can be considered to be either nuclear-related or not. The non-nuclear-related parameters, besides including such diverse technological elements as plant conversion efficiencies, plant load factors and siting, incorporate the economic variables associated with the light water reactor and fast breeder plants. These consist of such items as the capital cost of nuclear units, associated maintenance, the cost of raw materials and so forth.

The nuclear parameters govern the quantity of available plutonium and its possible uses. These subsequently limit the growth rate of fast breeder reactors. The costs of generating electricity will be substantially reduced if there is an established market for the plutonium produced. This market ultimately will be the plutonium-fueled breeders. The breeder generating costs, on the other hand, will decrease as a greater supply of plutonium becomes available for their use.

NUCLEAR PARAMETERS AFFECTING GENERATING COSTS

All of the nuclear variables that affect the generating costs are embodied in an assessment of the production of plutonium and its subsequent use. Some of the factors that directly influence the plutonium supply are the specific and ex-core inventories and plutonium production rates. Implicit in these values are atom densities and cross sections of each material averaged over the reactor energy spectrum, average neutron fluxes, and irradiation times. The requirements and production rates are considered in turn for the fast breeder and light water reactors.

Fast Breeder Reactor Plutonium Requirements

The plutonium requirements of a fast breeder reactor are determined by its design characteristics. These include items such as core geometry, desired fuel lifetime, maximum heat generation rate, and fuel properties. Since the combination of these is different for various reactor concepts, the resulting specific inventory (quantity of fuel required per unit of energy output) can differ over a wide range. Early 1000 MWe fast breeder designs have required from 1.79 to 5.77 ^{Kg}fiss/MWe [47] while later demonstration plants of lower output have narrowed this to the range 2.2 to 3.9 ^{Kg}fiss/MWe [48]. Along with this quantity of plutonium which resides in the reactor, a certain fraction of this amount is held up in the ex-core fuel cycle activities. This allows for cooling, reprocessing, fabrication, and shipment between each step. The magnitude of this fraction is governed by the amount of time required relative to that of the reactor residence time. Current estimates of ex-core time vary from just under a year [49] to as much as 1.5 years [50]. For a reactor with a 1.5 year fuel lifetime, this would correspond to an ex-core inventory of 0.6 to 1.0. It is expected that with future advances in reprocessing technology not so much time will be required for cooling, and the ex-core inventory may ultimately be reduced to 0.2 or 0.3. In the present work the ex-core inventory was considered to be 50% in the reference case but, in order to test for sensitivity, this parameter has been varied from 10% to 100%.

Fast Breeder Reactor Plutonium Production

The plutonium production in a fast breeder reactor is measured in terms of its breeding ratio and doubling time. The production rate is extremely dependent upon the amount of fuel exposure, generally decreasing with increasing burnup at the normally high burnups [52]. In this work the results of the Atomics International calculations (see Table IV) have been used to establish the rate of plutonium production. However, the approximate annual plutonium production of any breeder reactor can be estimated by

$$P_F = \frac{R_F(SDT) + SI_{TOT}}{SDT} \tag{17}$$

where: P_F is the annual plutonium production in the fast reactor, Kg/yr
R_F is the annual fast breeder reactor plutonium requirement, Kg/yr
SDT is the simple doubling time, yr
SI_{TOT} is the total initial specific inventory, Kg

Annual plutonium production from fast breeder reactors will be highly dependent on the breeder installed capacity which is in turn limited by the breeder growth rate. The fast breeder reactor plutonium demand and supply is shown in Figure 6 assuming all plutonium generated in light water reactors has been accumulated so that fast breeder reactors are installed at the most rapid possible rate after 1985, limited only by the plutonium available and the rate of addition to nuclear generating capacity. Consequently, these assumptions result in the upper limit of breeder reactor deployment and plutonium demand.

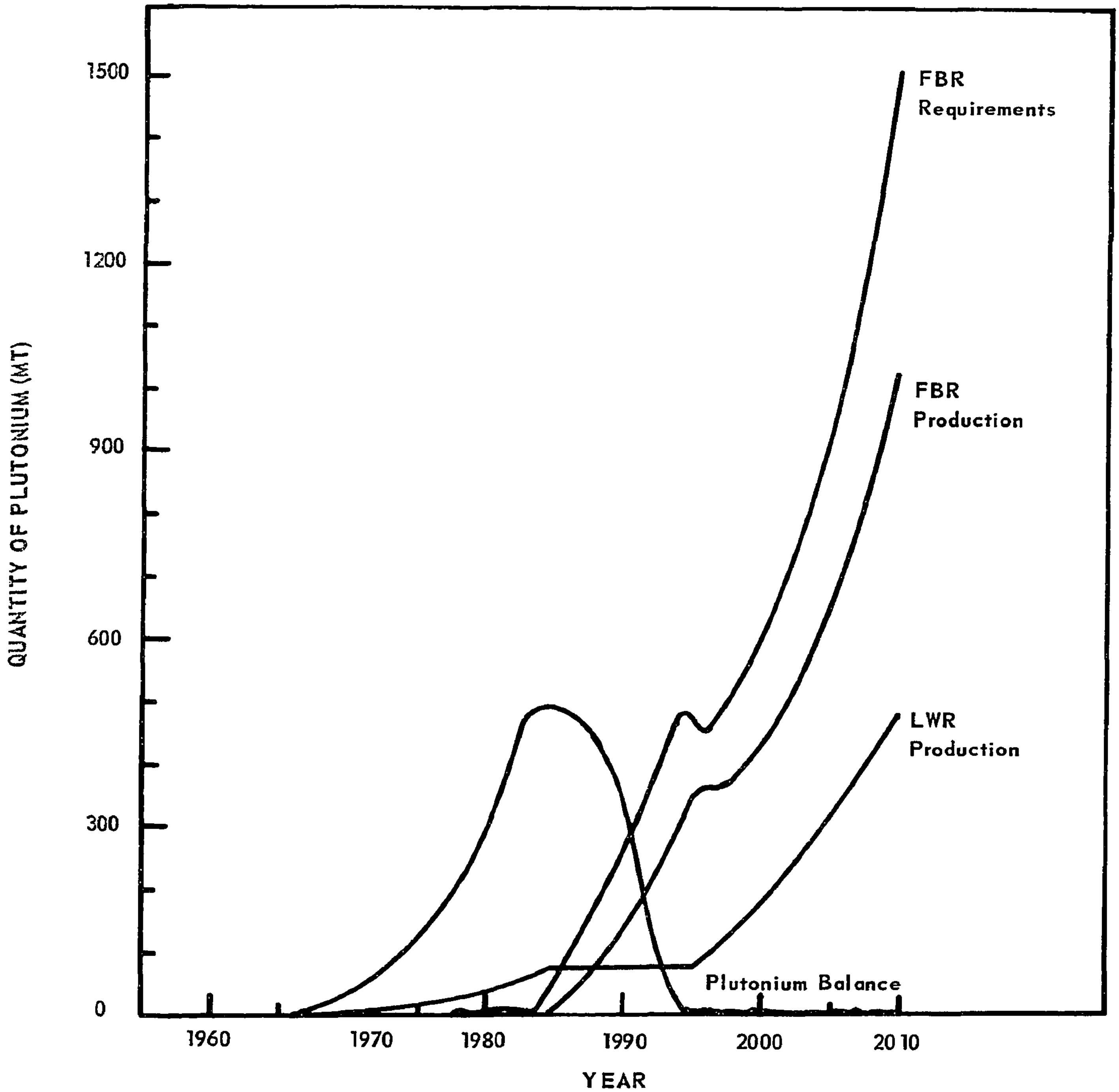

Figure 6: Annual Plutonium Production, Requirements, and Balance for Fastest Breeder Growth Rate Following 1985 Introduction

In lieu of sufficient plutonium production to sustain the desired rate of addition of fast breeder reactors, their start up on enriched uranium is a possibility. However, it has been found that due to the greater value of plutonium in a fast system, the reactor operator cannot afford to pay more than about 2/3 the value of plutonium for ^{235}U in competition with plutonium [53]. With the current cost of fully enriched uranium at about $12/g, due to the inherently expensive enrichment process, this practice no doubt will find limited application.

Light Water Reactor Plutonium Production

The production of plutonium in light water reactors is seen to increase with burnup (cf. Figure 4) at the level of present technology. The plutonium production rate (grams/MWe) appears to be slightly greater in a boiling water reactor than in a pressurized water reactor although this difference is not appreciable [54]. While the discharge fissile plutonium content per KgU charged is greater in a pressurized water reactor, the difference (per MWe) between the two reactor types results from the higher specific power of the PWR.

A comparison of the annual light water reactor plutonium production used in these calculations shows agreement with some results [55]. However, others [56] have estimated annual production figures less than the present ones. A reason for the discrepancy may be the fact that the reference burnup is higher than what is presently being achieved [57]. The higher burnup should correspond more nearly to the future technology but to minimize these differences, the effect of burnups as low as 10,000 MWD/MTU have been considered. The LWR plutonium production is also shown in Figure 6.

Another effect of long burnups is that there is present in the fuel a greater fraction of the higher plutonium isotopes: 240, 241, and 242. Since these isotopes grow-in sequentially, there soon becomes an unfavorably high proportion of nonfissile isotopes [58]. This results in the plutonium being less desirable for use as fuel for a fast reactor and especially for recycle in a light water reactor since higher plutonium isotopes (with the exception of 241) act as neutron poisons. The variation in this quantity is represented by the values of 239/fissile Pu fractions that have been considered. These ranged from 0.80 to 0.94 typical of Pu generated in light water reactors to "commercially pure" or weapons grade material.

Light Water Reactor Plutonium Requirements

If plutonium is used for recycle in light water reactors, the amount of plutonium utilizied in this manner will be somewhat uncertain. The reason for this is that up to about one-third of the fissile uranium in the reactor core can be replaced by plutonium while the reactor still retains the physics properties of an enriched uranium core having about 20,000 MWD/MTU fuel exposure [59]. However, a greater fraction of the fissile content could be plutonium, and studies have been performed in which the entire uranium enrichment has been replaced with plutonium [60]. One result of this was that plutonium could not be economically employed in equilibrium recycle if its price was in excess of $10 or $11/g. This is considerably higher than the breakeven price found in an earlier analysis. Here the ceiling price in some light water reactors was $8.50 for "commercially pure" plutonium, and $2.30/g for once recycled material [61]. These factors all contribute to the uncertainty of the degree of employment of recycle and the quantity of plutonium demanded for it.

As an outer limit, the generating costs have been calculated assuming all plutonium that is produced is burned in light water reactors. The other limiting case, the accumulation of all plutonium produced in light water reactors, has already been considered above.

Plutonium Value

> When the well's dry they know the Worth of Water.
>
> B. Franklin
> Poor Richard's Almanack (1758)

The importance of the value of plutonium to the light water reactor fuel cycle has been frequently noted [62, 63]. Formerly the U. S. Atomic Energy Commission had agreed to purchase all the plutonium anyone could produce at a fixed "buy back price" of $9.28/g. However, now the AEC purchase agreement has expired, and the price of plutonium is expected to adjust to a nearly-free market level. The only controls still imposed by the AEC are ceilings on the quantities that may be sold and to whom [64].

A light water reactor can be viewed as producing joint products - electrical energy and plutonium. It is recognized that a relation exists between the market price of one joint product and the supply price of the other joint product. The supply price of a quantity of electrical energy is the total costs of generation for that quantity of electricity minus the demand price of the quantity of plutonium consistent with the quantity of electrical power generated. When the AEC "buy back price" was in effect, the supply price of electrical power could be reduced $9.28 for each gram of plutonium produced at every level of power generation.

The revenue from plutonium is directly proportional to the plutonium price and so the LWR fuel cycle costs decrease with increasing plutonium price. At the AEC's fixed market price, the plutonium produced during irradiation can mean a reduction of 0.15 to 0.20 mils/KWH or approximately 10% of the light water reactor fuel cycle costs. Now, without the AEC purchase agreement, the relation is far more complicated in that the plutonium price is a market-determined price. The basic relation still holds that in a light water reactor there will exist an inverse relation between the market price of plutonium and the supply price of the electrical energy generated.

The situation in a fast breeder reactor is somewhat different. Unless the breeder has an exceptionally high breeding ratio ($\gtrsim 1.6$), the fast reactor fuel cycle costs increase with increasing plutonium price [29]. This is primarily due to the inventory charges on the amount of capital that is tied-up in the reactor inventory and in the ex-core activities. This charge component also increases with burnup and fuel lifetime. Based on the same plutonium price mentioned above, the fast breeder reactor inventory charges (0.5 to 0.6 mils/KWH) can be from 60% to over 100% of the net fuel cycle costs while at the same time the aggregate plutonium credit will be from 30% to 70% of the net fuel cycle costs [65].

Numerous studies have been performed to determine how the value of plutonium might fluctuate for different reactors at different points in time [5, 9, 10]. The usual approach is to calculate the "indifference value" of the fuel to that of enriched uranium in the given reactor [66]. Fuel cycle costs for the reactor employing both fuels are plotted against the fuel value. The point at which the two curves intersect is the point of indifference, and the fuel value corresponding to this is the "indifference value" of the fuel. This means the same fuel costs result whether the reactor is fueled with uranium or plutonium. Such "shadow-pricing" methods yield a value for plutonium from 80% that of fully enriched uranium in a light water reactor, to 1.5 to 2.5 times the uranium price in a fast reactor. What must not be forgotten regarding the results of this type of analysis are: 1) That the comparison is one based on comparative neutronic properties alone; 2) That the value is not a function of the inherent energy residing in the fuel; and 3) That the indifference value is the maximum market price which the fuel can assume for that reactor in competition with enriched uranium.

The major problem intrinsic in this type of value analysis is that plutonium may have one value in a fast reactor and an entirely different value in a thermal reactor. These represent only "reference" values for those respective reactor types. The market value may be quite different from these [67].

The British viewpoint on indifference values is advanced by Iliffe:

> "For any nuclear power system which is large enough to be self-sufficient in plutonium . . . generating costs based on the assignment of a fixed value of plutonium are wellnigh meaningless. Nevertheless, generating costs

> determined in this way still appear to be fairly popular and may well be responsible for a widely held view that the cost of nuclear power depends, amongst other things, on the value of plutonium. But insofar as plutonium is a by-product of nuclear power for re-use with it, it would appear to be the value of plutonium that depends on the cost of nuclear power and not the other way about. In any event, a significant nuclear power programme would be dealing in several tonnes of plutonium a year and it would seem imprudent in this case to base a national power policy on the assumed existence of predictable markets for such quantities of plutonium well into the future. Again, the use of indifference curves is so hedged with restrictions that it can yield little information of practical value." [68]

From the viewpoint of economics, a fast breeder reactor is an electrical generating plant which requires a greater capital investment but has lower annual expenses (due to lower fuel costs) than a light water reactor. It has been stated that in this context the value of plutonium is that which makes the annual fixed charges on the plutonium investment the same as the alternative annual costs that are avoided through the use of plutonium [69]. The only result of such a solution is to have the annual costs by either method identical. In this condition there appears to be no advantage to either method of generation, especially not where there is a predominence of one type plant over another. It would seem that the preferred value for plutonium in such a case would be that which would amplify any differences.

The possibility of using a dual value concept has been proposed in which marginal power costs would be equated to marginal plutonium costs. A marginal value of plutonium results from the additional expenditure occasioned by the withdrawal of a unit of plutonium during one year and its re-introduction at the start of the next. The economic effect entailed by this withdrawal is the price of plutonium in that year. This method is said to be definitive and not for one year only. Hence, it is suggested that there is an optimum combination of thermal and fast reactors making it possible to minimize the total expenditure apart from plutonium [70].

The results of a number of different analyses of the future value of plutonium is shown in Figure 7. (One forecast has been divided into three regions in which there is either transient plutonium stocks, zero plutonium stocks or inevitably rising plutonium stocks [71].) One point on which almost everyone seems to be agreed is that in the long term, when there are a large number of breeder reactors producing great quantities of plutonium so that the supply overcomes the demand, the price will decline. The degree of price decline due to oversupply is not consistent, however. It is expected that during a period such as this, the excess plutonium could be burned in light water reactors. It is evident that any successful prediction of plutonium value must be based on supply and demand.

What is needed, and what will be the more realistic case, is the worth of plutonium in a mixed reactor economy as a function of time. Such a market price, besides including the effect of a higher neutronic value in a fast reactor, will take into account the increased fabrication charges that must be paid for remote handling. This is required by the greater degree of radioactivity and toxicity of plutonium than that of uranium. In an attempt to identify the correct market price, plutonium prices from $0 to $30/g have been examined to identify the importance of this variable with regards to: 1) total discounted energy costs; 2) its effect on the fast breeder introduction date; and 3) the effect on breeder growth rate.

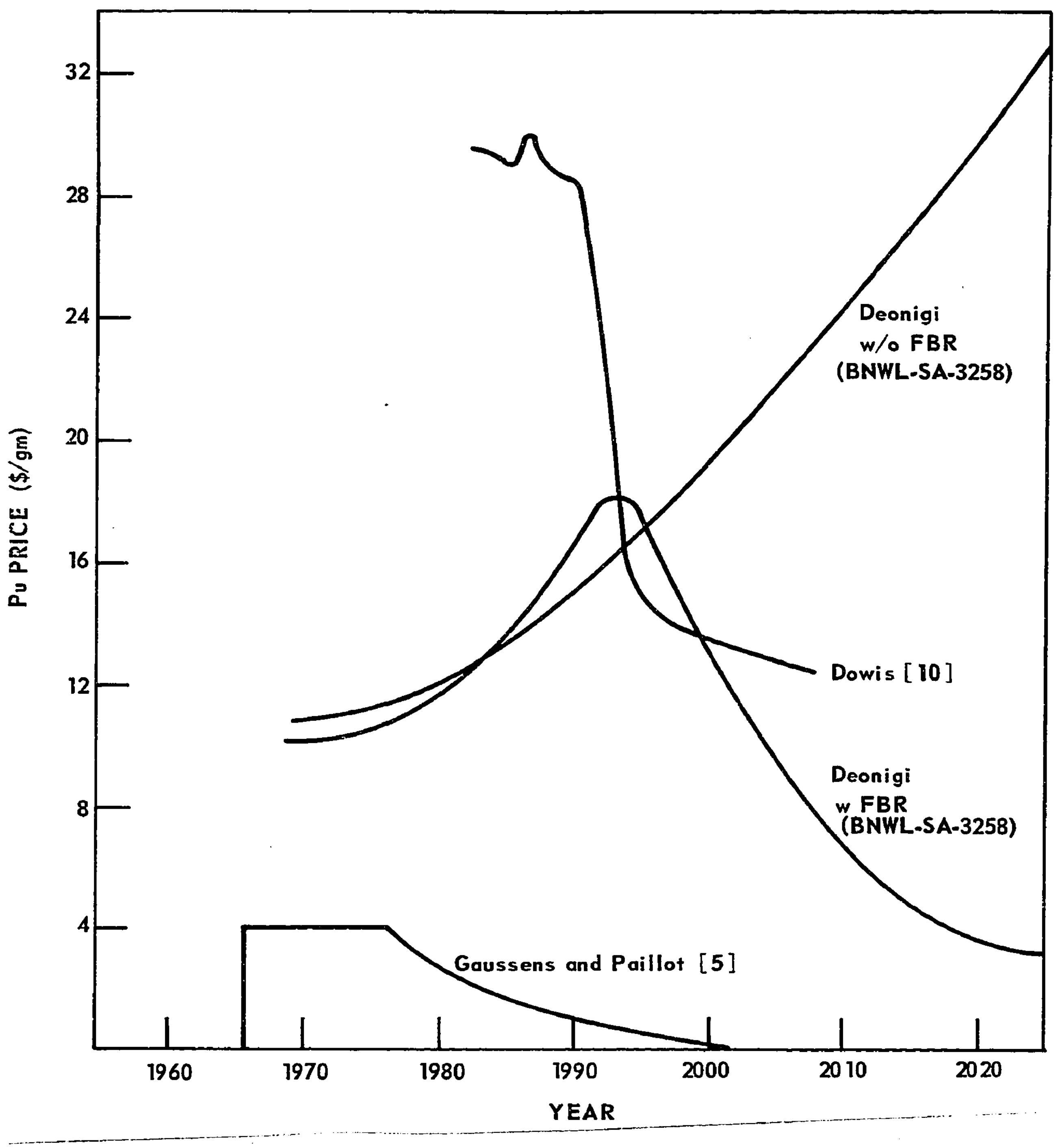

Figure 7: Contradistinctive Prognoses of Future Plutonium Worth

NON-NUCLEAR FACTORS AFFECTING NUCLEAR GENERATING COSTS

There are myriad non-nuclear parameters which can affect the unit generating costs. The plant conversion efficiency and load factors both have the potential to greatly increase or reduce the generating costs. While the former is generally constant over the life of the plant, the latter is found to vary considerably due to plant start-up problems early in life and obsolescence in later life. The absolute plant costs ($/KWe) can be significantly influenced by plant rating and plant site. Although these factors would not substantially affect the differential dollars per kilowatt between the two plants [72], they do have a large effect on the differential generating costs as the fixed charges are a greater fraction of fast breeder reactor generating costs than of light water reactor costs. Decreases in economic life also adversely affect the generating costs. However, the use of present-worth accounting tends to minimize this as the unrealized future revenues would be those having very low present-worth factors. Thus the non-nuclear technological factors will be considered as fixed. The economic factors, which cannot be considered to be constant, must be commented upon.

Capital Costs

Although it is extremely difficult to project the future costs of large components, there have been a number of attempts to do so [41, 42, 43, 73]. These generally commence with the present capital costs and assume some sort of "learning curve" decrease to represent savings which will be wrought through standardization and increased production. In the manufacturing industry the trend in standardization and experience gained has generally followed a 90% learning curve, i.e., each time the number of manufactured units is doubled, the unit costs are reduced by 10% [74]. Extrapolation of capital costs based on learning curves can be risky and is perhaps naive. Based on events of the past few years, a strong argument could be made for assuming no cost reduction due to learning at all [75].

Another potential source for reduction of these costs is the increase in unit size which yields some savings. This reduction is not being considered here as the units are assumed to be constant in size for all time.

The resulting projections of the capital costs are shown in Figure 8. These capital costs are presented in constant dollars, i.e., no allowance has been made for inflation. Four different initial capital costs were chosen for the present day light water reactor costs. These cover the range of $175/KWe to $250/KWe representing the scatter in costs currently being quoted [76]. The current trend is toward the higher costs. Historically, there has been an inherent lower bias in the estimated capital costs of plants which have not yet been built. Further problem areas, which often require large capital expenditures, are either not anticipated or are minimized [77]. For this reason, an additional 25% has been added to the costs of the light water plants to obtain the costs for the fast breeder reactors. Conversion of capital costs from $/KWe to mils/KWH was made on the basis of 14% fixed charges and 80% load factor yielding 0.02 $\frac{\text{mils/KWH}}{\text{\$/KWe}}$.

Operating, Maintenance, and Insurance Costs

Operating and maintenance charges are determined assuming a decrease in time based on experience similar to a learning curve. They are based on current data presented in WASH-1082 [78]. The variation with time is that given in

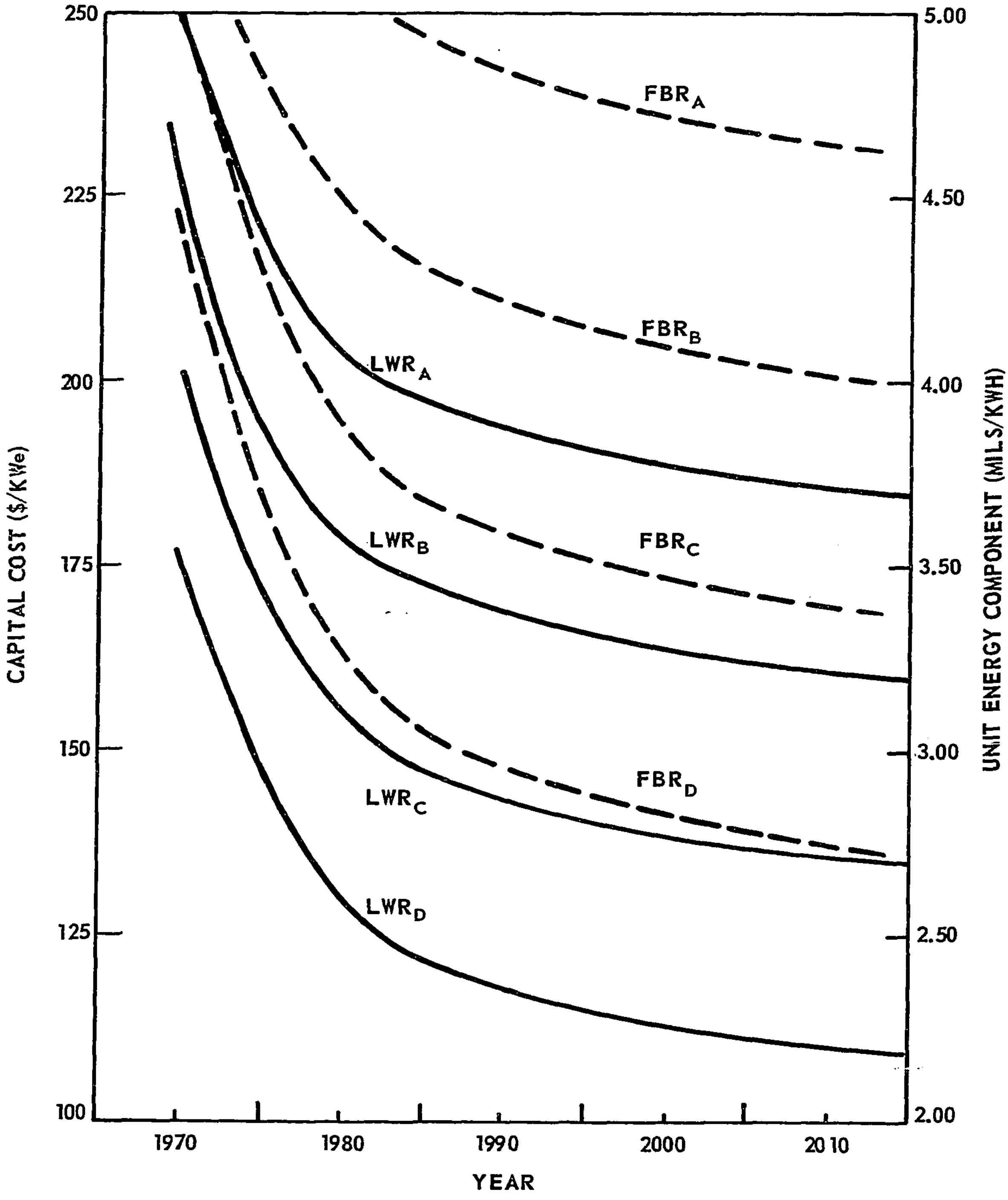

Figure 8: Potential Range of Future Capital Costs for Light Water and Fast Breeder Reactors

the 1962 Report to the President [79]. Again the same penalty is added to obtain the LMFBR operating and maintenance costs. The resulting charges are plotted in Figure 9.

Insurance costs include property insurance as well as nuclear liability insurance and government indemnity. Initial rates have been obtained from the former report [78] and are considered to reduce in the future based on good records, refunds, etc. When computing insurance costs, no penalty is assumed for LMFBRs. Figure 9 also shows the portion of the generating costs that are allotted to insurance.

Bases for Fuel Cycle Costs

The LMFBR fuel cycle technology is presumed to change at five year intervals as described in the Atomics International Follow-on Design [80]. The first five year period begins with the introduction of the LMFBR in 1985. Bases initially are: fabrication costs $225/KgH for core, $35-45 for blanket; reprocessing charges and shipping charges are $70/KgH and $20/KgH, respectively. All these charges reduce during the five year periods. U_3O_8 prices are assumed to be $8/lb and increase slightly while enrichment costs are $30/unit of

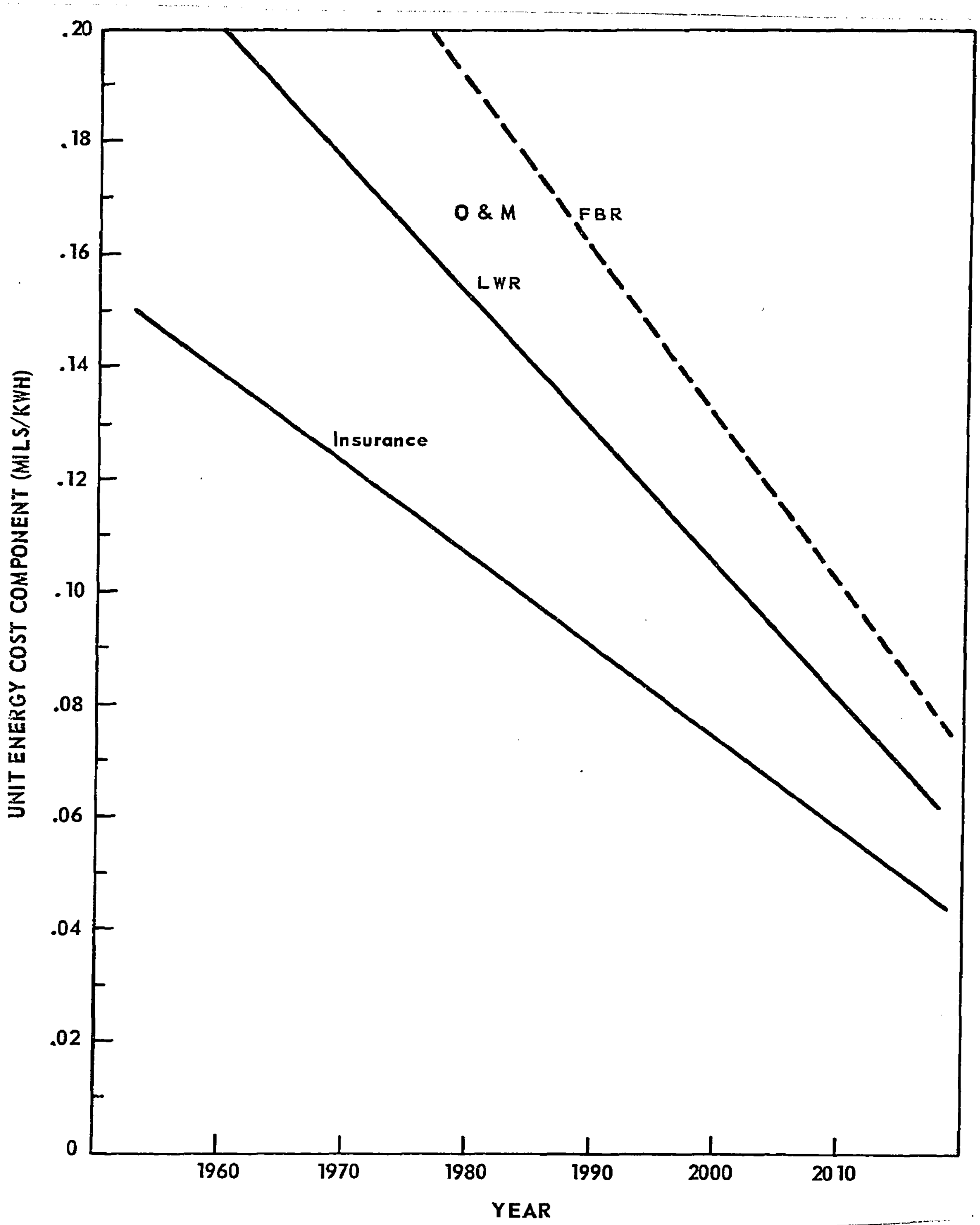

Figure 9: Estimated Future Operating, Maintenance, and Insurance Costs for Light Water and Fast Breeder Reactors

separative work and conversion charges amount to \$2.20/Kg. The latter charges are assumed to remain constant. Future increases in any of these values (like the recent rise in separative work charges) will result in the plutonium market price rising comparably.

Light water reactor fuel technology is also presumed to be time-varying in the same manner as that of the LMFBR. Estimates of this were obtained from the AEC report on the Future Potential of Light Water Reactor Plants (WASH-1082) [81]. Fabrication costs for uranium fuel are considerably less than for plutonium fuel and at the inception of these estimates (1970), the price is \$70/KgU.

Instead of assuming traditional 1% fabrication and reprocessing losses, these have been varied in subsequent calculations from 0% to 10 and 5%, respectively. Besides affecting the fuel cycle costs, these losses decrease the quantity of plutonium that is available for future uses. The total generating costs for the plants consist of the sum of the capital, operating, maintenance, insurance, and fuel cycle components. These costs for both the light water reactor and the fast breeder are shown in Figure 10 as a function of time. These costs have been determined

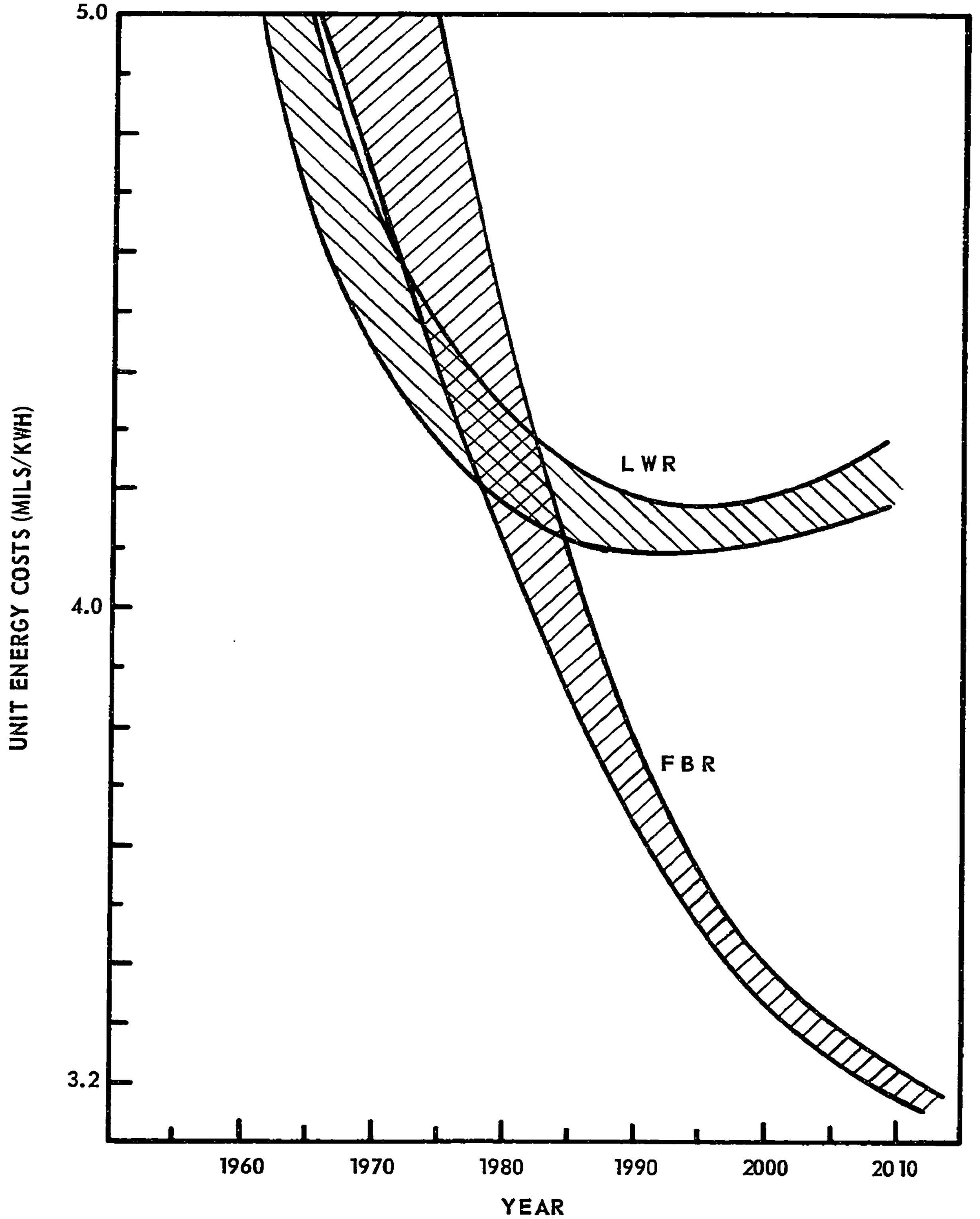

Figure 10: An Appraisal of Future Unit Energy Costs of Light Water and Fast Breeder Reactors at a Plutonium Price of $0/g

at zero plutonium price. Figure 11 shows the effect of plutonium price on the generating costs of each reactor.

Discount Rate

Around the mysteries of finance
We must perform a ritual dance
Because the long term interest rate
Determines any project's fate.
At four percent the case is clear;
At five some sneaking doubts appear;
At six it draws its final breath,
While seven percent is certain death.

Prof. Kenneth Boulding
University of Michigan

The economic optimum allocation of resources requires that capital resources be used in the manner providing the largest return, i.e., where the difference between benefits (revenues) and costs are the greatest. This necessitates the comparison of disparate items: dollars now versus dollars later. Such a comparison requires converting future dollars to current dollars through the process of discounting. (See footnote, page 21).

Almost all projects generally involve a series of annual costs and a flow of benefits over time. Calculation of the present value of costs and benefits through discounting gives consideration to the time periods in which benefits

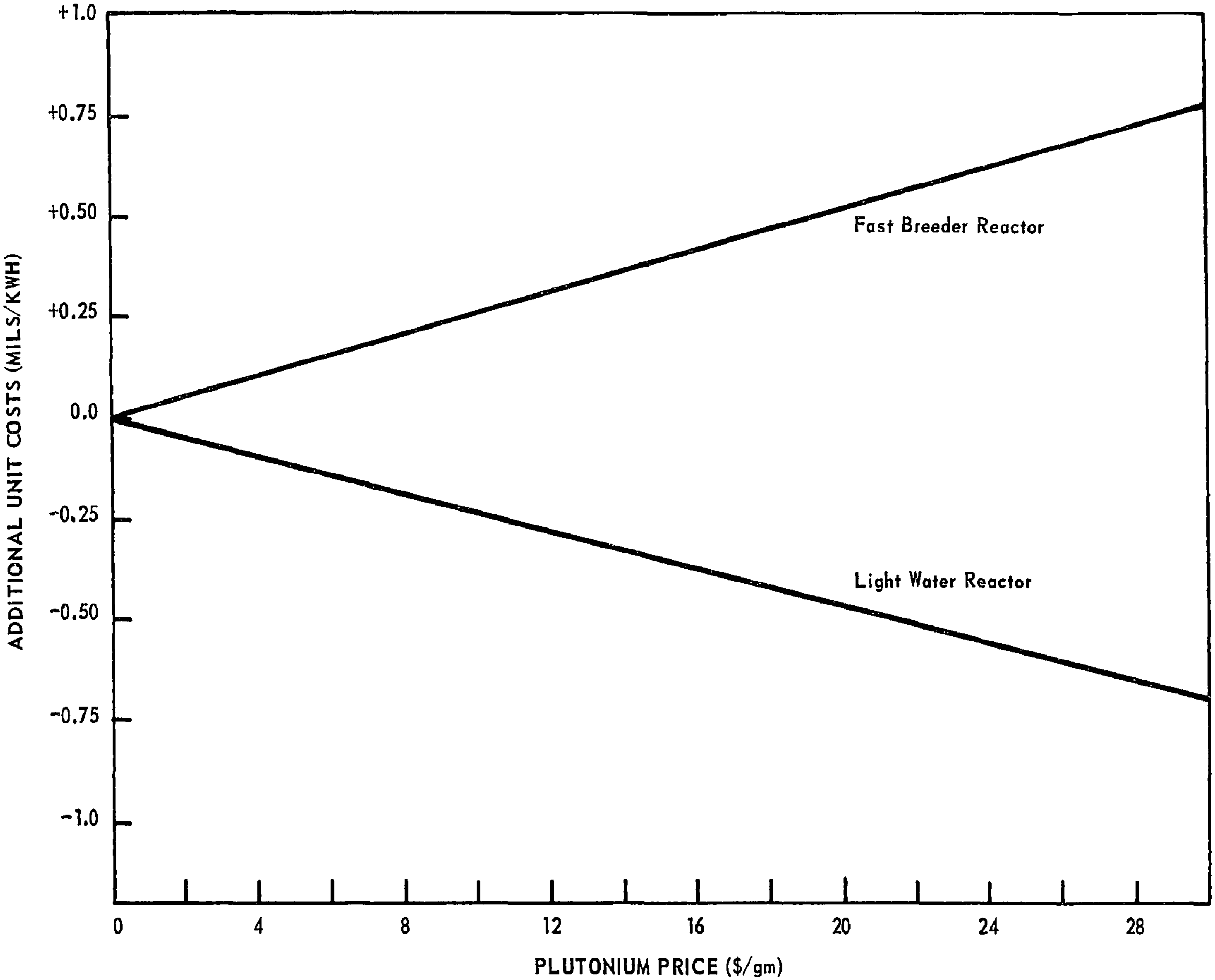

Figure 11: Variation in Light Water and Fast Breeder Reactor Fuel Cycle and Unit Energy Costs for Particular Plutonium Prices

will be realized and costs incurred and the time value of money. The present value of $100 in the future is shown in Figure 12 for various discount rates. At a low or zero interest rate, the present-worth of expenditures in the distant future is very nearly the current worth. At high interest rates, the present-worth of future undertakings is very small. This means that a project proposed at a high discount rate will have to show much higher future benefits than the same project at a lower rate of return. The selction of the discount rate is of particular importance in our problem since the discount rate has a large impact on benefits distant in time [82].

In private capital markets, investors do not choose investments to maximize the present value of expected returns alone, but to maximize the present value of returns with the risk factor adequately weighed. To do this, they employ either the time-preference discount rate or the opportunity cost rate. Time preference assigns current values to future consumption and need not take the form of a constant discount rate [83]. Opportunity cost is a measure of the value to the investor of the next best alternative to which his capital might have been put.

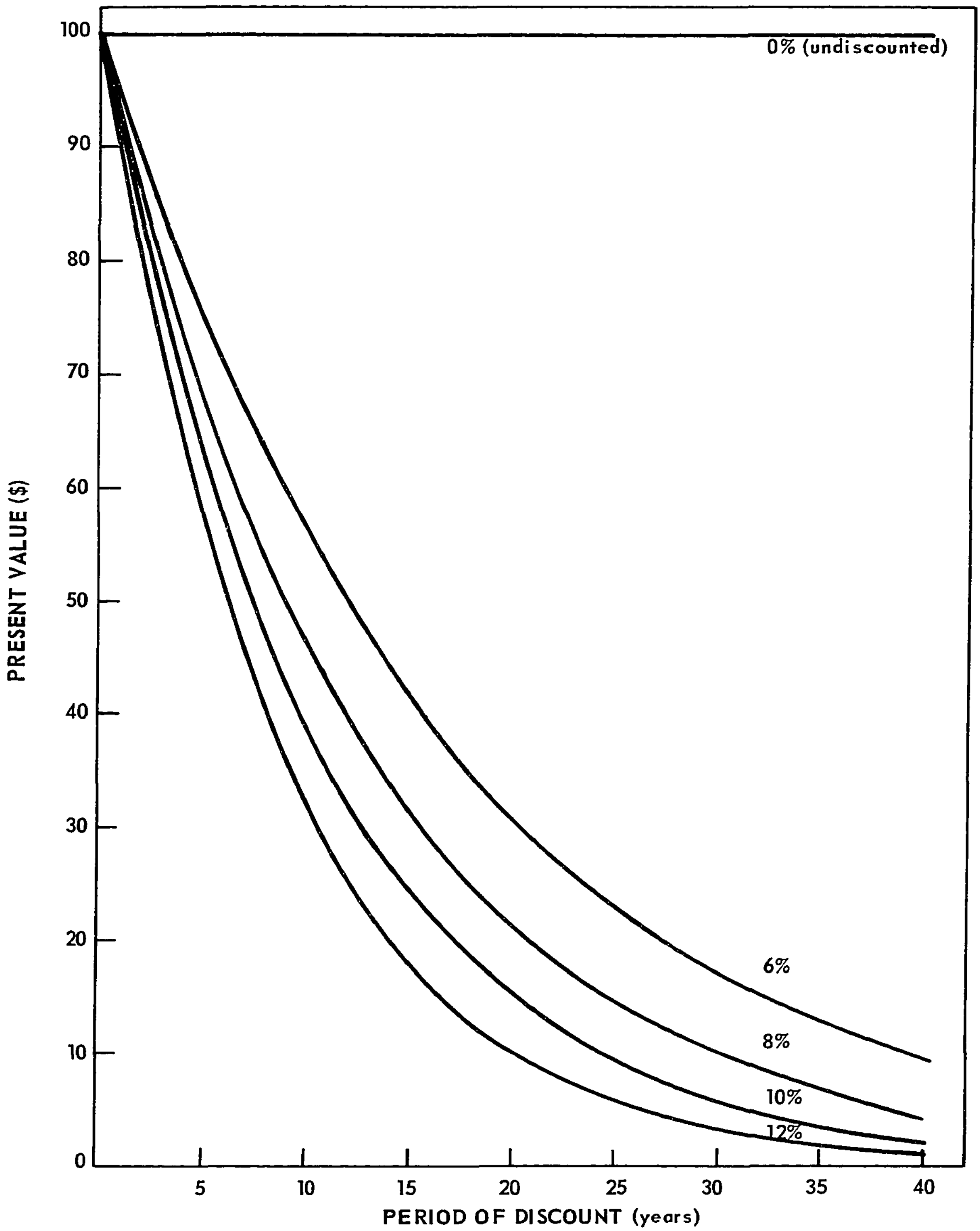

Figure 12: Dependence of the Present Value of $100 on Discount Rate for Years in the Future

There are three basic problems in identifying the social discount rate with the market rate. These are first a divergence between private values and market behavior because of capital market imperfections; second, a divergence between social (public) values and private costs in the products of government investment activity; and third, the divergence between social and private values with regard to perspectives for the future [84].

The argument in favor of this last is simply that when the marginal social discount rate (or rate to achieve benefits that will accure to future generations) is lower than the market rate then it is the obligation of the community in its collective political capacity to properly see to it that investment opportunities with future returns too low to justify private exploitation without the intervention of the state are, in fact, undertaken [85]. In the public sector paralleling the two types of discount rates being used in the private sector are social time preference and social opportunity cost. Under social time preference, public investments provide benefits for future generations, and it is unlikely that the current cost of capital provides the correct interest rate for evaluating public investments. Thus it is contended that current interest rates do not permit future generations to express their preference, and that the government ought to adjust their current rate downward to assure these necessary projects. In perfect capital markets, however, since investments are discounted in both time and risk, the discount rate obtained in these markets should be used to evaluate public investments. Thus a single discount rate should be used, whether a project is private or public, in making efficiency calculations for any given state-pattern of returns. When the recommendation is made to employ for government investments the private market discount rate for "comparable" projects, it must be understood that "comparable" projects are those having the same proportionate time-state distribution of returns [86].

It is acknowledged that the social time preference rate would probably be the best discount rate in a perfectly competative, perfectly functioning market economy. Since the actual market economy that is envisioned here is somewhat less than perfect, it is necessary to identify what other actual investments or consumption are foregone, and what their return would have been [87].

Another school of thought maintains that the overall cost of money in the public sector is the composite rate individuals and corporations in the private sector earn on their marginal incomes. Marginal incomes are defined as that part of society's total income that is foregone in paying the last increment of federal income taxes. This composite rate, called the opportunity cost of money, is very difficult to compute and able economists arrive at different values [88]. However, nearly all of the computations made result in the opportunity rate being considerably higher than the government's cost of long-term borrowing [89].

The social opportunity cost is a measure of the value to society of the next best alternative use to which funds employed in the public project might otherwise have been put. The opportunity cost of consumers is at least equal to the rate they can receive on riskless Government bonds currently estimated to be about 5-1/2 percent. Judged by interest rates consumers are willing to pay, rather than forego current consumption, the opportunity cost of capital to consumers is considerably higher, ranging upwards from 7 percent. Thus perhaps the relevant interest rate for use in evaluating public investments should be in the range 8 to 10 percent [90].

The issue which must be resolved is whether it is appropriate to discount public investments in the same way as private investments. There are several positions on this issue. One is that risk should be discounted in the same way for public investments as for private investments. A second position is that government, being better able to cope with uncertainty than private investors, should ignore uncertainty and behave as if it were indifferent to risk. In support of this position, it is argued that the government invests in a greater number of diverse projects and is, therefore, able to pool risks to a much greater extent than private investors. A third viewpoint asserts that time and risk preference relevant for government action should be a constant for all projects, established as a matter of National Policy. The rate of discount and attitudes toward risk would be specified by the appropriate authorities, and the procedures for evaluation would incorporate these time and risk preferences [91].

As far as government financing is concerned, it has been suggested that an interest rate equal to the cost to the Federal Government of borrowing be employed. This concept has been explored, and it was estimated that including lost tax revenues and other adjustments the true cost of government borrowing, even at an apparent rate of 3.2 to 5%, was actually 7.6% [92]. In its role as an investor it was felt the government should make those worthwhile investments which private investors cannot undertake, fail to undertake, or undertake in insufficient quantity.

A U. S. Joint Congressional Subcommittee on Economy in the Government recommended that no public investment be deemed "economic" or "efficient" if it fails to yield overall benefits which are at least as great as those which the same resources would have produced if left in the private sector [93]. The reason for the study conducted by this Joint Committee was that the range of interest rates applied by government agencies extends from 0% to more than 20% [94]. The effect of this discrepancy is to bias the decision process in favor of projects using low or zero interest rates as against those using higher rates. By applying a standard discount rate to alternatives within a single program, the agency is in a better position to select the most economical alternative. The need for a common discount rate is especially important for deciding between many competing projects in diverse fields of endeavor.

As its conclusion, the Joint Subcommittee found that the appropriate discount rate to be utilized by the government for investing in the public sector was the opportunity cost of displaced private spending [95]. Thus the discount rate which should be employed by all large scale capital projects, public or private, is somewhere in the neighborhood of 10%. In order to incorporate this development into the present calculations, a reference rate of 10% has been used for discounting. A range of discount rates from 5% to 12% has also been considered so that the final results should be applicable to either private market discount or to the recommended social rate of discount.

RESULTS

Numerous interesting consequences arise out of performing the calculations described above. The discounted nuclear generating costs accumulated through the year 2010 in all of the cases considered ranged from a lower of $167 billion to a high of $425 billion. This study is primarily concerned with the determination of the effect of each variable on the cumulative discounted nuclear generating costs. However, it is also possible to predict from the same results the effect of these variables on the plutonium price to achieve equilvalent unit generating costs, the introduction date of fast breeder reactors, the achievable breeder growth rate, the peak fraction of breeder reactors, the ultimate fraction of breeders and the plutonium price as a function of time.

The fast breeder reactor introduction date is considered to be the year in which the unit energy costs of the breeder equal those of the light water reactor. At this time, it is considered to be economically feasible for their commercial introduction. The breeder growth rate that has been utilized here is the greatest rate technologically achievable, i.e., limited only by constraints such as plutonium availability. Such a breeder growth rate can result, for some cases, in breeder reactors being the only addition for a number of years. There are some obvious reasons why this may not be the most desirable alternative.

The breeder fraction is defined to be the fraction of installed breeder reactors to all installed nuclear capacity, not just the fraction of one year's nuclear addition that is breeder. The peak breeder fraction is the maximum fraction of total installed capacity which breeder reactors can achieve due to limitations from breeder deployment policy or plutonium availability. The ultimate fraction is that level of fast breeder activity that may be sustained indefinitely. These new concepts of peak and ultimate breeder fractions have been found to be useful criteria for measuring the effectiveness of different fast breeder reactor introduction and growth strategies.

The variables will be considered separately so that their effects may be isolated. The effect of different generating capacity estimates and the various capital cases is discussed first since they are the least able to be quantified and predicted with confidence. The estimate of capacity and relative capital costs have so great an effect that it is desirable to fix these for the duration of an analysis so that the effects of the other variables may be determined. Later when comparing the results of the other variables, the costs are normally shown for a single capacity estimate and capital case. The lowest cost is usually shown so that any differences will be more evident. It should be mentioned, however, that the trend in the results does hold true from one capital case to another although the differences are less pronounced at higher capital cases.

Effect of Nuclear Generating Capacity and Capital Case

The difference in nuclear generating capacity estimates has a nearly proportionate influence on the total amount of money expended in generating costs. The reason it does not have an exactly proportionate effect is that there is a difference in the time distribution of the expended costs which is affected by discounting. When the discounted costs are accumulated, they are not proportionate to capacity as seen in Figure 13. The extent of the nuclear generating capacity has little effect upon the plutonium price at which a breeder and light water reactor yield equivalent unit generating costs (see Table V) and, hence, on the breeder introduction date.

The installed nuclear generating capacity does have considerable effect on the ultimate fraction of fast breeder reactors that can be built. Figure 14 shows that for the same capital cost case in the two different generating capacity estimates, the fast breeder reactor maximum portion occurs at about the same fraction. However, as time proceeds in the lower estimate this fraction drops off to approximately 60% while in the higher estimate it is possible to maintain a fraction slightly greater than 68%. The difference is attributable entirely to the difference in installed capacity and thus the different absolute amount of plutonium that is available for use. About 8% difference in the two ultimate fractions corresponds to an installed fast breeder reactor capacity of some 120-150,000 MWe. If the higher capacity does materialize, it would mean that there would be sufficient

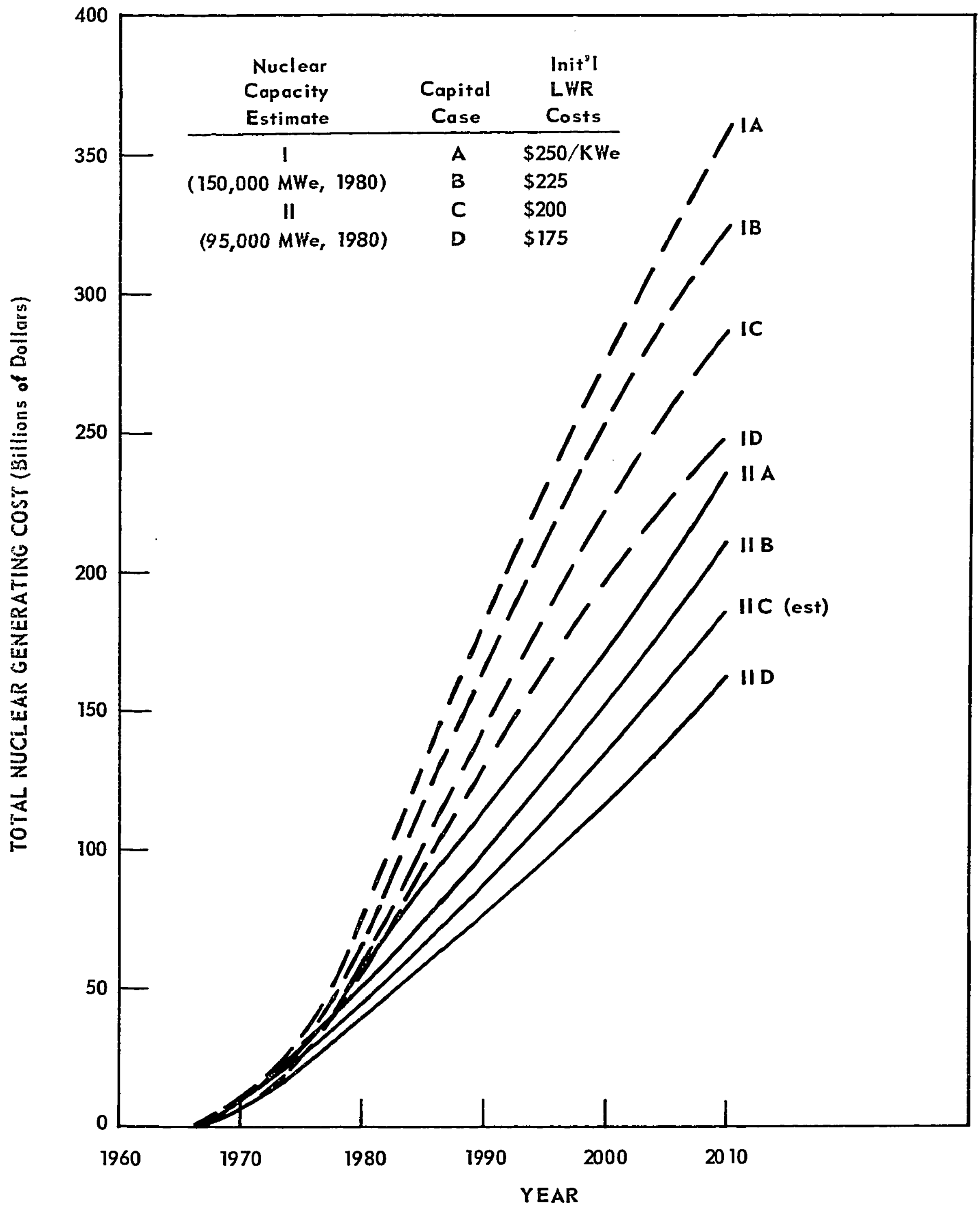

Figure 13: Cumulative Ideal Generating Costs in Future Years as Affected by Generating Capacity Estimates and Capital Case

TABLE V

CONDITIONS FOR COMPETITIVE LWR-FBR UNIT ENERGY COSTS

Nuclear Generating Capacity	Capital Case	Initial LWR Capital Cost* ($/KWe	Equivalence Achieved at Year for Pu = $10/g	Pu Price for 1985 ($/g)
I	A	250	2000	Not Economic
(150,000 MWe, 1980 500,000 MWe, 1990 1,100,000 MWe, 2000)	B	225	1998	2.00
	C	200	1996	4.50
	D	175	1990	7.00
II	A	250	2001	Not Economic
(45,000 MWe, 1980 270,000 MWe, 1990 734,000 MWe, 2000)	B	225	2000	2.00
	C	200	1996	4.50
	D	175	1991	7.00

*In all instances FBR capital costs = 1.25·(LWR capital costs)

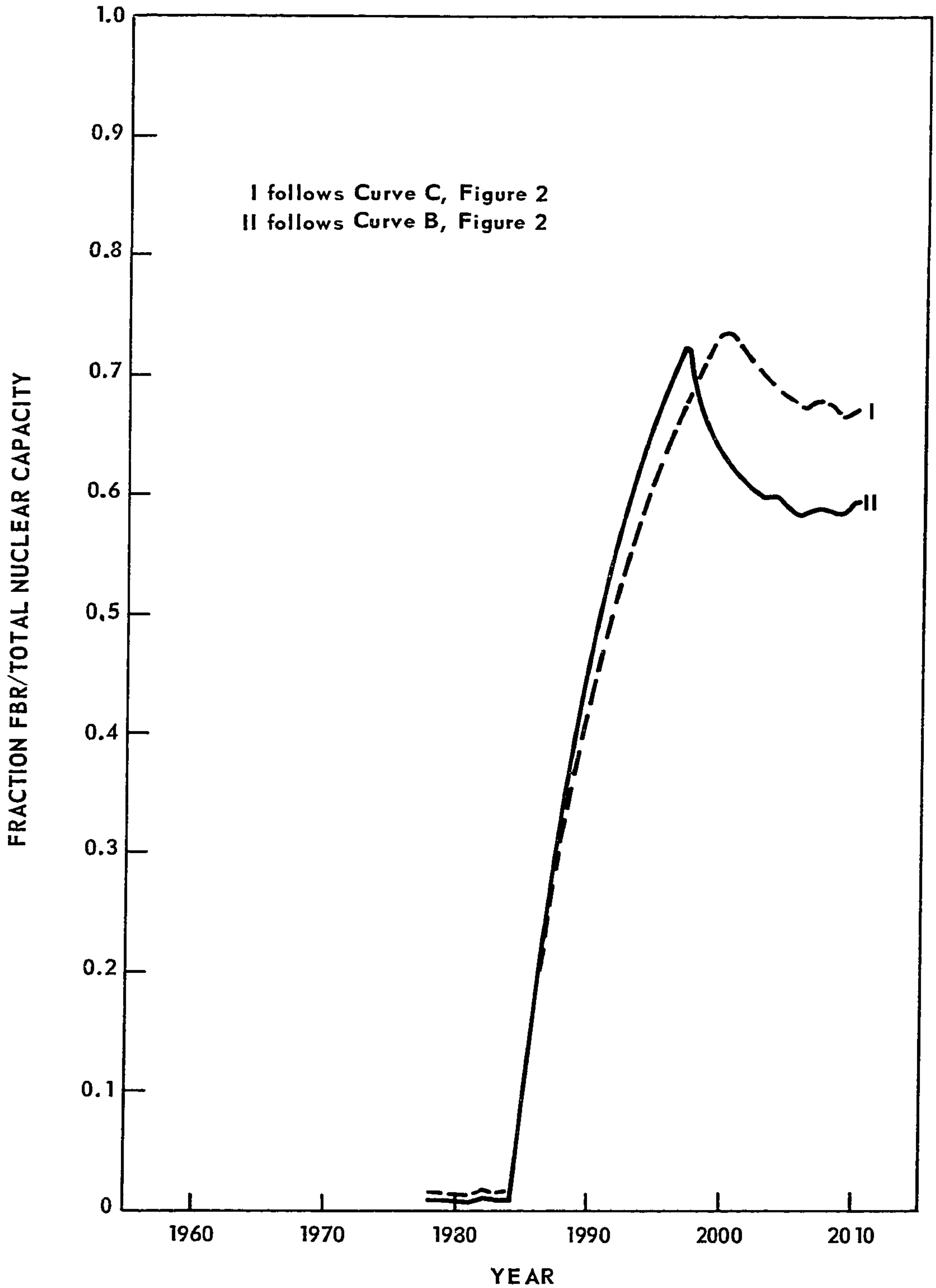

Figure 14: Largest Possible Fast Breeder Reactor Fraction Versus Time for Two Nuclear Capacity Estimates

additional plutonium to fuel more than one hundred fast breeder reactors of 1000 MWe capacity.

As might be expected, the magnitude of the capital costs has a considerable effect on the cumulative nuclear generating costs (see Figure 13). The higher capital costs result in greater accumulated generating costs; there being at any time a constant ratio between the two. Capital costs should not and do not affect the rate of growth of breeder reactors because of the way the model has been defined. However, since capital costs comprise a greater fraction of fast breeder reactor unit costs than in the case of the light water reactor, they bear heavily on the date of economic competition between the two reactor types for a given plutonium price (see Table V). Conversely, the plutonium price required to achieve equivalent unit energy costs in 1985 is widely diverse. A greater differential between light water reactor and fast breeder reactor capital costs will require a later introduction time or a lower plutonium price for 1985 introduction.

Thus, from a consideration of Table V it can be seen that in order to have breeders that will economically compete with light water reactors by 1985 or 1990 either: 1) The capital cost must be toward the lower portion of the range considered; or 2) The fast breeder reactor-light water reactor capital cost differential must be lower than considered; or 3) The plutonium price must be extremely low to offset the higher capital costs.

Effect of Plutonium Price

One of the most important variables affecting the total nuclear generating costs as well as the breeder introduction date and rate of growth is the price of plutonium. This is because the energy costs of light water reactors calculated according to present practices improve with increasing plutonium price (credit) while those of fast breeder reactors worsen*. Since the unit energy costs of the two plant types are greatly influenced by plutonium price, the annual generating costs can vary by as much as 25% depending upon the breeder fraction in that year and the plutonium price. A difference of this magnitude can

*In this analysis, the plutonium credit and charges have been included in the nuclear fuel cycle cost as is the practice in the nuclear industry.

amount to more than $10 billion in annual generating costs for some of the later years. Because of this great difference, the most economical reactor type should be as great a portion of the installed nuclear capacity as possible. Figure 15 shows such a variation for capital case C in the year 1985; the LWR-FBR break-even point can be noticed at a plutonium price of about $4.50/g (cf. Table V). This same pattern is found to apply for all other capital cases considered as well.

This figure also suggests that there is a "mix" of light water reactors and breeders which is insensitive to variations in the price of plutonium. Such a relationship has been found to occur in all capital cases for a fast breeder fraction of 47%. Furthermore for a given case, the fast breeder fraction yielding this insensitivity to plutonium price remains constant for the duration of the study. This suggests that the impact of varying plutonium prices can be minimized if the breeder fraction is kept adjusted to this value.

While the 47% fraction is the result of the parameters used in this model, the concept of a "mix" insensitive to plutonium price is valid for whatever type of reactors

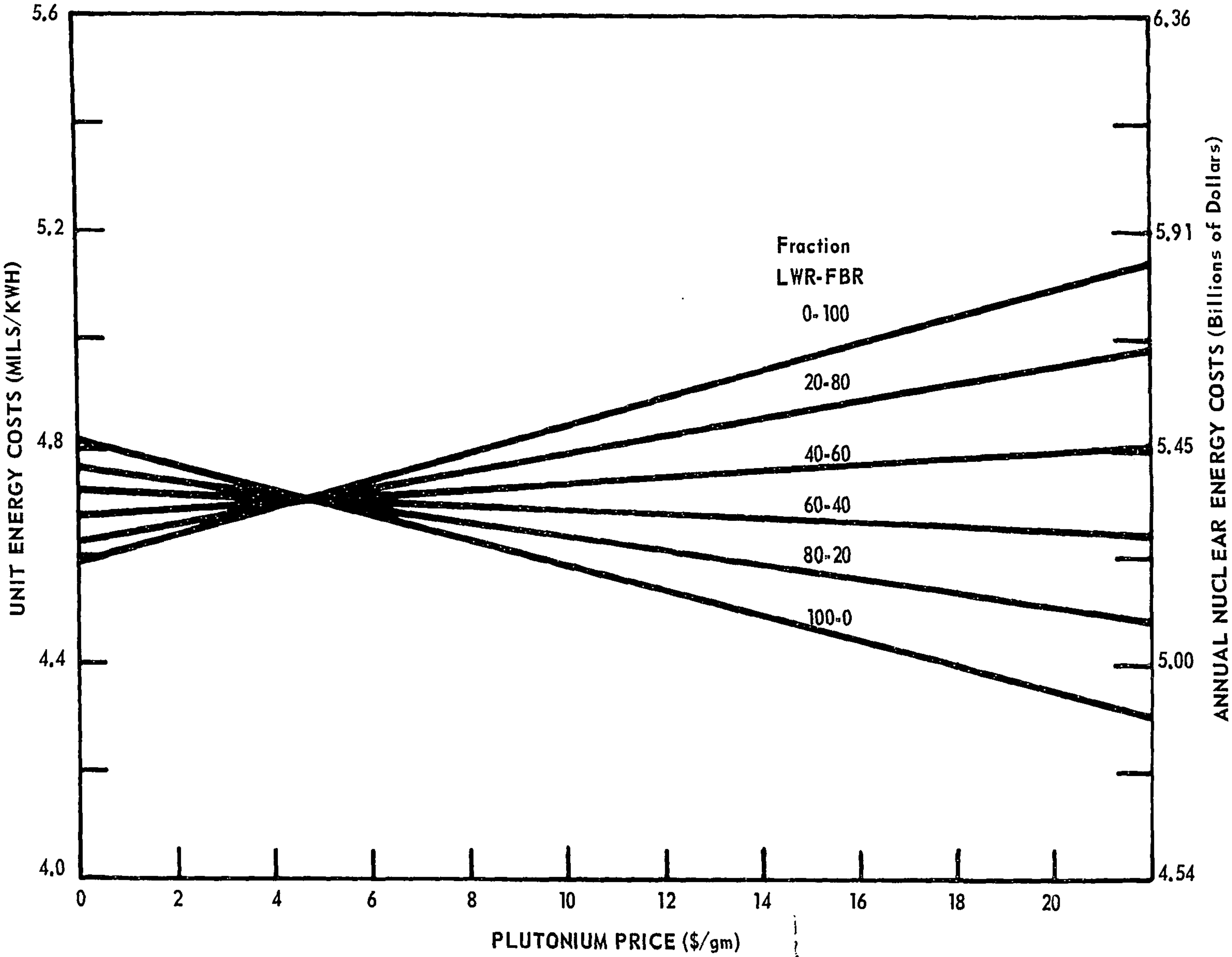

Figure 15: Unit Energy and Annual Generating Costs in the Year 1985 as a Function of Plutonium Price for Various LWR-FBR Mixes of Capital Case C

make up a system and whatever parametric values are used in the analysis.

Figure 16 indicates the earliest economic breeder introduction time and rate of growth as a function of plutonium price for the lowest capital case (II-D) where the conditions for breeder introduction are most favorable. All other capital cases result in later FBR competitiveness (cf. Table V) but similar trends in growth rate. Even this low capital cost case does not permit competitive breeders by the year 2010 for plutonium prices above \$21/g.

The effect of plutonium price on the four capital cases assuming the faster nuclear capacity growth is shown in Figure 17. This figure is a plot of the additional cumulative costs versus plutonium price. The increase in plutonium price from 0 to \$25/g alone adds as much as \$20 billion (discounted) through the year 2010 to the nuclear generating cost. This represents an increase well over ten percent of the total generating costs.

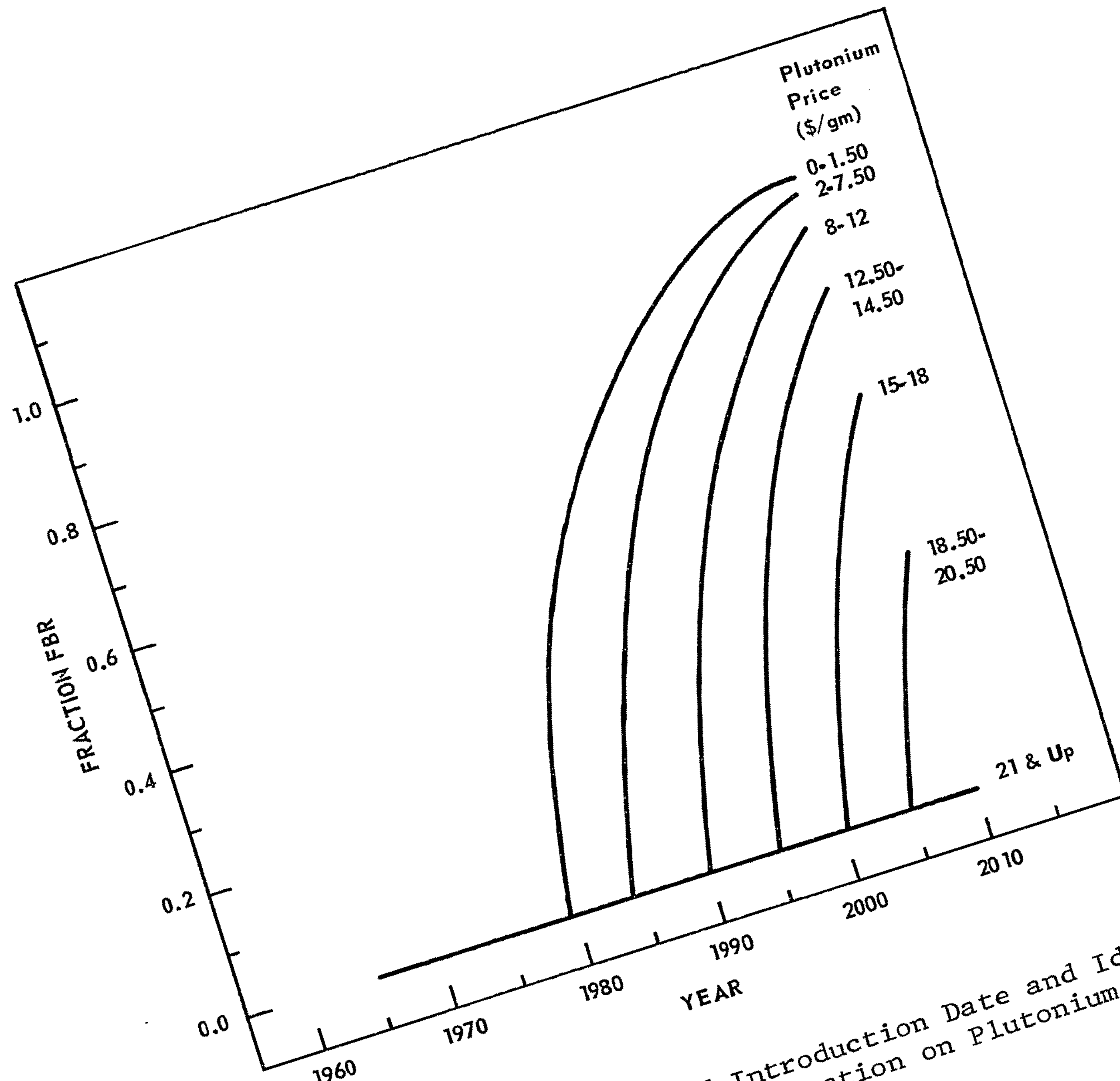

Figure 16: Dependence of Introduction Date and Ideal Breeder Reactor Fraction on Plutonium Price for Capital Case D

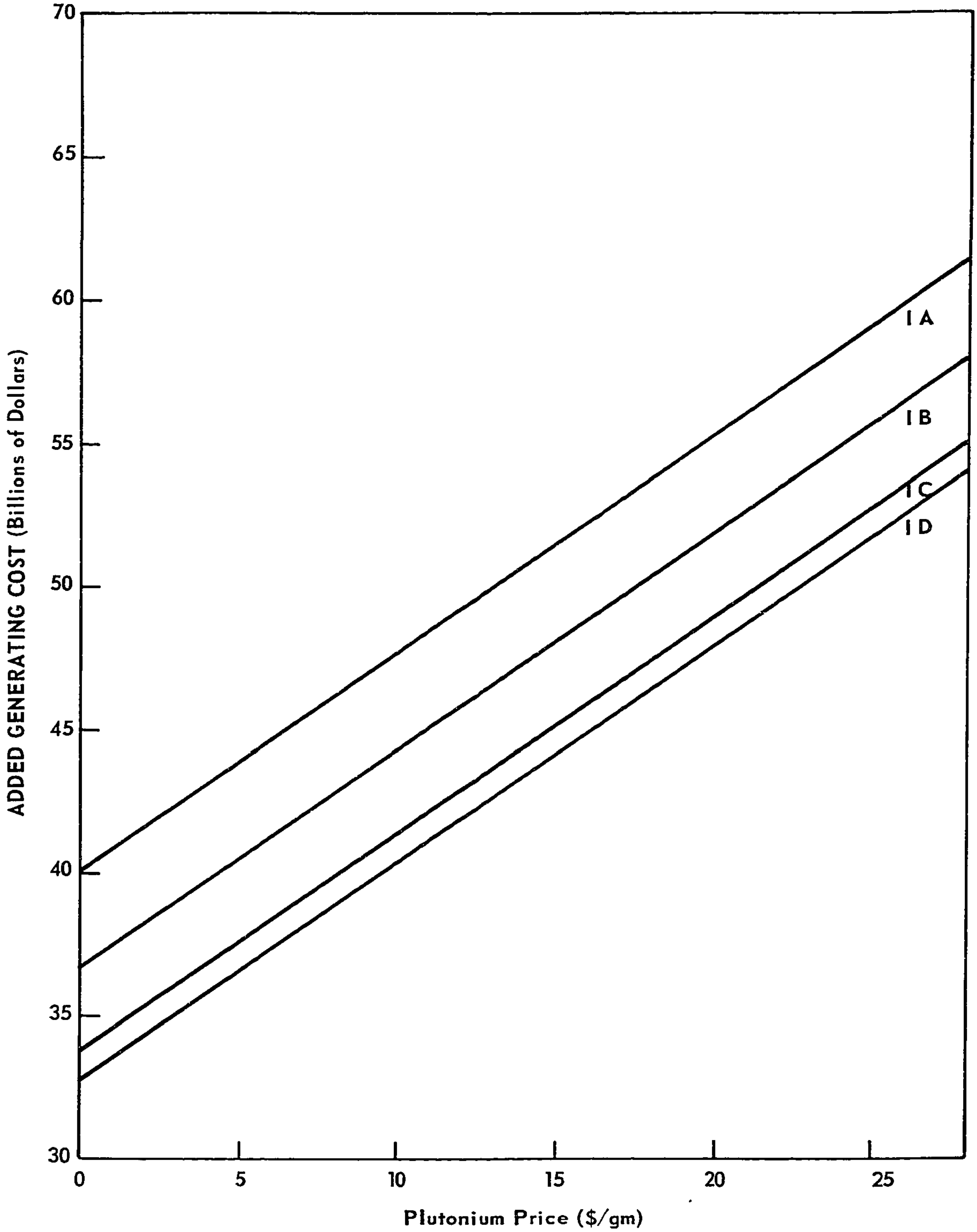

Figure 17: Added Nuclear Generating Costs (to the Year 2010) as a Function of Plutonium Price for the Various Capital Cases

Effect of Plutonium Utilization

The policy that has been pursued regarding plutonium utilization in light water reactors affects the cumulative generating cost, the breeder growth rate, and both peak and ultimate breeder fractions. The two extremes are to hoard all the plutonium that is generated in light water reactors for future use in fast breeder reactors or to burn all the plutonium recycling it in light water reactors as fast as it is produced. There are, of course, a variety of intermediate strategies which could be assumed such as recycling all plutonium except that produced perhaps five years before the breeder introduction date.

The economic consequences of the extreme plutonium recycle philosophies are demonstrated in Figure 18. Comparing curves 1 and 2 which are for the same plutonium price ($5/g) and discount rate (10%), the first shows the added generating costs associated with total recycle; the second with all plutonium being stockpiled for exclusive use in fast breeder reactors. It is seen that plutonium recycling pays dividends in the short term by reducing the added costs. However, if the comparison is continued for a longer period, the reverse situation is true by the

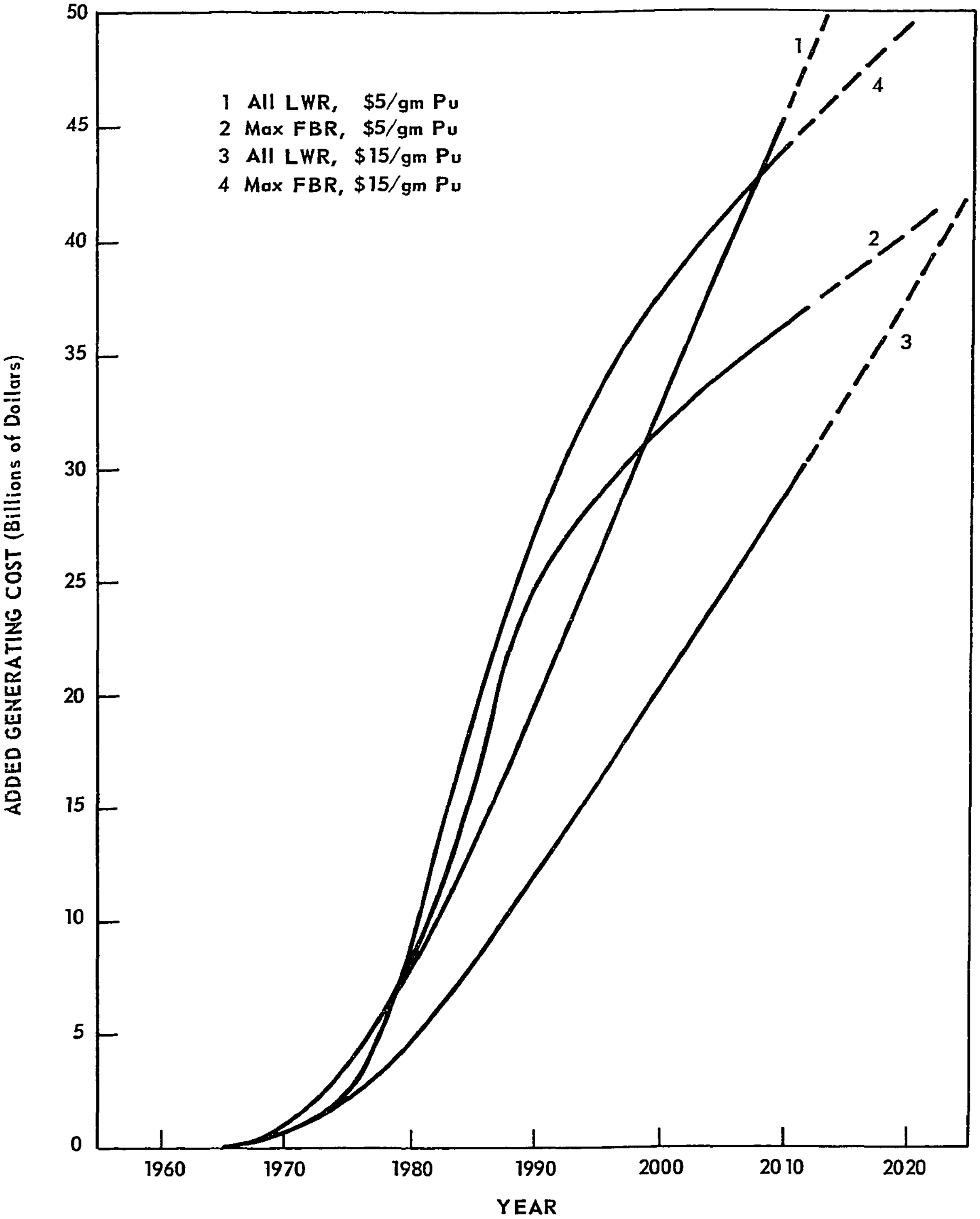

Figure 18: Added Nuclear Generating Costs (to the Year 2010) for Extreme Plutonium Utilization Schemes and Representative Plutonium Prices

year 2000. Thus, of the two extremes, saving plutonium for the total commitment to fast breeder reactors is found to be eventually less expensive even including the costs of plutonium inventory. Curves 3 and 4 show that the same trend still appears to hold true for a higher plutonium value ($15/g). Here, however, one must wait still longer for the investment to bear fruit.

This figure thus demonstrates the need for using a sufficiently long horizon in a study of this kind. Had the results been compared through 1995, for instance, a different conclusion would be arrived at.

While the economic results (discounted cumulative generating costs) are greatly dependent on the plutonium price along with the strategy of plutonium disposition, the maximum fast breeder reactor growth rate is controlled purely by the quantity of available plutonium rather than by economic factors.

The amount of plutonium that would be required in order for the breeder to be added at the fastest possible rate has been presented in Figure 6 (p. 55). It can be seen that, even in the case where all plutonium has been stockpiled, the rate of breeder addition must be sharply curtailed after about eight to ten years. Such limitations on plutonium supply severely limit both the peak and the ultimate fast breeder fraction. If the alternate strategy is pursued, there is no plutonium with which to fuel the fast breeder. Even with breeders being introduced at the fastest possible rate, more than thirty percent of the plutonium produced in the year 2010 is from light water reactors.

Since light water reactors must be built within ten years, it may not be desirable to install solely breeders following their introduction but to strike for a balance in addition between the two reactor types. This arrangement would reduce the total plutonium requirements of the fast breeder reactor and permit a greater amount of recycle in light water reactors.

The way in which plutonium is utilized will have an obvious impact on the variation of plutonium price with time. If there is a small supply of plutonium when breeders are introduced, the demand for plutonium will be great. This demand will force the plutonium market price as high as the breeder fuel cycle costs can tolerate.

Effects of Reactor Variables and Losses

There are three principal design parameters associated with a light water reactor that influence the generating costs and the breeder growth rate. These are the initial fuel enrichment; the degree of burnup and, consequently, the plutonium production; and the ratio of ^{239}Pu to fissile plutonium. The first two of these heavily influence the LWR fuel cycle cost and, hence, the unit energy costs. The last two primarily influence the quantity of available plutonium and, therefore, limit the breeder growth rate.

Since the light water reactor initial enrichment requirement, burnup, and plutonium production are all related, the effect of these can be considered together. The effect of variations in these parameters on the cumulative generating costs is shown in Figure 19. The principal detail which is immediately evident is the increase in generating costs with increasing plutonium price. The extent of these differences is not too appreciable, however, accounting for a variation of about $10 billion out of $40 billion added cost and $200 billion total. The variation of the costs with plutonium price indicates that although there is a great difference in the total plutonium

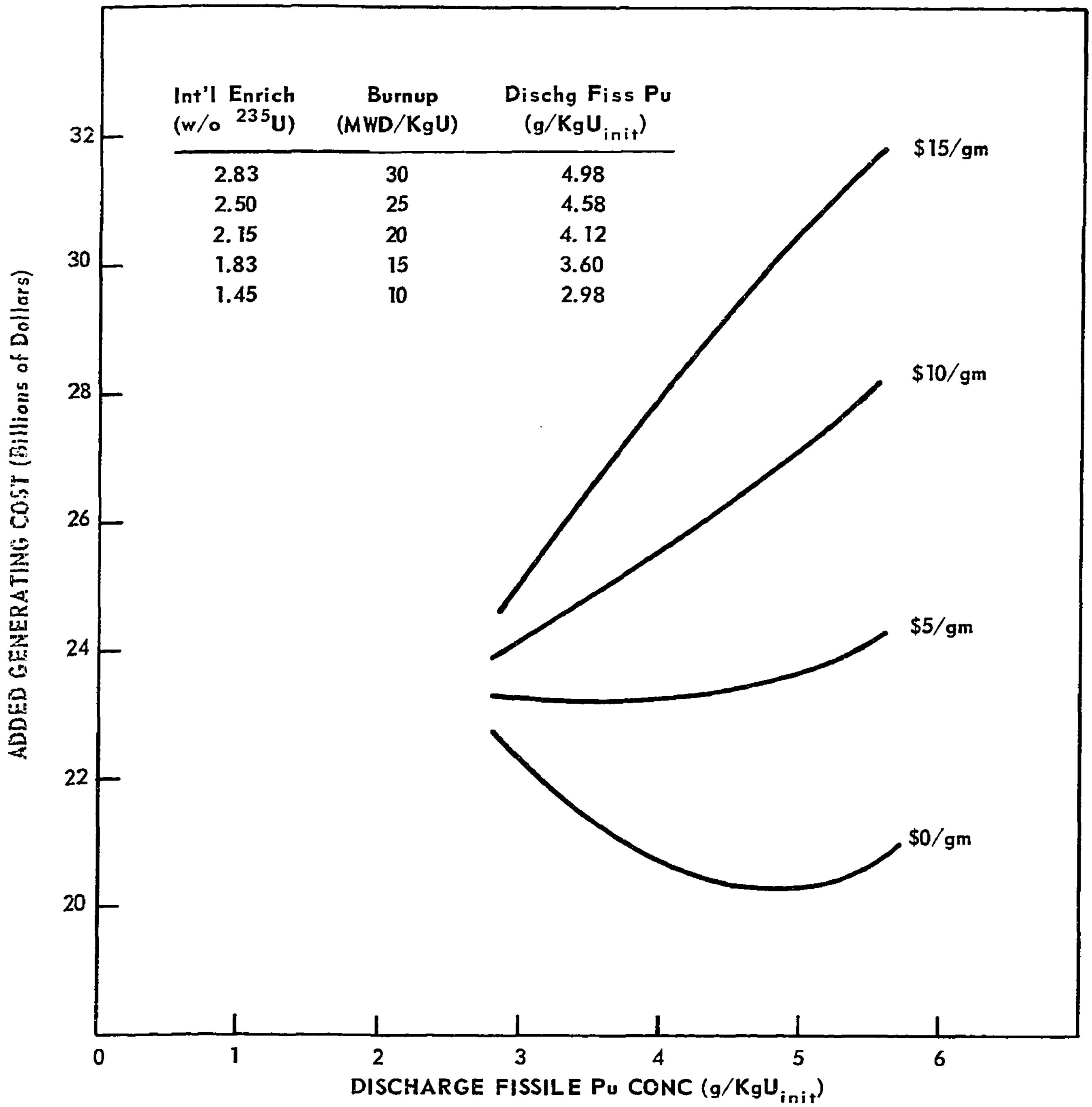

Figure 19: Added Nuclear Generating Costs (to the year 2010) as a Function of Discharge Plutonium Concentration for Various Plutonium Prices

production, the charges for early plutonium inventory soon override any benefit of high production. Even though cumulative generating costs generally increase at high burnup, higher burnups are required to justify light water reactor fabrication and reprocessing. Thus these costs are to some extent compensated for by the quantity of power which may be extracted per dollar paid in fuel reuse.

The light water reactor plutonium production is a factor which seriously affects the potential growth rate of fast breeder reactors. This is a factor, however, which can be regulated to a certain degree. Since electrical energy and plutonium are joint products of the same process, there could be trade off adjustments made if so desired and if the increase in plutonium revenues would balance the economic penalty to the electrical production. The amount of plutonium produced in light water reactors also influences the price of plutonium. Thus in producing greater quantities of plutonium there is the real possibility of reducing its market value.

Because a reduction in the fraction of ^{239}Pu to total fissile plutonium is like losing plutonium, and since this and the fabrication and reprocessing losses are of the same order of magnitude, their effect can be considered together. These losses which have an uppermost limit of about 10% (see Figure 20) do not make very significant deviations in the cumulative generating costs. The maximum difference in all of these cases is less than 10% of the added cost and much less of the total costs. The effect on the added generating cost is relatively small for all plutonium prices considered.

The fast breeder reactor growth rate is slightly reduced with higher losses due to less plutonium being available. Since these losses should not amount to more than a few percent, the actual limitation on breeder installation is almost negligible compared to other factors.

The effect due to higher LMFBR specific inventory has a number of different facets. If the breeding ratio remains constant, the relative amounts of plutonium required and generated in fast breeder reactors does not change but the doubling time (cf. Equation 2) increases. The

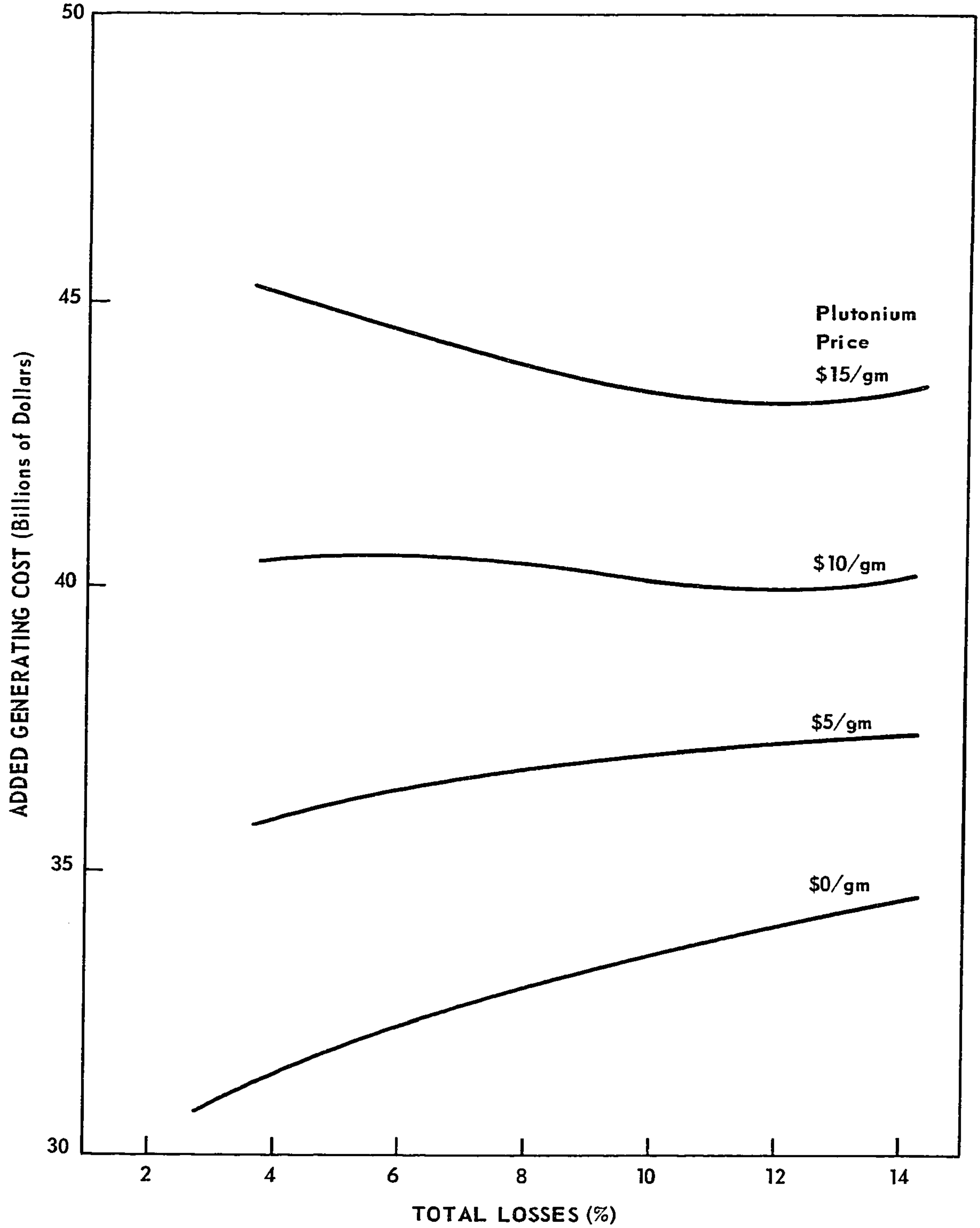

Figure 20: Changes in Added Nuclear Generating Costs (to the Year 2010) Resulting from Losses with Plutonium Price as a Parameter

difference in generating costs for two specific inventories (1830 kg/MW and 2187 kg/MW) are shown at the bottom of Figure 21. A change of roughly ten percent in specific inventory does not significantly influence the net generating costs. However, the maximum and ultimate fractions of the breeder reactor are limited. The increase in the difference is due to the greater plutonium demanded by the higher specific inventory reactor and, hence, a reduction in the external inventory charges (this is not considered to be a part of the fuel cycle costs).

Later on, however, due to the lower doubling time the reactor with the lower specific inventory is able to continue additions at a greater pace while the higher specific inventory reactor has had to curtail additions. This results in a greater fraction of fast breeder reactors to total nuclear capacity (about six percent greater or 125,000 MWe in the case considered here) and, hence, a continual decrease in generating costs.

If a decrease in specific inventory is accomplished at the expense of breeding ratio, which would be the normal case due to higher leakage, etc., no great change in the doubling time would be expected. This should then result in no

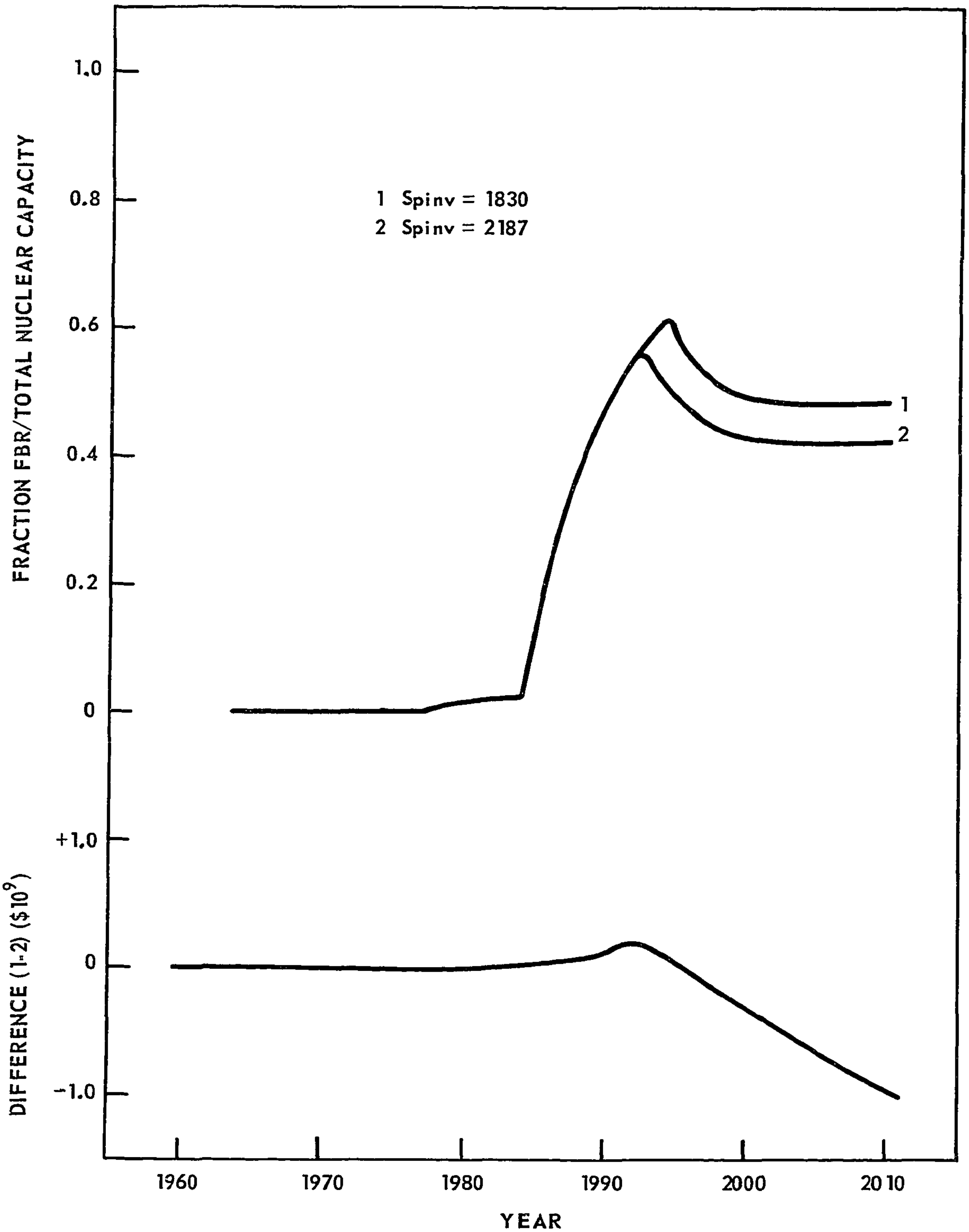

Figure 21: Differences in the Added Nuclear Generating Costs and the Fast Breeder Reactor Fraction due to FBR Specific Inventory

appreciable change in the final breeder fraction or in the generating costs.

Effect of Ex-core Inventory

The ex-core inventory has an appreciable effect on the cumulative nuclear generating costs as well as on the peak and final fast breeder reactor fraction of total nuclear generating capacity (similar to upper curves of Figure 21). Until the peak the rate of growth is not appreciably affected because breeders are considered to be normally added at the maximum possible rate. The results of variations in ex-core inventory are shown in Table VI. The ultimate FBR fraction is severely limited by the ex-core inventory decreasing from 70% to about 40% of the total nuclear capacity as the ex-core inventory increases. It is seen that higher ex-core inventory results in an earlier peak fraction and a lower final fraction fast breeder reactor capacity.

The effects of ex-core inventory changes on the additional cumulative generating costs range from $6 billion at a plutonium price of $0/g to $10 billion at $30/g plutonium price. It can be seen from this that there is an appreciable savings to be made if the ex-core inventory

TABLE VI

EFFECT OF EX-CORE INVENTORY ON CASE II-D

	FBR Fraction of Nuclear Capacity				
Ex-core Inventory (% of SI)	Year of Peak	Peak (%)	Ultimate Level (%)	Final Cap (MWe)	Added Cost ($\$10^9$)
10	2000	81	73-74	1,352,000	20.0
20	1997	74	63-64	1,168,000	21.6
30	1995	68	55-56	1,021,000	22.9
40	1994	65	49-50	911,000	24.1
50	1993	62	44-45	819,000	25.0
60	1993	62	43-44	800,000	25.2
70	1993	60	42-43	782,000	25.4
80	1992	58	41-42	764,000	25.6
90	1992	58	40-41	745,000	25.8
100	1992	56	39-40	727,000	26.0

is kept low since the greater savings per percent reduction in ex-core inventory occur at lower fractions. Thus, if ex-core inventories can be reduced to the range of 20%, a significant saving can be realized in both dollars and in earlier breeder introduction.

Effect of Discount Rate

The discount rate chosen has a considerable effect on the cumulative ideal costs. While undiscounted cumulative generating costs through the year 2010 total over $600 billion, the application of discounting procedures reduce this until at 12% the generating costs discounted to 1985 are reduced to $200 billion. In discounting to this year, the past expenditures are weighted more heavily (discount factor greater than one) while the future expenditures produce a smaller increase (discount factor less than one). For higher discount rates, this factor disproportionately weights the past costs and de-emphasizes the future ones (cf. p. 21).

The effect of the discount rate on the added costs is shown for various plutonium values in Figure 22. As the plutonium price becomes more appreciable, it combines with the earlier years' plutonium inventories; and the interest

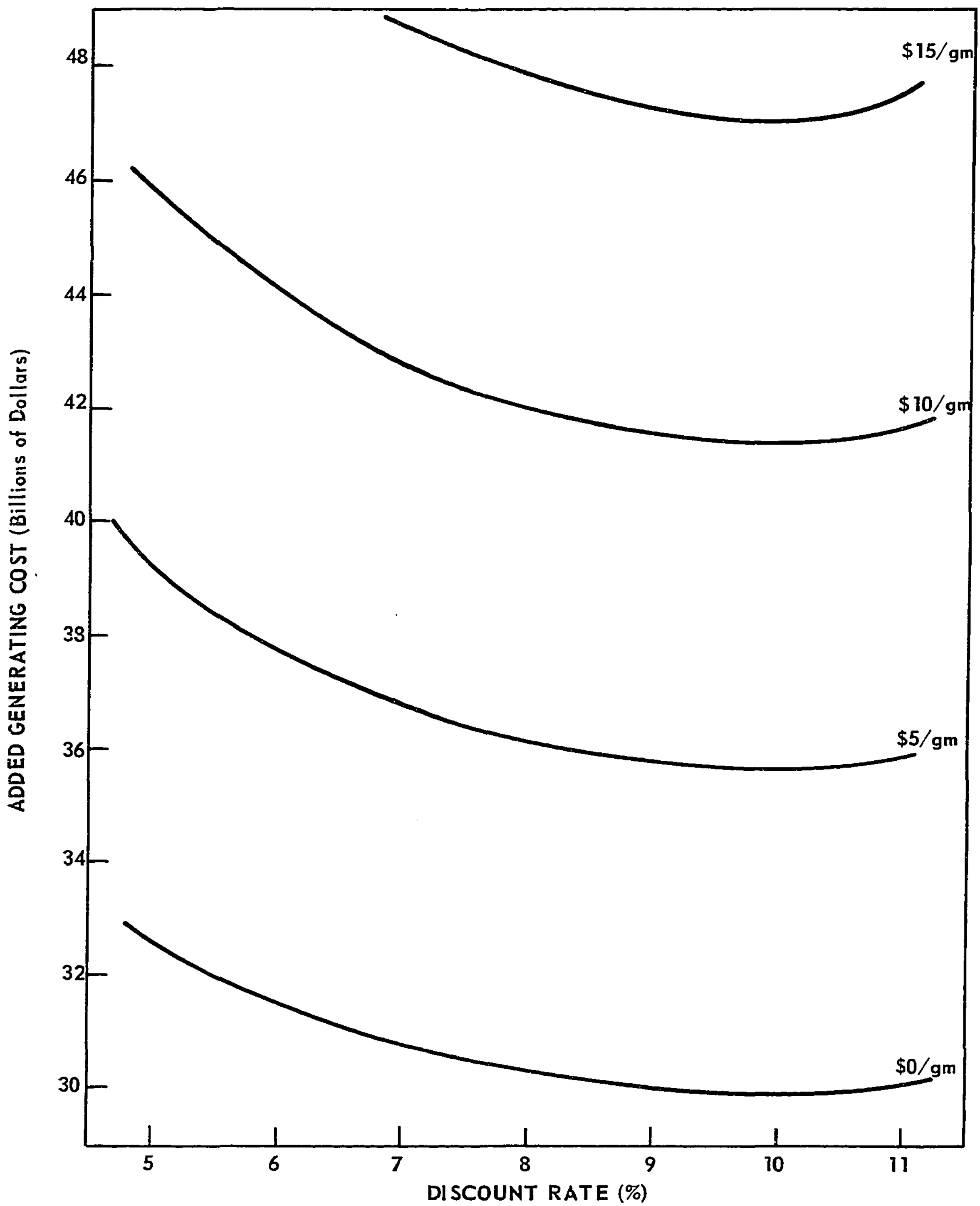

Figure 22: Effect of Discount Rate on the Added Nuclear Generating Costs (to the Year 2010) with Plutonium Price as a Parameter

rate mechanism mentioned above to produce an up-turn in the costs. It appears as though for the starting point, ending point, and year to which costs have been present-worthed, the minimum costs are obtained at 10% interest rate.

The discount rate can also have an effect, not considered here, on the supply of plutonium. At a given plutonium price and discount rate it is only economical to store plutonium for a particular period of time. If the price of plutonium remains the same but the interest rate increases it is not economical to retain the plutonium for as long a time. Thus at higher interest rates plutonium that could otherwise be saved is consumed.

Recapitulation

The most important variables associated with the nuclear generating costs for a mixed LWR-FBR system besides the capital costs and the rate of growth of nuclear capacity have been shown to be the price of plutonium, discount rate, and ex-core inventory for the fast breeder reactor. The plutonium price is an especially insidious and important parameter as the value this assumes has side effects on many of the other variables. This interdependence is shown in Table VII.

TABLE VII

INTERDEPENDENCE OF PLUTONIUM PRICE AND OTHER IMPORTANT PARAMETERS ON CUMULATIVE GENERATING COSTS

	Cumulative Generating Costs			
Parameter	Range at \$0/g (\$$10^9$)	Difference 25-0 \$/g (\$$10^9$)	Range at \$25/g (\$$10^9$)	Effect seen in
Discount Rate	3	17-25	9	Figure 22
Ex-core Inventory	6	5-21	10	Table VI
FBR Spec. Inventory	2	12	3	Figure 21
LWR Pu Production	2	3-10	6	Figure 19
Fissile Fraction, Losses	4	10-15	3	Figure 20

Since the price of plutonium must be determined from a supply-demand relationship, a firmer grasp on the price of plutonium as a function of time in a breeder economy may be obtained from the following considerations:

1. Plutonium derives its value only from its marketability. Therefore, the price for plutonium will be determined by its utility in fast breeder reactors in competition with

light water reactors selling their plutonium to the breeders. Thus, the price of plutonium as a function of time cannot exceed the break-even price in the least expensive breeder. A higher capital cost breeder would have to purchase plutonium at even lower prices in order to compete.

2. Eventually, and it appears to be longer than the time period utilized in this work, the amount of plutonium being produced in breeders will exceed their requirements. (This presumes the breeder reactor doubling times become less than both the nuclear and the total generating capacity doubling time.) Then the price of plutonium will begin to decrease, ultimately stabilizing no lower than the minimum recycle price in light water reactors.

These two restrictions are shown in Figure 23 along with the estimates of others concerning future plutonium price.

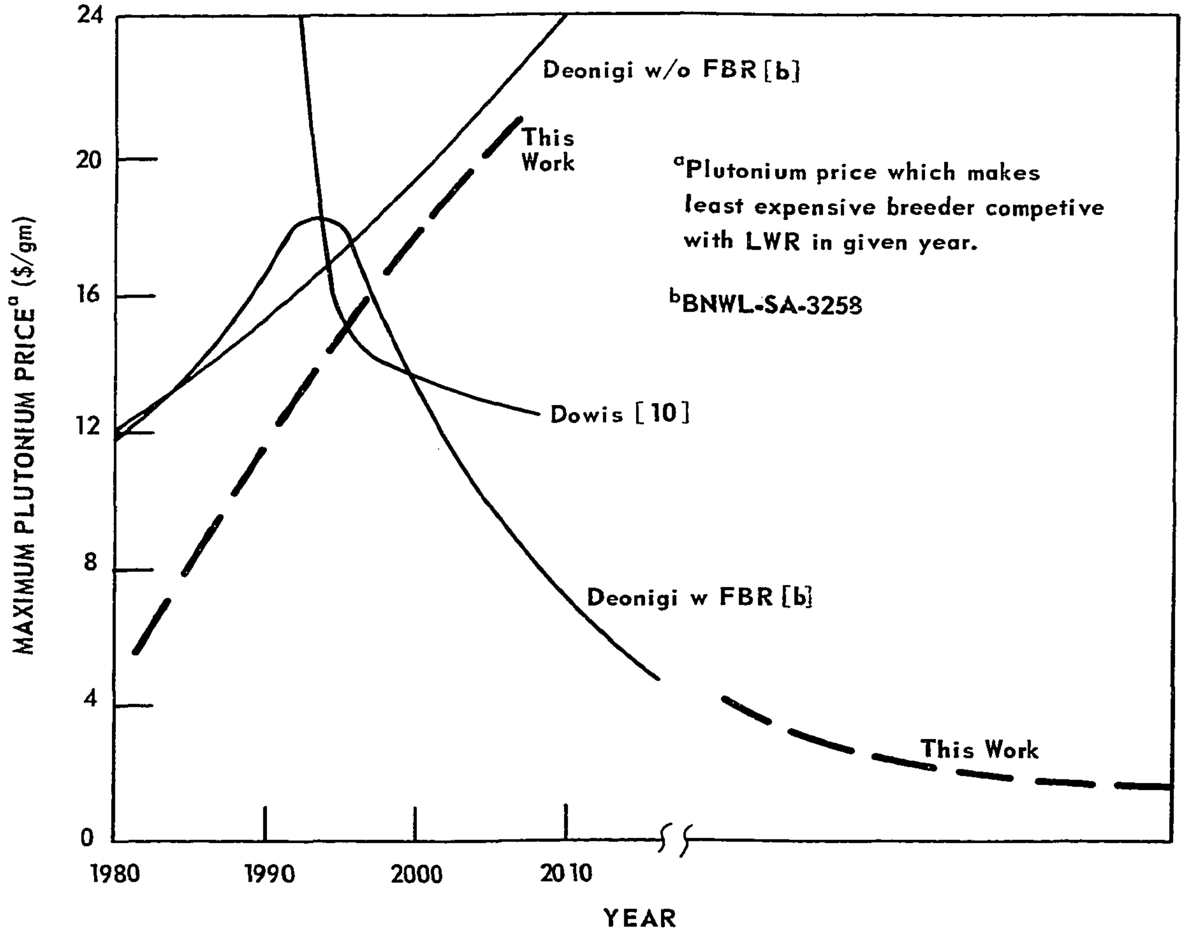

Figure 23: Forecast of Future Plutonium Price Limited by Supply-Demand and Market Constraints

There has been found to be a fast breeder fraction that makes generating costs insensitive to variations in plutonium price. The benefits of such a property to a nuclear generating system need no further embellishment. While the result found here, 47% breeder, is attributable to the simple mix of two reactor types, in principle a more complex system would combine to produce some other ratio of reactors that would produce the same type of effect. This fact would be especially useful to a particular utility which may choose to remain aloof of the plutonium market.

The method of plutonium utilization has been found to have significant impact on the supply of plutonium. This has consequences on the rate of breeder addition which in turn has economic repercussions. The extent of plutonium recycle in light water reactors will determine whether the savings that are achieved are short-term or long-range.

CONCLUSIONS

An assessment of the technical and economic parameters affecting fast breeder reactor deployment indicates an inevitable conflict between long-range benefits and short-term gains. The factors which contribute to this can be altered by improvements in technological variables or by more organized and deliberate planning.

As might be expected, the fast breeder reactor ex-core inventory has the potential to limit the growth of breeders by suppressing the plutonium supply. In order to permit the greatest number of breeders to be installed with a constant quantity of plutonium, the ex-core inventory must be as small as possible.

Another fact which is not overly surprising is that losses from fabrication and reprocessing and differences in fissile fraction are generally negligible in their effect on generating costs when compared to such factors as ex-core inventory. However, it may be possible to make a series of small savings with the same net result as a single large one.

The absolute level of capital costs and operating and maintenance expenses are not extremely important as these are presumed to vary in the same way for light water reactors and fast breeders. However, the differential capital and operating costs between these two plant types is a factor of great importance in determining the breeder introduction date. Lower capital differentials will permit competitiveness at higher plutonium price. This is an encouraging development as overall reductions in capital costs, especially when considering inflation, seem remote. All that is necessary is for the cost associated with the breeder to advance at a slightly slower pace.

The discount rate makes an appreciable difference as to what appears as the most economic situation. This is primarily due to the distribution of expenditures in time and the subsequent effect of discounting. It appears as if the groundwork has at least been laid for standardization and better definition of this essential parameter [93].

The variation of fuel cycle costs with plutonium price strongly affects the competitiveness of breeder reactors with light water reactors. In the future, the price of plutonium will be set in a supply and demand market structure. The maximum stabilized (i.e., other than transient situations such as experimental purposes) future price of plutonium is the price which, in the least expensive fast breeder, yields generating costs competitive with light water reactors. The minimum future price is the minimum recycle value in the least economical light water reactor.

A decrease in the range of plutonium price will lessen to some extent the dependence of generating costs on this highly uncertain parameter. Certain fractions of fast breeder reactors to total installed nuclear capacity, however, yield generating costs insensitive to variations in plutonium price. These exist for all capital cases and for all time. This would be a desirable goal as the ultimate fraction since it provides a hedge against a fluctuation in price for plutonium users and producers. Similar conclusions have been arrived at by different types of analyses for other economies [5, 7]. Thus such a result is independent of the model utilized.

The philosophy adopted regarding plutonium recycle in light water reactors will have a great influence on the rate of growth of breeders and their ultimate fraction of the generating capacity. Although minimum short-term savings may be achieved through recycle, it is clear that this policy does not lead to long-range savings for all discount rates and plutonium prices. If desired, the amount of plutonium produced in a light water reactor may be altered by trading off electrical energy generation for plutonium production. However, this would necessitate either a rise in generating costs or in plutonium price or both.

It does not seem advisable to add only fast breeder capacity for eight to ten years following their commercial introduction even if sufficient plutonium is available. Although the costs associated with the suspension and later resumption of light water reactor manufacture are unknown, it is expected they would be great enough to warrant striking a balance in additions of the two reactor types.

As far as commercial LMFBR introduction is concerned, there are several alternatives which could assure this by 1985 or 1990. Either 1) The capital costs of the reactor type must be in the lower portion of the region considered, or 2) FBR-LWR capital cost differentials must be lower than that assumed, or 3) Plutonium price must be extremely low (considerably below \$10/g). A small change in all these areas may combine to make 1985 introduction feasible.

If it were considered necessary to store all the plutonium produced so that breeders could be added at the fastest possible rate, there is a method that would accomplish this economically. Since it is not entirely proper to receive credit on plutonium until it is sold, and if no revenue from plutonium sale is considered in the LWR fuel cycle calculations, any plutonium generated can be justifiably carried without inventory charges. Although this type of accounting increases light water reactor unit energy costs slightly (about 5%), it will ultimately prove more economical since it enables faster breeder growth without the need for interim inventory charges. When the plutonium is finally sold, a revenue (probably greater than would be possible in the case of recycle) is realized. Thus a method of recovering any losses that have occurred in past generating costs as well as insuring lower future costs from breeder generation is provided.

IMPLICATION OF CONCLUSIONS

If credit for plutonium produced in light water reactors is not taken in the fuel cycle calculations, no price has been assumed paid for the plutonium and it can be carried without the need to charge inventory. The credit that is taken in the fuel cycle calculations is proportionate to the price expected to be received for the plutonium; thus this much is "invented" in the plutonium, and inventory charges are mandatory. Although taking no credit for plutonium will make present light water reactor fuel cycle costs about 10% greater and total generating costs perhaps 3-5% higher, such action would permit the long-term storage of plutonium at essentially no expense.

If it were feasible for the plutonium to be stored for long times for use in breeder reactors, the desire for immediate recycle would be lessened. Much expense could be saved in developing plutonium recycle technology and higher fuel costs associated with preparing plutonium fuels. This action, however, would entail an increase in uranium enrichment demands. Subsequent improvement and upgrading of existing cascades would be required along with a larger number of new enrichment facilities.

The very low ex-core inventories desirable will be difficult to achieve because of the short cooling time required. Present technology does not favor ex-core inventories under approximately fifty percent. To achieve a shorter turn around outside the core will require more advanced reprocessing methods and fuel fabrication procedures that can deal with hotter materials. A great cost penalty will be paid in the fabrication of this material.

The prolonged practice of recycle in light-water reactors will reduce the quantity of plutonium that is available for use in fast breeder reactors. The government could overcome this obstacle by providing its stockpile of weapons-grade plutonium for sale in the interest of making greater quantities of energy affordable by all of its citizens. This material, because of its higher fissile content, would be especially desirable as a fuel for the first generation of breeders. Such action would assure an adequate supply of otherwise unavailable plutonium at a critical time. This would offer a means of reducing near-future generating costs as well as providing minimum long-term costs.

If it is not advisable to add only fast breeder reactors but to keep the manufacture of light water reactors viable in the years immediately following the commercial introduction of the breeder, it must be determined in what proportion these two should be added. In a changing plutonium market, the earliest achievement of the breeder fraction insensitive to plutonium price would result in increased savings and an independence of the plutonium market. Thus the breeder fraction yielding total annual generating costs insensitive to plutonium price would be a desirable choice for this proportion. As noted previously (p. 25), because of the uncertainties involved the possible introduction of fusion reactors has been ignored. Should this energy source be developed for commercial use within this century the balance of fission reactors would be affected from that time on. Since unrestrained fluctuations in plutonium price could result, the installed FBR fraction impervious to changes in plutonium price would prove advantageous in this instance.

FUTURE WORK

There are additional investigations which have yet to be carried out in the area of generating costs and plutonium supply.

Better attempts to define the plutonium market structure are necessary in order to predict more accurately the effect of plutonium price changes on future generating costs. This is a difficult problem as all the factors affecting uranium supply are also involved.

An examination should be made to determine the effect on such an analysis of discounting the costs to different times. Although no change in the relative order of the results would be expected, it would prove most disconcerting if there should be any.

The effect of employing different FBR-LWR capital cost differentials needs to be determined. The direction which changes of this kind would entail is known, but the magnitude and impact on generating costs is undetermined.

The effects of different isotopic compositions in the feed of fast breeder reactors is not well-known. Neither are the effects of repeated high burnup and frequent recycle of the same material.

Finally, it might be instructive to compare these results with the degree of competition offered by conventional electric generating stations. Although it may be more difficult to estimate fossil fuel costs with time, determining the comparative costs could suggest an alteration of trends in the ratio of nuclear and conventional capacities. This would permit even greater commensurate savings in total electric generating costs.

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APPENDIX I

Further Description

of

Light Water Reactor

The typical light water reactor is fueled with slightly enriched UO_2 and both moderated and cooled by means of pressurized H_2O. The design characteristics are presented in Table VIII. The reactor is cooled by seven loops, with one pump and one steam generator per loop. A single pressurizer serves to regulate the water pressure in all seven loops. Flow through the core is single-pass upward. The active core is 11 feet high and 12.8 feet in diameter. The reactor contains 264 fuel assemblies and 109 control rods. A cross section drawing of a fuel assembly and cruciform-shaped control rod is shown in Figure 24. The fuel assembly contains a 16 × 16 square array of rods. The rods with highest specific power, near the control rods, are of a reduced diameter. Chemical poison control in the form of a boric acid solution is used for shim control to reduce the control rod requirements.

TABLE VIII

DESCRIPTION OF TYPICAL LIGHT WATER REACTOR

Reactor Power

Core nuclear power, MW(th)	3220
Net electrical power, MW(e)	1002
Net thermodynamic efficiency, %	31.1

Coolant

Composition	H_2O
Core inlet pressure, psia	2050
Core pressure drop, psi	34
Flow rate, lb/hr	160×10^6
Core inlet temperature, °F	546
Mean core outlet temperature, °F	598
Maximum hot channel outlet temperature at rated overpower, °F	639
Number of coolant loops	7
Coolant velocity in core, ft/sec	12.7

Core Thermal Performance

Average heat flux at rated power, $BTU/hr \cdot ft^2$	163,000
Maximum heat flux at rated power, $BTU/hr \cdot ft^2$	544,000
Maximum fuel pin surface temperature, °F	640
Peak-to-Average power ratio	3.3
Average core power density, KW/liter	80.7
Average specific power, KW/kg of fertile material	31.7
Ratio of maximum to average enthalpy rise	1.8
Flow reduction factor used	1.07
Fluid mixing factor used	0.94
Minimum DNB ratio at rated overpower	1.23 (boiling)
Rated overpower factor	1.15

TABLE VIII (CONTINUED)

Description of Fuel Cycle

Fuel management scheme	three batch scatter reloading
In-core residence time (at 0.8 load factor), yr	2.3
Average core fuel exposure, MWD/MT	25,000
Average exposure in maximum rod, MWD/MT	30,000

Control System

Method of shim control	soluble poison
Method of safety control	poison rods
Number of rods	109
Rod material	Ag, In, Cd

Reactor Vessel

Type	cylindrical
Material	stainless steel clad carbon steel
Inside diameter, ft	15.8

Turbine Plant

Throttle steam pressure, psig	635
Throttle steam temperature, °F	495
Type of steam cycle	saturated with reheat
Feedwater return temperature, °F	443
Arrangement of turbine generators	compound, six flow

TABLE VIII (CONTINUED)

Description of Core and Fuel

Moderator material	H_2O
Reflector material	H_2O
Fuel material	UO_2
Fuel fabrication	pelletized
Fuel theoretical density	96.5
Maximum $\int k d\theta$ at rated power, w/cm	41.2
Fuel life, yr	3
Equivalent diameter of core, ft	12.8
Active height of core, ft	11.0
Number of fuel assemblies	264
Fuel element spacing, in	8.4
Fuel rod outside diameter, in	0.378 and 0.320
Cladding material	Zircaloy 4
Cladding thickness, in	0.020

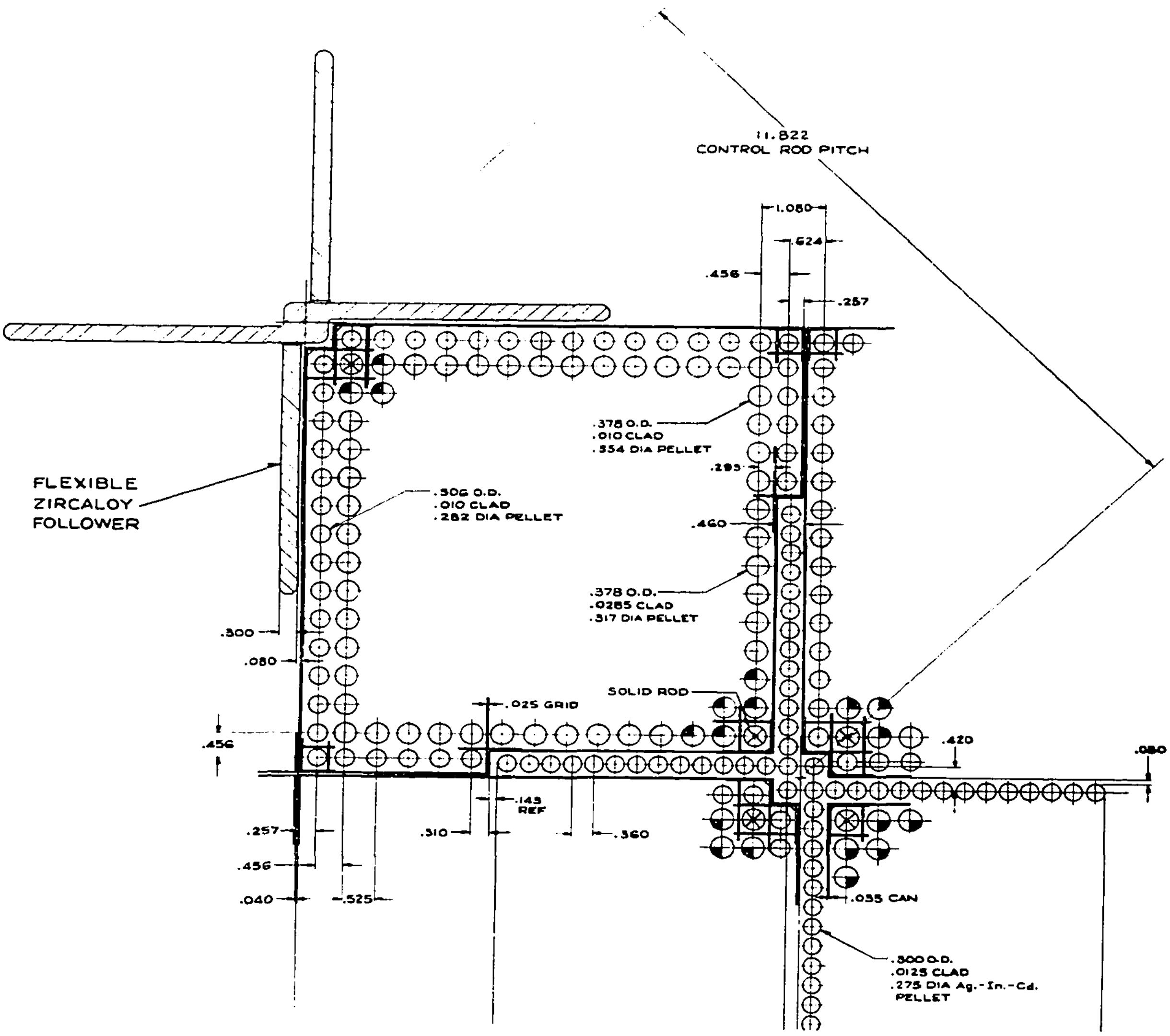


Figure 24: Horizontal Cross-Sectional Diagram of LWR Fuel Assembly and Cruciform-Shaped Control Rod (after ORNL-3686)

The typical light water reactor has a maximum-to-average heat flux ratio of 3.3, a core power density of 80.7 $\frac{KW}{liter}$, and a coolant outlet temperature of 598°F. Although chemical shim is used to limit the power distortion normally due to the presence of control rods, no use is made of varying fuel enrichment to flatten the power distribution. However, fuel rods having smaller diameters than normal rods are placed next to the water gap (where the control rods would be were they inserted) to reduce the heat rating. Short control rod followers that extend 3.7 feet into the 11 foot core and other mixing devices force the interchange of coolant between and within assemblies.

The fuel element of the pressurized water reactor design is 155 inches long, with an active fueled length of 132 inches. It consists of 194 tubes 0.378 inches in diameter and 40 smaller tubes 0.320 inches in diameter. These tubes have 0.020 inch thick Zicaloy-4 walls and are filled with UO_2 pellets of 96.5% theoretical density. They are designed to operate for three years at a linear heat rating of 16 $\frac{KW}{ft}$ and a maximum heat flux of 544,000 $BTU/hr \cdot ft^2$ to a maximum burnup of 30,000 MWD/MT of uranium. The peak cladding temperature is 640°F; coolant pressure is 2050 psi.

The reactor is shutdown once each year for refueling, and one-third of the 264 fuel assemblies are replaced each time. The reactor vessel head and the control rod driver and drive support grid are removed to gain access to the fuel. Semi-remote methods and special power-driven hoisting devices are used for handling the fuel. Fuel assemblies are withdrawn from the reactor into the flooded reactor cavity and then moved through a canal and an underwater lock to the fuel storage pit.

Physics calculations of the 1000 MW(e) pressurized water reactor were performed by Oak Ridge National Laboratory. These were made with the TONG point depletion code, describing the neutron spectrum in 15 gourps. The reference fuel management scheme was the "three-batch roundelay" or "scatter-reload" program in which one-third of the core loading is discharged at each shutdown. The reference design specified that the initial core loading have three batches of fuel (each occupying one-third of the core) with enrichment ratios approximating the ratios existing at the start of an equilibrium cycle. This was simulated in the TONG calculations by specifying three batches of fuel (homogeneously mixed) having enrichment ratios (relative to average core enrichment) of 0.7, 1.0, and 1.3, respectively. The fuel with the lowest enrichment would be discharged at the first shutdown and replaced with new fuel. Excess reactivity (with rods withdrawn) at the start of each cycle was specified, and the enrichment required in the reloaded zone to obtain that reactivity was determined by a direct eigenvalue calculation. During the depletion cycle, a uniform poison concentration was determined to keep the reactor critical. Initial excess reactivity (i.e., feed fuel enrichment) was treated as a parameter in these calculations in order to optimize fuel costs.

APPENDIX II

Further Description

of

Fast Breeder Reactor

The typical first generation LMFBR consists of a core of mixed (uranium and plutonium) oxide fuel, suitably contained and subdivided to assure adequate heat removed by the circulating liquid-sodium coolant. The core operates in a fast neutron flux, and power is regulated by moving neutron-absorbing control elements into or out of the core. The core is surrounded both radially and axially by natural or depleted uranium blankets. The entire system, along with vacant positions for fuel storage, is housed in a stainless-steel reactor vessel which provides containment for the sodium coolant. The upper end of the vessel is closed by means of a thick double rotating plug shield which is also part of the fuel handling system. At full load, sodium enters the vessel at the lower end at 760°F, flows up through the core, and exists from the vessel at 1060°F. The design characteristics of the reference LMFBR are given in Table IX.

The reactor core is made up of 256 vertical hexagonal elements of a 5.389 triangular lattice (cf. Figure 25). The core is surrounded by two rows of radial blanket elements and a single row of stainless steel reflector elements. Fifteen control and safety rods are provided for reactivity control. Tantalum has been selected as the reference absorber material.

TABLE IX

DESCRIPTION OF ASSUMED FIRST GENERATION LMFBR

Reactor Power

Total reactor power, Mw(th)	2500
Core power fraction (mid cycle)	0.899
Radial blanket power fraction	0.069
Axial blanket power fraction	0.032
Net electrical power, Mwe	1004
Net thermodynamic efficiency, %	40.7

Coolant

Composition	Sodium
Reactor outlet pressure, psig	1
Core pressure drop, psi	100
Core flow rate, lb/hr	93×10^6
Core inlet temperature, °F	760
Mean coolant outlet temperature, °F	1060
Number of coolant loops	3
Coolant velocity in core (max), ft/sec	32.8

Core Thermal Performance

Average heat flux at rated power, BTU/hr·ft^2	495,000
Maximum heat flux, BTU/hr·ft^2	785,000
Maximum fuel pin surface temperature, °F	1200
Peak fuel pin power, kw/ft	16
Cladding hot channel factor	1.16
Peak-to-Average power ratio	1.65
Radial peaking factor	1.26
Axial peaking factor	1.25
Average core power density, kw/liter	390
Average specific power of fuel material, kw/kg	190

TABLE IX (CONTINUED)

Core and Fuel (mid equilibrium)

Core fissile enrichments at %	
inner zone	11.4
outer zone	15.4
Fissile mass (Pu + U-235), kg	
core	1780
axial blanket	116
radial blanket	368
Average breeding ratio	1.29
Average fuel burnup MWD/kgH	75
Doubling time, yr	10
Core residence time @ .8 LF, yr	1.5
Geometry	hexagonal
Lattice spacing, in	5.389
Pins per subassembly/o.d. (in)	
fuel and axial blanket	217/0.25
inner radial blanket	91/0.47
outer radial blanket	61/0.58
Fuel and cladding material	mixed PuO_2 UO_2 304 or 316 SS
Blanket and cladding material	depleted UO_2 304 or 316 SS

Control and Safety

Reactivity swing over equilib. cycle, $	5.0
Absorber material	tantalum
Pins in array	
shim-safety	16
safety	9
Average rod worth, $	
shim-safety	1.6
safety	2.0
Reactivity coefficient	
doppler constant, t dk/dt	-0.0096
maximum radial sodium void, $	6.82
total sodium void, core only, $	6.03
isothermal sodium temperature, dk/°F	3.3×10^{-6}

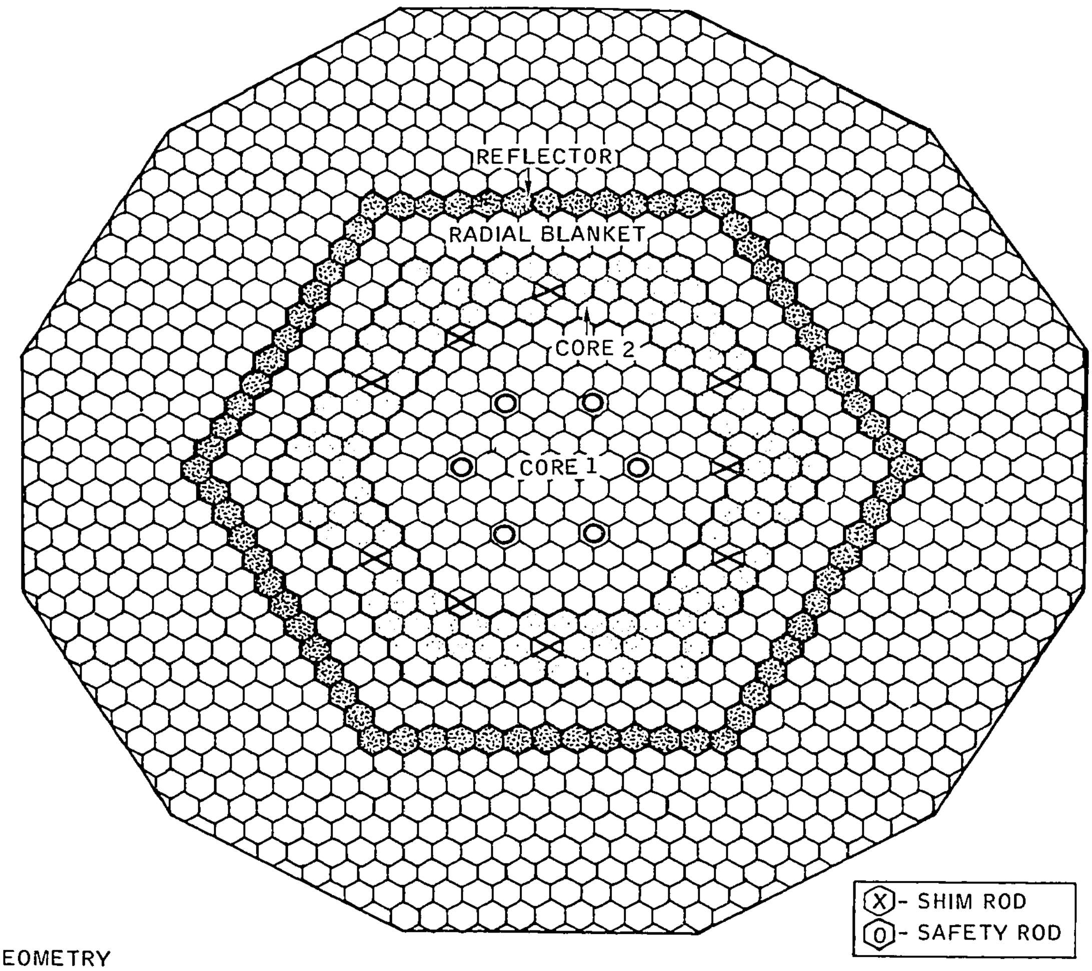
TABLE IX (CONTINUED)

Reactor Vessel

Type	cylinder
Material	304 stainless steel
Inside diameter, ft	22

Turbine Plant

Main steam pressure, psig	2400
Main steam temperature, °F	900
Final feedwater temperature, °F	478
Type of steam cycle	superheat with reheat
Type of turbine	cross-compound



BASE CORE GEOMETRY

ZONE 1:	118 FUEL ELEMENTS +	9 CONTROL RODS =	127
	138 FUEL ELEMENTS +	6 CONTROL RODS =	144
	256	15	271

RADIAL BLANKET

INNER (RB1) 60
OUTER (RB2) 66

REFLECTOR 72

TOTAL LOCATIONS = 469

Figure 25: Horizontal Cross-Sectional Diagram of LMFBR Core and Blankets (after AI-12792)

Nine control rods are used as combined shim and safety rods, and six are used strictly for safety.

A fast fuel element consists of a bundle of 217 fuel pins vertically supported at their lower ends on support bias inside a hexagonal SS housing. Fuel pellets of mixed PuO_2 and UO_2, 0.215 inch diameter, are contained in 0.250 o.d., 0.015 inch wall thickness, SS cladding. The cladding is a gastight container for the fuel and sufficient excess length is provided for the storage of fission gas to achieve the required fuel burnup (cf. Figure 26). The fast fuel elements have a 50 inch active fuel section and 12 inch axial blanket section at each end. The inner and outer radial blankets are identical in configuration to the fast elements except that the inner blanket element have 91 pins 0.47 inch diameter, and the outer have 61 pins 0.58 inch diameter. The reflector elements are made of stainless steel plates. Fuel elements are transferred between core and storage by an in-core fuel handling machine.

The reactor will be refueled on a six month cycle with 1/3 of the core, 1/6 of the inner blanket, and 1/9 of the outer blanket being replaced each cycle. Refueling is performed during scheduled plant shutdown. Spent fuel is removed from

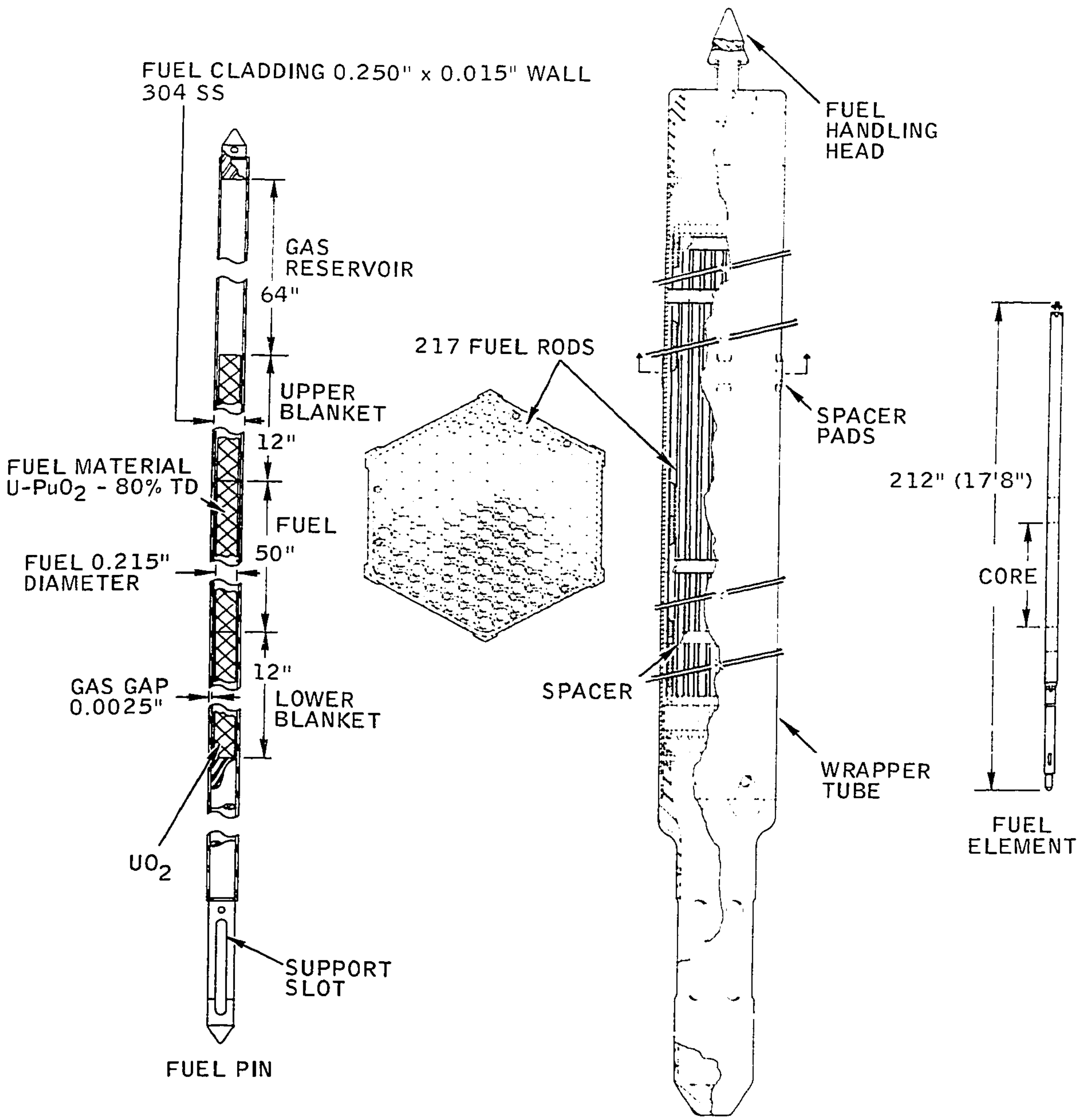


Figure 26: Typical LMFBR Fuel Pin and Element Design (after AI-68-Memo-37, Vol. I)

the core and placed in one of the in-vessel storage positions for decay during the subsequent power cycle. The average exposure of the spent core fuel is 74,000 MWD/MT. The fast core elements have an average reactor residence time of 1.5 years, the inner radial blanket 3 years, the outer radial blanket 4.5 years, and the shim control rods 8 years. Thus, on the average, 103.3 core assemblies are exchanged at each refueling. Additionally 1/9 of the outer blanket elements are rotated 180° to permit uniformity of the Pu buildup at the edge of the core where there is a sharp flux gradient. The downtime per refueling is estimated at about ten days.

The sodium heat-transfer system consists of three heat-transfer circuits operating in parallel. Each circuit consists of a radioactive primary sodium loop which flows through the core in series with a non-radioactive secondary sodium loop. The primary and secondary loops are connected by means of an intermediate heat exchanger. The secondary sodium transports the thermal energy to the steam generator banks where it is transferred to the steam system. The operating pressure in the secondary-sodium side of the intermediate heat exchangers is maintained at a higher pressure than the primary sodium side so that a leak in the intermediate heat exchangers will not lead to radioactive contamination of the unshielded secondary system.

The combined primary loop sodium flow is from the lower plenum of the reactor up through the core and into the upper plenum. The flow then divides and goes through the three separate loops to a primary centrifugal pump through two intermediate heat exchangers in parallel and then back to the reactor lower pelnum where it recombines with the sodium flow from the other loops. At full power operation, 94×10^6 lb/hr of sodium enters the reactor at 760°F and exits at 1060°F. Each intermediate heat exchanger has a design duty of 1425×10^6 BTU/hr and is about 70 inches diameter and 30 feet long. The overall fuel element peak-to-average power ratio at midcycle equilibrium is 1.605. The corresponding peak linear power rating is 15.7 KW/ft with a maximum coolant flow velocity of 30 feet/sec and clad temperature of 1200°F.

The steam-generator system utilizes both superheaters and reheaters to produce 900°F steam at 2500 psi. This steam is admitted to the high pressure section of a double-flow turbine. Exhaust steam from this section at 575 psia and 515°F is reheated in the sodium-steam reheats and returned to the intermediate-pressure section at 515 psia and 575°F. The turbine-generator is rated at 1240 Mva.

The fuel burnup calculations were performed by Atomics International with the PABUC computer program. The calculations were performed in one-dimensional geometry using neutron-diffusion theory. The PABUC code incorporates a modified version of ANISN for flux and eigenvalue (k_{eff}) calculation and the NUCY subroutine for solution of the nuclide production and depletion chain. The principal calculations were performed in cylindrical geometry. Two core enrichment regions were employed to facilitate control of the peak-to-average power ratio. Each enrichment region was subdivided into three burnup zones to provide greater detail in the calculations. Each of the burnup zones was divided into three equal-volume fuel batches to simulate the fuel-management scheme. The time history of the changes in isotopic composition of each batch was calculated on a cycle-by-cycle basis. At each refueling one batch from each burnup zone was discharged and replaced with fresh fuel.

The radial blanket was similarly treated with six fuel batches in the inner-ring blanket and nine fuel batches in the outer-ring blanket. A uniformly distributed tantalum poison was used in the outer-core enrichment region to simulate the control rods. Refer to Figure 5 for a horizontal section of the core. The vertical cross section is shown in Figure 27. Equilibrium operation had been achieved at the tenth refueling cycle.

The isotopic composition for the initial loading is assumed to be 60% ^{239}Pu, 24% ^{240}Pu, 12% ^{241}Pu, and 4% ^{242}Pu. This is felt to be representative of early LWR discharge compositions. The startup core employs three different enrichments in each of the two major enrichment zones to minimize the swing in reactivity during the approach to equilibrium. The lower-enrichment batches are replaced first to provide a smooth transition to high-burnup, high-enrichment fuel.

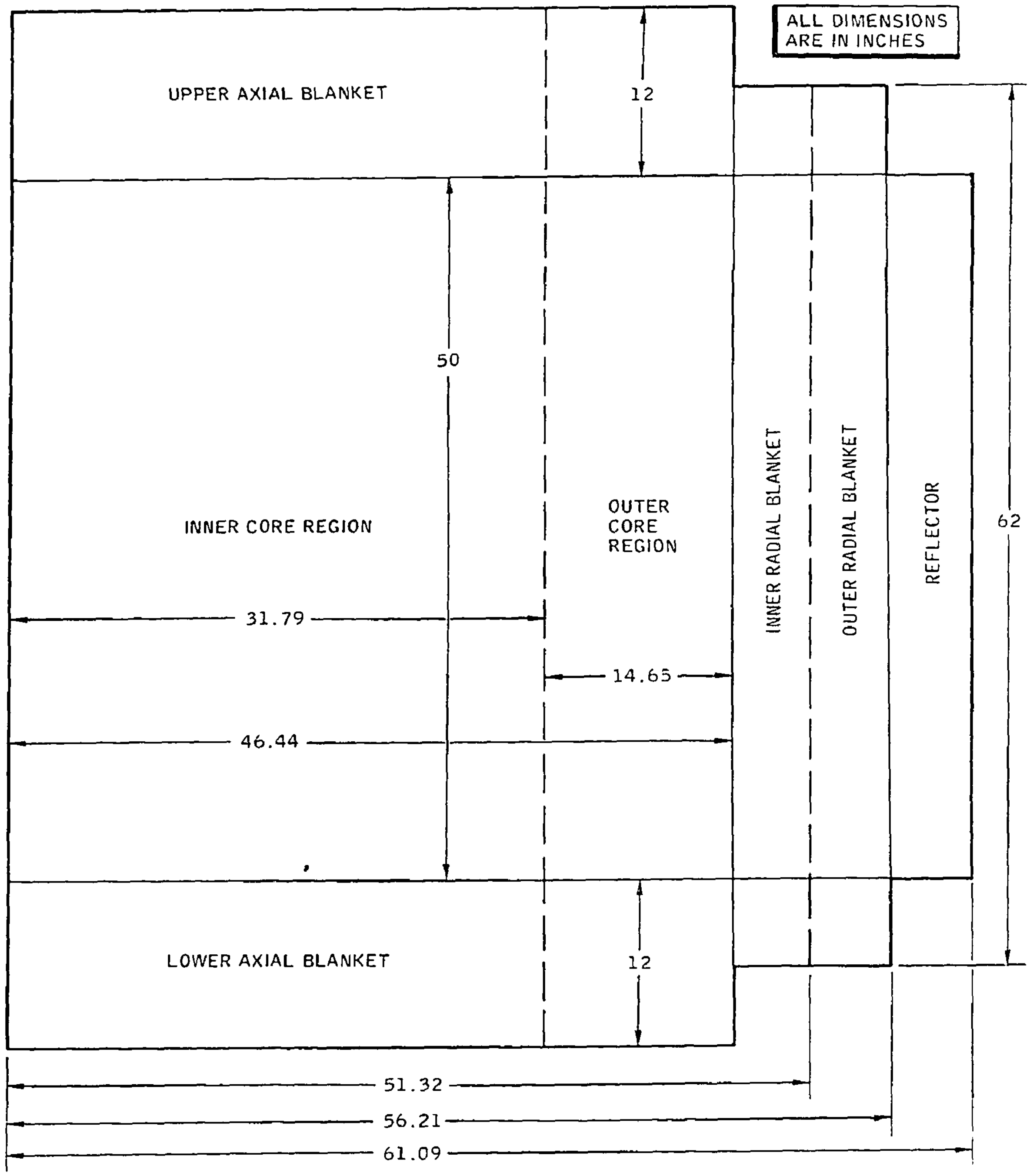


Figure 27: Vertical Cross Section of LMFBR Core Showing Fuel Regions and Dimensions (after AI-68-Memo-37, Vol. II)

Each cycle corresponds to 144 days of full power (1000 Mwe) operation. During equilibrium operation, 610 kg of fissile plutonium are charged to the reactor and 721 kg are discharged at each refueling shutdown. AI calculates a total breeding ratio of 1.29 and with their assumption of the excore fuel inventory of 797 kg and 1% losses they conclude the simple doubling time (cf. Equation 2) is 8.7 years.

APPENDIX III

Listing

of

Computer Program

MIN-E-COST

```
               C          MIN-E-COST - A PROGRAM TO CALCULATE THE FASTEST GROWTH RATE OF
               C                       FAST BREEDER REACTORS TO YIELD MINIMUM NUCLEAR
               C                       GENERATING COSTS

 0001                  DIMENSION JEAR(46),NGCP(46),CCL(46),CML(46),UNS(46),FCCLO(46),FCCF
                      1O(46),A(138),B(184),C(92),MINCST(46),DINCST(46),CENGCO(46),PUPRO(4
                      26),CST(46),DCST(46),CDNGC(46),XPUPR(46),CBNGCP(46),LWRFCC(46),FBRF
                      3CC(46),UNCLWR(46),UNCFBR(46)
 0002                  COMMON NGCP,KAPL,KAPF,KAP,MKAPF,MKAPL,KNCF,KNCL,INGCP,INCL,INCF,CC
                      1L,CML,UNS,FCCLO,FCCFO,SPINV,XCOR,PUPF,CEFFF,CEFFL,BURNL,EXPL,UCHG,
                      2AVLWR,AVFBR,PUPR,FABLOS,REPLOS,DISRAT,N,PUBAL,FPHPY,TNGC,CENGC,NYE
                      3AR,PUSL,PURF,PUSF,TINV,ACFBR,ACLWR,PWF,PLWF,PFBR,EPLWR,EPFBR,ANGC,
                      4PUINV,ADCCST,DNGC,EANGC,DENGC,F,MINCST,DINCST,CENGCO,PUPRO,CST,DCS
                      5T,CDNGC,XPUPR,COENGC,LWRFCC,FBRFCC,UNCLWR,UNCFBR,XCRR
 0003                  COMMON/ONE/M
 0004                  REAL NGCP,OBNGCP,KAPL,KAPF,KAP,MKAPF,MKAPL,KNCF,KNCL,INGCP,INCL,IN
                      1CF,MINCST,LWRFCC
               C          INITIALIZE CASE COUNTER
 0005                  L = 0
 0006                  READ(5,10) (JEAR(I),NGCP(I),CCL(I),OML(I),UNS(I),FCCLO(I),FCCFO(I)
                      1,I=1,46)
 0007               10 FORMAT (I4,E10.4,5F10.5,16X)
 0008                  WRITE (6,12)
 0009               12 FORMAT (1H1,T30,'CAPITAL CASE   I-D'///T10,'YEAR',6X,'NUCLEAR',7X,'
                      1LWR    OPERATING LIABILITY  LWR FUEL   FBR FUEL'/T19,'GENERATING
                      2CAPITAL   & MAINT.  INSURANCE  COSTS AT   COSTS AT'/T20,'CAPACITY',5
                      3X,'COSTS       COSTS       COSTS      PUPR = 0   PUPR = 0'/T21,'(MWE)',6X
                      4,'(MPKWH)     (MPKWH)     (MPKWH)     (MPKWH)     (MPKWH)'///)
 0010                  WRITE (6,13)  (JEAR(I),NGCP(I),CCL(I),CML(I),UNS(I),FCCLO(I),FCCFO
                      1(I),I=1,46)
 0011               13 FORMAT (T10,I4,F15.2,5F10.5)
 0012                  READ (5,15          ) SPINV,XCOR,PUPF,CEFFF,CEFFL,BURNL,EXPL,UCHG,AVL
                      1WR,AVFBR,XCRR,FABLOS,REPLOS,DISRAT,F
 0013               15 FORMAT (F15.5,65X)
 0014               16 WRITE (6,18)
 0015               18 FORMAT (1H1,T16,'INPUT DATA'///)
 0016                  WRITE (6,20)
 0017               20 FORMAT (' ',F15.5)
 0018                  WRITE (6,22) SPINV
 0019               22 FORMAT (T10,'SPINV  =',F15.5)
 0020                  WRITE (6,20)
 0021                  WRITE (6,24) XCOR
 0022               24 FORMAT (T10,'XCOR   =',F15.5)
 0023                  WRITE (6,20)
 0024                  WRITE (6,26) PUPF
 0025               26 FORMAT (T10,'PUPF   =',F15.5)
 0026                  WRITE (6,20)
 0027                  WRITE (6,28) CEFFF
 0028               28 FORMAT (T10,'CEFFF  =',F15.5)
```

```
      WRITE (6,20)
      WRITE (6,30) CEFFL
   30 FORMAT (T10,'CEFFL   =',F15.5)
      WRITE (6,20)
      WRITE (6,32) BURNL
   32 FORMAT (T10,'BURNL   =',F15.5)
      WRITE (6,20)
      WRITE (6,34) EXPL
   34 FORMAT (T10,'EXPL    =',F15.5)
      WRITE (6,20)
      WRITE (6,36) UCHG
   36 FORMAT (T10,'UCHG    =',F15.5)
      WRITE (6,20)
      WRITE (6,38) AVLWR
   38 FORMAT (T10,'AVLWR   =',F15.5)
      WRITE (6,20)
      WRITE (6,40) AVFBR
   40 FORMAT (T10,'AVFBR   =',F15.5)
      WRITE (6,20)
      WRITE (6,42) XCRR
   42 FORMAT (T10,'XCRR    =',F15.5)
      WRITE (6,20)
      WRITE (6,44) FABLOS
   44 FORMAT (T10,'FABLOS  =',F15.5)
      WRITE (6,20)
      WRITE (6,46) REPLOS
   46 FORMAT (T10,'REPLOS  =',F15.5)
      WRITE (6,20)
      WRITE (6,48) DISRAT
   48 FORMAT (T10,'DISRAT  =',F15.5)
      WRITE (6,20)
      WRITE (6,50) F
   50 FORMAT (T10,'F       =',F15.5)
C
C
C           INITIALIZE VARIABLES
   52 NYEAR = 1964
      DO 54 I = 1,45
      MINCST(I) = 1000.0
      CONGC(I) = 0.0
   54 CST(I) = 10000.0
      M = 0
      N = 1
      KAP = 0
      KAPL = 0
      KAPF = 0
      PUBAL = 0.0
      FPHPY = 8766.0
      TNGC = 0.0
      MKAPL = 0
      MKAPF = 0
      CENGC = 0.0
   55 NYEAR = NYEAR + 1
```

```
                  INGCP = NGCP(N) - KAP
                  NUMB = NYEAR - 1978
                  IF (NUMB .NE. 0) GO TO 60
                  INCF = 1000.0
                      GO TO  70
               60 NUMB = NYEAR - 1982
                  IF (NUMB .NE. 0) GO TO 62
                    INCF = 1000.0
                      GO TO  70
               62 CONTINUE
                      GO TO  70
               64 NUMB = NYEAR - 1985
                  IF (NUMB .GE. 0) GO TO 66
               45 INCF = 0
                      GO TO  70
               66 TINV = SPINV * XCOR
                  IF (TINV .LE. 0.0) GO TO 51
                  UNCF = PUBAL / TINV
               51 IF (TINV .GT. 0.00) GO TO 68
                  WRITE (6,53) TINV
               53 FORMAT (T30,'TINV = ',F15.5)
               68 CONTINUE
                  NNCF = UNCF
                  INCF = 1000 * NNCF
                  IF (INCF .LT. INGCP) GO TO 70
                  INCF = INGCP
               70 INCL = INGCP - INCF
C                     COMPUTE AND PRINT PLUTONIUM BALANCE
                  CALL PUBA
                  CONTINUE
                  IF (N .GT. 1) GO TO 74
                  WRITE (6,72)
               72 FORMAT (1H1,'YEAR  NUCLEAR      LWR',6X,'LWR',9X,'LWR',9X,'FBR',6X,
                 1'FBR',7X,'FBR',12X,'FBR',9X,'PLUTONIUM'/T7,'GENERATINGGENERATING F
                 2RAC-     PLUTONIUM     GENERATING FRAC-     PLUTONIUM',6X,'PLUTONIUM',
                 37X,'BALANCE'/T8,'CAPACITY  CAPACITY   TION      PRODUCTION     CAPACI
                 4TY  TION   REQUIREMENTS      PRODUCTION'/T9,'(MWE)',6X,'(MWE)',16X,
                 5'(KG)',11X,'(MWE)',15X,'(KG)',11X,'(KG)',10X,'(KG)'///)
               74 WRITE(6,80) NYEAR,NGCP(N),KAPL,PLWR,PUSL,KAPF,PFBR,PURF,PUSF,PUBAL
               80 FORMAT (I5,2F10.0,F7.3,F15.4,F10.0,F7.3,3F15.4)
                  KAP = NGCP(N)
                  N = N + 1
                  IF ( N .LE. 46) GO TO 56
C                     REINDEX INITIAL CONDITIONS OF VARIABLES
               81 PUPR = 0.0
                  WRITE(6,104)PUPR
               82 N = 1
                  KAP = 0
                  NYEAR = 1964
                  KAPL = 0
                  KAPF = 0
                  PUBAL = 0.0
                  TNGC = 0.0
```

```
0125          MKAPL = 0
0126          MKAPF = 0
0127          CENGC = 0.0
0128          CODNGC = 0.00
0129          CCENGC = 0.0
        C        REINCREMENT YEAR,REDETERMINE INCREMENTALS OF CAPACITY
0130       84 NYEAR = NYEAR + 1
0131          INGCP = NGCP(N) - KAP
0132          NUMB = NYEAR - 1978
0133          IF (NUMB .NE. 0) GO TO 85
0134            INCF = 1000.0
0135          GO TO 92
0136       85 NUMB = NYEAR - 1982
0137          IF (NUMB .NE. 0) GO TO 86
0138            INCF = 1000.0
0139          GO TO 92
0140       86 CONTINUE
0141          GO TO 92
0142       88 NUMB = NYEAR - 1985
0143          IF (NUMB .GE. 0) GO TO 90
0144          INCF = 0
0145          GO TO 92
0146       90 UNCF = PUBAL / TINV
0147          NNCF = UNCF
0148          INCF = 1000 * NNCF
0149          IF (INCF .LT. INGCP) GO TO 92
0150          INCF = INGCP
0151       92 INCL = INGCP - INCF
        C        RECOMPUTE PLUTONIUM BALANCE
0152          CALL PUBA
0153          CONTINUE
        C        COMPUTE ENERGY COSTS
0154          CALL ENRGCT
0155          CONTINUE
        C        COMPUTE ECONOMIC IDEAL
0156          CALL ECNIDL
0157          CONTINUE
0158          ADCOST = TNGC - CENGCO(N)
0159          M = M + N
0160          IF (M .LE. 67022)GO TO 103
        C        PRINT ECONOMIC RESULTS
0161          IF (N .GT. 1) GO TO 100
0162          WRITE (6,96)
0163       96 FORMAT (    ' YEAR    ANNUAL     PLUTONIUM    PRESENT  DISCOUNTED  CUM
             1ULATIVE  ECON   ECON     ANN       DISCOUNTED CUMULATIVE ADDITIONAL'/T
             29,'NUCLEAR    INVENTORY      WORTH       NUCLEAR       NUCLEAR LWR   FBR
             3     NUCLEAR      ECONOMIC     ECONOMIC    NUCLEAR'/T8,'GENERATING',13X'
             4FACTOR   GENERATING  GENERATINGFRAC- FRAC-  GENERATING GENERATING
             5GENERATING GENERATING'/T10,'COSTS       COSTS',18X,'COSTS',7X,'COSTS
             6     TION    TION    COSTS',6X,'COSTS',6X,'COSTS',6X,'COSTS'/T9,'($ B
             7IL)    ($ BIL)',16X,'($ BIL)       ($ BIL)',16X,'($ BIL)      ($ BIL)
             8  ($ BIL)     ($ BIL)'///)
0164      100 WRITE (6,102)(NYEAR,ANGC,PUINV,PWF,DNGC,TNGC,EPLWR,EPFBR,EANGC,DEN
```

```
          1GC,CENGC,ADCOST)
      102 FORMAT (I5,2F11.5,F11.6,2F11.5,2F6.3,4F11.5)
          A(N) = NYEAR
          A(46+N) = PFBR
          A(92+N) = EPFBR
          B(N) = NYEAR
          B(46+N) = TNGC
          B(92+N) = CENGC
          B(138+N) = ADCOST
          C(N) = NYEAR
          C(46+N) = ADCOST
C            ADVANCE VARIABLES
      103 CONTINUE
          KAP = NGCP(N)
          N = N + 1
C            TEST FOR COMPLETION
          IF (M .GT. 67022 ) GO TO  101
          IF (N .LE. 46) GO TO 84
          PUPR = PUPR + 0.50
          IF (M .LT. 67022) GO TO 82
          IF (M .EQ. 67022) GO TO 105
          IF (PUPR .GT. 30.00) GO TO 81
      101 CONTINUE
          IF (N .LE. 46) GO TO 84
          WRITE (6,93)
       93 FORMAT(1H1,T15,'GENERATING  AND  FUEL  CYCLE  COSTS  (MILS/KWH)'//
         1/T10,'YEAR',9X,'UCLWR',9X,'LWRFCC',9X,'UCFBR',9X,'FBRFCC'/)
          WRITE (6,94) (JEAR(I),UNCLWR(I),LWRFCC(I),UNCFBR(I),FBRFCC(I), I =
         11,46)
       94 FORMAT (T10,I4,4F15.5)
C            PLOT RESULTS
          CALL PLOT9 (1,A,45,3,0,FUNC,2014.0,1965.0,0.985,-0.015)
          CONTINUE
          CALL PLOT9 (2,B,46,4,0,FUNC,2014.0,1965.0,250.000,0.000)
          CONTINUE
          CALL PLOTS (3,C,46,2,0,FUNC,2014.0,1965.0,ADCCST,2.000)
          CONTINUE
C            TEST AND ADVANCE PLUTONIUM PRICE
          IF (PUPR .GT. 30.00) GO TO 105
          PUPR = PUPR + 0.50
          WRITE (6,104)PUPR
      104 FORMAT ('1',T30,'PUPR = ',F5.2)
          GO TO 82
      105 CONTINUE
          WRITE (6,106)
      106 FORMAT (1H1,T20,'MINIMUM GENERATING COSTS'///' YEAR',6X,'MINIMUM',
         18X,'MINIMUM',8X,'MINIMUM      PLUTONIUM'/T11,'ANNUAL',8X,'DISCOUNTE
         2D      CUMULATIVE      PRICE'/T11,'NUCLEAR',8X,'NUCLEAR',7X,'DISCOUN
         3TED     YIELDING'/T10,'GENERATING      GENERATING      GENERATING
         4MINIMUM'/T12,'COSTS',10X,'COSTS',10X,'COSTS',6X,'GENERATING'/T11,'
         5($ BIL)',8X,'($ BIL)',8X,'($ BIL)',6X,'COSTS'///)
          WRITE (6,107)(JEAR(I),MINCST(I),DINCST(I),CENGCC(I),PUPRO(I),I=1,4
         16)
```

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FORTRAN IV G LEVEL  19                    MAIN                DATE = 71158          22/51/17

 0205          107 FORMAT (I5,3F15.5,F10.2)
 0206              IF (M .EQ. 67022) GO TO 81
           C          INCREMENT CASE COUNTER
 0207              L = L + 1
 0208              IF (L .GT.5) GO TO 108
 0209              XCOR =  XCOR + 0.1
 0210              GO TO 16
 0211          108 XCOR = 1.5
 0212              IF (L .GT. 9) GO TO 110
 0213              XCRR =  XCRR - 0.1
 0214              GO TO 16
 0215          110 XCOR = 1.5
 0216              IF (L .GT. 13) GO TO 112
 0217              BURNL = BURNL - 5.0
 0218              UCHG = 103080 + 21.9158 * BURNL
 0219              EXPL = 0.51282 - 0.001328 * BURNL
 0220              GO TO 16
 0221          112 BURNL = 30.0
 0222              UCHG = 103080 + 21.9158 * BURNL
 0223              EXPL = 0.51282 - 0.001328 * BURNL
 0224              IF  (L .GT. 18) GO TO 114
 0225              DISRAT = DISRAT - 0.01
 0226              GO TO 16
 0227          114 DISRAT = 0.10
 0228              IF (L .GT. 23) GO TO 116
 0229              DISRAT = DISRAT + 0.01
 0230              GO TO 16
 0231          116 DISRAT = 0.10
 0232              IF  (L .GT. 25) GO TO 118
 0233              FABLOS = FABLOS + 0.05
 0234              GO TO 16
 0235          118 FABLOS = 1.05
 0236              IF (L .GT. 27) GO TO 120
 0237              REPLOS = REPLOS -0.02
 0238              GO TO 16
 0239          120 STOP
 0240              END
```

```
                              COMMON BLOCK /         / MAP SIZE     CB8
SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
NGCP            0      KAPL           B8      KAPF           BC      KAP            CC      MKAPF          C4
MKAPL          C8      KNCF           CC      KNCL           D0      INGCP          D4      INCL           D8
INCF           DC      CCL            E0      CML           198      UNS           250      FCCLO         308
FCCFC         3C0      SPINV         478      XCOR          47C      PUPF          480      CEFFF         484
CEFFL         488      BURNL         48C      FXPL          490      UCHG          494      AVLWR         498
AVFBR         49C      PUPR          4A0      FABLOS        4A4      REPLOS        4A8      DISRAT        4AC
N             4B0      PUBAL         4B4      FPHPY         4B8      TNGC          4BC      CENGC         4C0
NYEAR         4C4      PUSL          4C8      PURF          4CC      PUSF          4D0      TINV          4D4
ACFBR         4D8      ACLWR         4DC      PWF           4E0      PLWR          4E4      PFBR          4E8
EPLWR         4EC      EPFBR         4FC      ANGC          4F4      PUINV         4F8      ADCOSI        4FC
DNGC          500      EANGC         504      DENGC         5C8      F             50C      MINCST        510
DINCST        5C8      CENGCO        68C      PUPRO         738      CST           7F0      DCST          8A8
CDNGC         960      XPUPR         A18      COENGC        AD0      LWRFCC        AD4      FBRFCC        B8C
UNCLWR        C44      UNCFBR        CFC      XCRR          CB4

                              COMMON BLOCK /ONE      / MAP SIZE       4
SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
M               0

                              SUBPROGRAMS CALLED
SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
IBCOM#         1FC     PUBA          20C      ENRGCT        204      ECNIDL        208      PLOT9         20C
PLOTS          210

                              SCALAR MAP
SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
L              28C     I             290      NUMB          294      UNCF          298      NNCF          29C
CCDNGC         2A0     FUNC          2A4

                              ARRAY MAP
SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
JEAR           2A8     A             36C      B             588      C             868      OBNGCP        9D8

                              FORMAT STATEMENT MAP
SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
    10         A90         12        A9E          13        BC2          15        BD0          18        BD7
    20         BED         22        BF5          24        CC6          26        C17          28        C28
    30         C39         32        C4A          34        C5B          36        C6C          38        C7D
    40         C8E         42        C9F          44        CB0          46        CC1          48        CD2
    50         CE3         53        CF4          72        D04          80        E56          96        E70
   102        1077         93       1092          94       10FC         104       1107         106       111A
   107        1267
```

```
      SUBROUTINE PUBA
      COMMON NGCP,KAPL,KAPF,KAP,MKAPF,MKAPL,KNCF,KNCL,INGCP,INCL,INCF,CC
     1L,OML,UNS,FCCLO,FCCFO,SPINV,XCOR,PUPF,CEFFF,CEFFL,BURNL,EXPL,UCHG,
     2AVLWR,AVFBR,PUPR,FABLOS,REPLOS,DISRAT,N,PUBAL,FPHPY,TNGC,CENGC,NYE
     3AR,PUSL,PURF,PUSF,TINV,ACFBR,ACLWR,PWF,PLWR,PFBR,EPLWR,EPFBR,ANGC,
     4PUINV,ADCOST,DNGC,EANGC,DENGC,F,MINCST,DINCST,CENGCO,PUPRO,CST,DCS
     5T,CDNGC,XPUPR,COENGC,LWRFCC,FBRFCC,UNCLWR,UNCFBR,XCRR
      DIMENSION JEAR(46),NGCP(46),CCL(46),CML(46),UNS(46),FCCLO(46),FCCF
     1O(46),A(138),B(184),C(92),MINCST(46),DINCST(46),CENGCO(46),PUPRO(4
     26),CST(46),DCST(46),CDNGC(46),XPUPR(46),OBNGCP(46),LWRFCC(46),FBRF
     3CC(46),UNCLWR(46),UNCFBR(46)
      REAL NGCP,OBNGCP,KAPL,KAPF,KAP,MKAPF,MKAPL,KNCF,KNCL,INGCP,INCL,IN
     1CF,MINCST,LWRFCC
      K = 0
      PUPL = (BURNL ** EXPL) * UCHG * 0.001 * 0.001
      PUBALI = PUBAL
      IF(BURNL .LE. 0.00) GO TO 202
      PUPL = (BURNL ** EXPL) * UCHG * 0.001
  202 IF(BURNL .GT. 0.00) GO TO 206
      WRITE (6,204)BURNL
  204 FORMAT (T20,'BURNL =',F15.5)
  206 CONTINUE
      PUSL = PUPL * KAPL * 0.001 * REPLOS
      PUSF = PUPF * KAPF * 0.001 *REPLOS
      PURL = 0.0
      PURF=(INCF*0.001*SPINV*XCOR + KAPF*0.001*XCRR*SPINV/2.0) * FABLOS
      PUBAL = PUBALI+ PUSL + PUSF - PURF - PURL
      IF (PUBAL .GE. 0.0) GO TO 208
      INCF = INCF - 1000.0
      INCL = INGCP - INCF
      GO TO 206
  208 CONTINUE
      NUMB = NYEAR - 1985
      IF (NUMB .LT. 0) GO TO 210
      IF (K .EQ.100) GO TO 210
      IF (INCF .EQ. INGCP) GO TO 210
      IF (PUBAL .LT. 3500.0) GO TO 210
      INCF = INCF + 1000.0
      INCL = INGCP - INCF
      K = K + 1
      IF (INCF .LE.INGCP) GO TO 206
      INCF = INCF - 1000.0
      INCL = INGCP - INCF
      GO TO 206
  210 CONTINUE
      KAPL = KAPL + INCL
      KAPF = KAPF + INCF
      PLWR = KAPL / NGCP(N)
      PFBR = KAPF / NGCP(N)
      PUBAL = (F * PUBAL) + (1.0 - F) * PUBAL * EXP(-0.0479)
      CONTINUE
      RETURN
      END
```

COMMON BLOCK / / MAP SIZE DB8

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
NGCP	0	KAPL	B8	KAPF	BC	KAP	C0	MKAPF	C4
MKAPL	C8	KNCF	CC	KNCL	D0	INGCP	D4	INCL	D8
INCF	DC	CCL	E0	CML	198	UNS	250	FCCLO	308
FCCFO	3C0	SPINV	478	XCOR	47C	PUPF	480	CEFFF	484
CEFFL	488	BURNL	48C	EXPL	490	UCHG	494	AVLWR	498
AVFBR	49C	PUPR	4AC	FABLOS	4A4	REPLOS	4A8	DISRAT	4AC
N	4B0	PUBAL	4B4	FPHPY	4B8	TNGC	4BC	CENGC	4C0
NYEAR	4C4	PUSL	4C8	PURF	4CC	PUSF	4D0	TINV	4D4
ACFBR	4D8	ACLWR	4DC	PWF	4E0	PLWR	4E4	PFBR	4E8
EPLWR	4EC	EPFBR	4FC	ANGC	4F4	PUINV	4F8	ADCOST	4FC
UNGC	500	EANGC	504	DENGC	508	F	50C	MINCST	510
DINCST	5C8	CENGCO	68C	PUPRO	738	CST	7F0	DCST	8A8
CONGC	960	XPUPR	A1E	COENGC	AD0	LWRFCC	AD4	FBRFCC	B8C
UNCLWR	C44	UNCFBR	CFC	XCRR	DB4				

SUBPROGRAMS CALLED

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
FRXPR#	D4	IBCOM#	D8	EXP	DC				

SCALAR MAP

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
K	F4	PUPL	F8	PUBALI	FC	PURL	100	NUMB	104

ARRAY MAP

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
JEAR	108	A	1C0	B	3E8	C	6C8	OBNGCP	838

FORMAT STATEMENT MAP

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
204	8F0								

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FORTRAN IV G LEVEL  19                 ENRGCT              DATE = 71158          22/51/17
0001              SUBROUTINE ENRGCT
0002              COMMON NGCP,KAPL,KAPF,KAP,MKAPF,MKAPL,KNCF,KNCL,INGCP,INCL,INCF,CC
                 1L,OML,UNS,FCCLO,FCCFO,SPINV,XCOR,PUPF,CEFFF,CEFFL,BURNL,EXPL,UCHG,
                 2AVLWR,AVFBR,PUPR,FABLOS,REPLOS,DISRAT,N,PUBAL,FPHPY,TNGC,CENGC,NYE
                 3AR,PUSL,PURF,PUSF,TINV,ACFBR,ACLWR,PWF,PLWR,PFBR,EPLWR,EPFBR,ANGC,
                 4PUINV,ADCOST,DNGC,EANGC,DENGC,F,MINCST,DINCST,CENGCO,PUPRO,CST,DCS
                 5T,CDNGC,XPUPR,CDENGC,LWRFCC,FBRFCC,UNCLWR,UNCFBR,XCRR
0003              DIMENSION JEAR(46),NGCP(46),CCL(46),CML(46),UNS(46),FCCLO(46),FCCF
                 1O(46),A(138),B(184),C(92),MINCST(46),DINCST(46),CENGCO(46),PUPRO(4
                 26),CST(46),DCST(46),CDNGC(46),XPUPR(46),OBNGCP(46),LWRFCC(46),FBRF
                 3CC(46),UNCLWR(46),UNCFBR(46)
0004              REAL NGCP,OBNGCP,KAPL,KAPF,KAP,MKAPF,MKAPL,KNCF,KNCL,INGCP,INCL,IN
                 1CF,MINCST,LWRFCC
0005              CCF = CCL(N) * 1.25
0006              CMF = OML(N) * 1.25
0007              UCLWR = CCL(N) + CML(N) + UNS(N) + FCCLO(N) - (0.023 * PUPR)
0008              UNCLWR(N) = UCLWR
0009              UCFBR = CCF + OMF + UNS(N) + FCCFO(N) + (0.0257 * PUPR)
0010              UNCFBR(N) = UCFBR
0011              PCLWR = CCL(N) + CML(N)+ UNS(N)
0012              LWRFCC(N) = UCLWR - PCLWR
0013              PCFBR = CCF + OMF + UNS(N)
0014              FBRFCC(N) = UCFBR - PCFBR
0015              ACLWR = UCLWR * AVLWR * FPHPY * 0.001
0016              ACFBR = UCFBR * AVFBR * FPHPY * 0.001
0017              ANGC = NGCP(N) * ((PLWR * ACLWR) + (PFBR * ACFBR)) * 0.000001
0018              PUINV = PUBAL * PUPR * DISRAT * 1000.0 * 0.000001 * 0.001
0019              DISFAC = (1 + DISRAT) ** (N - 21)
0020              IF (DISFAC .GT. 0.005) GO TO 234
0021              IF (DISFAC .LT. 0.005) GO TO 230
0022          230 WRITE (6,232)DISFAC
0023          232 FORMAT (T30,'DISFAC = ',E15.5)
0024          234 CONTINUE
0025              PWF = 1 / DISFAC
0026              DNGC = PWF * (ANGC + PUINV)
0027              TNGC = TNGC + DNGC
0028              TOTCST = ANGC + PUINV
0029              IF (TOTCST .GT. CST(N)) GO TO 240
0030              CST(N) = TOTCST
0031              DCST(N) = DNGC
0032              CDDNGC = CDDNGC + DNGC
0033              CDNGC(N) = CDDNGC
0034              XPUPR(N) = PUPR
0035          240 CONTINUE
0036              RETURN
0037              END
```

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                                   COMMON BLCCK /       / MAP SIZE     CB8
SYMBCL    LOCATION       SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
NGCP             0       KAPL            B8     KAPF            BC     KAP             C0     MKAPF           C4
MKAPL           C8       KNCF            CC     KNCL            D0     INGCP           D4     INCL            D8
INCF            DC       CCL             E0     OML            198     UNS            250     FCCLO          308
FCCFO          3C0       SPINV          478     XCCR           47C     PUPF           480     CEFFF          4B4
CEFFL          488       BURNL          48C     EXPL           490     UCHG           494     AVLWR          498
AVFBR          49C       PUPR           4A0     FABLOS         4A4     REPLOS         4A8     DISRAT         4AC
N              4B0       PUBAL          4B4     FPHPY          4B8     TNGC           4BC     CENGC          4C0
NYEAR          4C4       PUSL           4C8     PURF           4CC     PUSF           4D0     TINV           4D4
ACFBR          4D8       ACLWR          4DC     PWF            4E0     PLWR           4E4     PFBR           4E8
EPLWR          4EC       EPFBR          4FC     ANGC           4F4     PUINV          4F8     ADCOST         4FC
DNGC           500       EANGC          504     DENGC          508     F              50C     MINCST         510
DINCST         5C8       CENGCO         68C     PUPRO          738     CST            7F0     DCST           8A8
CDNGC          960       XPUPR          A18     COENGC         AD0     LWRFCC         AD4     FBRFCC         B8C
UNCLWR         C44       UNCFBR         CFC     XCRR           DB4

                                   SUBPROGRAMS CALLED
SYMBOL    LOCATION       SYMBOL    LOCATICN     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
FRXPI#          B8       IBCOM#          BC

                                   SCALAR MAP
SYMBOL    LOCATION       SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
CCF             C8       OMF             CC     UCLWR           D0     UCFBR           D4     PCLWR           D8
PCFBR           DC       DISFAC          EC     TOTCST          E4     CODNGC          E8

                                   ARRAY MAP
SYMBOL    LOCATION       SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
JEAR            EC       A              1A4     B              3CC     C              6AC     OBNGCP         81C

                                   FORMAT STATEMENT MAP
SYMBCL    LOCATION       SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
   232         8D4
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```
      SUBROUTINE ECNIDL
      COMMON NGCP,KAPL,KAPF,KAP,MKAPF,MKAPL,KNCF,KNCL,INGCP,INCL,INCF,CC
     1L,OML,UNS,FCCLO,FCCFO,SPINV,XCOR,PUPF,CEFFF,CEFFL,BURNL,EXPL,UCHG,
     2AVLWR,AVFBR,PUPR,FABLOS,REPLCS,DISRAT,N,PUBAL,FPHPY,TNGC,CENGC,NYE
     3AR,PUSL,PURF,PUSF,TINV,ACFBR,ACLWR,PWF,PLWR,PFBR,EPLWR,EPFBR,ANGC,
     4PUINV,ADCOST,DNGC,EANGC,DENGC,F,MINCST,DINCST,CENGCO,PUPRO,CST,DCS
     5T,CDNGC,XPUPR,COENGC,LWRFCC,FBRFCC,UNCLWR,UNCFBR,XCRR
      COMMON/ONE/M
      DIMENSION JEAR(46),NGCP(46),CCL(46),CML(46),UNS(46),FCCLO(46),FCCF
     1O(46),A(138),B(184),C(92),MINCST(46),DINCST(46),CENGCO(46),PUPRO(4
     26),CST(46),CCST(46),CDNGC(46),XPUPR(46),OBNGCP(46),LWRFCC(46),FBRF
     3CC(46),UNCLWR(46),UNCFBR(46)
      REAL NGCP,OBNGCP,KAPL,KAPF,KAP,MKAPF,MKAPL,KNCF,KNCL,INGCP,INCL,IN
     1CF,MINCST,LWRFCC
      ACECRC = ACFBR - ACLWR
      IF (ACECRC .GT. 0 ) GO TO 252
      KNCF = INGCP
      KNCL = 0.0
      KYEAR = NYEAR - 1995
      IF (KYEAR .LT. 0) GO TO 250
      J = N - 30
      ONGCP = NGCP(J - 1)
      NONGCP = NGCP(J)
      IF (J .GT. 1) GO TO 248
      ONGCP = 0.0
  248 OBNGCP(J) = NONGCP - ONGCP
      KNCF = KNCF + OBNGCP(J)
      KNCL = KNCL - OBNGCP(J)
      GO TO 254
  250 KNCL = 0
      GO TO 254
  252 KNCL = INGCP
      KNCF = 0
  254 MKAPL = MKAPL + KNCL
      IF (MKAPL .LE. 0.0) GO TO 256
      MKAPF = MKAPF + KNCF
      GO TO 258
  256 MKAPL = 0.0
      MKAPF = NGCP(N)
  258 EPLWR = MKAPL / NGCP(N)
      EPFBR = MKAPF / NGCP(N)
      EANGC = NGCP(N) * ((EPLWR *ACLWR) + (EPFBR *ACFBR)) * 0.000001
      DENGC = PWF * EANGC
      CENGC = CENGC + DENGC
      IF (M .GT. 67022) GO TO 262
      IF (EANGC .GE. MINCST(N)) GO TO 260
      MINCST(N) = EANGC
      DINCST(N) = DENGC
      COENGC = COENGC + DENGC
      PUPRO(N) = PUPR
      IF (N .GT.1) GO TO 259
      CENGCO(N) = COENGC
      GO TO 262
  259 CENGCO(N) = CENGCO(N-1) + DINCST(N)
  260 CONTINUE
      CENGCO(N) = CENGCO(N-1) + DINCST(N)
  262 CONTINUE
      RETURN
      END
```

```
                              COMMON BLOCK /          / MAP SIZE      DB8
SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
NGCP             0     KAPL            B8     KAPF            BC     KAP             C0     MKAPF           C4
MKAPL           C8     KNCF            CC     KNCL            D0     INGCP           D4     INCL            D8
INCF            DC     CCL             EC     OML            198     UNS            250     FCCL0          308
FCCF0          3C0     SPINV          478     XCOR           47C     PUPF           480     CEFFF          484
CEFFL          488     BURNL          48C     EXPL           49C     UCHG           494     AVLWR          498
AVFBR          49C     PUPR           4AC     FABLOS         4A4     REPLOS         4A8     DISRAT         4AC
N              4B0     PUBAL          4B4     FPHPY          4B8     TNGC           4BC     CENGC          4C0
NYEAR          4C4     PUSL           4C8     PURF           4CC     PUSF           4D0     TINV           4D4
ACFBR          4D8     ACLWR          4DC     PWF            4E0     PLWR           4E4     PFBR           4E8
EPLWR          4EC     EPFBR          4FC     ANGC           4F4     PUINV          4F8     ADCOST         4FC
DNGC           500     EANGC          504     DENGC          5C8     F              50C     MINCST         510
DINCST         5C8     CENGCO         68C     PUPRO          738     CST            7F0     DCST           8A8
CDNGC          960     XPUPR          A18     COENGC         AD0     LWRFCC         AD4     FBRFCC         B8C
UNCLWR         C44     UNCFBR         CFC     XCPR           DB4

                              COMMON BLOCK /ONE       / MAP SIZE        4
SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
M                0

                              SCALAR MAP
SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
ACECRC          FC     KYEAR          10C     J              104     ONGCP          108     NONGCP         10C

                              ARRAY MAP
SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
JEAR           110     A              1C8     B              3F0     C              6D0     OBNGCP         840
```

```
0001           SUBROUTINE PLOT9(NO,A,N,M,NFUNC,FUNC,XLAX,XLIN,YLAX,YLIN)
          C    PURPOSE - TO PLOT A GRAPH WITH ONE INDEPENDENT VARIABLE AND UP
          C    TO 9 DEPENDENT VARIABLES, WITH THE ADDITICNAL ABILITY TO PLOT A
          C    CALCULATED CURVE. THE INDEPENDENT VARIABLE IS PLOTTED ON A
          C    HORIZONTAL AXIS, THE DEPENDENT ONES CN A VERTICAL AXIS. WIDTH
          C    IS 100 PRINT POSITICNS, HEIGHT IS 50. EVERY PCINT OF EACH
          C    DEPENDENT VARIABLE IS INDICATED BY A NUMBER (1-9), WHILE THE
          C    CALCULATED POINTS ARE DENOTED BY ASTERISKS.
          C    PARAMETER USAGE.
          C        NO    A FIXED POINT NUMBER, UP TO 3 DIGITS, PRINTED AS THE
          C              CHART NUMBER
          C        A     A VECTOR WHOSE FIRST N POSITIONS CONTAIN THE INDEPENDENT
          C              VARIABLE, AND WHOSE NEXT M SETS OF N POSITIONS CONTAIN
          C              THE DEPENDENT VARIABLES
          C        N     NUMBER OF CBSERVATICNS
          C        M     NUMBER OF VARIABLES (INDEPENDENT & DEPENDENT)
          C        NFUNC GREATER THAN ZERO IF A CALCULATED CURVE IS TO BE
          C              PRINTED
          C        FUNC  SUBROUTINE TO GENERATE CALCULATED CURVE. IF ONE WANTED.
          C              ELSE IS A DUMMY. PROGRAM CALLING PLOT MUST HAVE AN
          C              'EXTERNAL FUNC'. SUBROUTINE CALLED BY CALL FUNC (X,Y),
          C              WHERE X IS GIVEN TO SUBROUTINE AND Y RETURNED.
          C        XLAX,XLIN,YLAX,YLIN  MAXIMUM AND MINIMUM VALUES OF THE
          C              INDEPENDENT AND DEPENDENT VARIABLES TC BE USED IN THE
          C              PLOT IF XLAX = XLIN, THE PRCGRAM CALCULATES ITS OWN
          C              MAXIMUM AND MINIMUM FOR THE INDEPENDENT VARIABLE.
          C              SIMILARLY FCR YLAX = YLIN
          C    REQUIRED SUBROUTINES. FUNC (IF USED), AND SCAL.
0002           DIMENSION IOUT(101),XPR(11),A(1),CALC(102)
          C    CALC IS 1 LARGER THAN NEEDED IN CASE XMIN + 1CC*XSCAL
          C    SHOULD BE LARGER THAN XMAX.  THIS PREVENTS SLOPOOVER INTO
          C    NEXT LOCATION.        LOOK AROUND CARD #950 TO SEE WHAT I MEAN.
          C    CALC IS WHERE CALCULATED FUNCTION GOES.
0003           EQUIVALENCE (IOUT(1),XPR(1))
0004         1 FORMAT(1H1,60X,7H CHART ,I3)
0005       118 FCRMAT (1H ,12X,2H- ,101A1,'-')
          C  2 FORMAT (1H ,E12.3,'+ ',101A1,'+',E12.3)
0006         2 FORMAT (1H ,F12.3,'+ ',101A1,'+',F12.3)
0007         7 FORMAT (1H ,14X,10('+.........'),1H+)
          C  8 FORMAT%1H0,9X,11E10.3<
0008         8 FORMAT(1H0,9X,11F10.3)
          C    PRINT CHART NO.
0009           WRITE(6,1) NO
0010           ICOUNT = 4
          C    IF NO EXTREMES OF X GIVEN, FIND THEM
0011           IF (XLAX - XLIN) 20,10,20
0012        10 XMIN = A(1)
0013           XMAX = XMIN
0014           DO 15 J = 1,N
0015           IF (A(J) - XMIN) 11,12,12
0016        12 IF (A(J) - XMAX) 15,15,14
0017        11 XMIN = A(J)
0018           GO TC 15
```

```
   14 XMAX = A(J)
   15 CONTINUE
      GO TO 202
   20 XMAX=XLAX
      XMIN=XLIN
C     CALCULATE RAW SCALE SIZE
  202 XSCAL=(XMAX-XMIN)/100.
C     ROUTINE TO CALCULATE EXACT SCALE SIZE AND END POINTS
      CALL SCALS(XSCAL,XMAX,XMIN)
C     IF NO EXTREMES OF Y GIVEN, FIND THEM
      IF (YLAX - YLIN) 110,112,110
  112 L  = N + 1
      YMIN = A(L)
      YMAX=YMIN
      LL = M*N
      DO 40 J = L,LL
      IF(A(J)-YMIN) 28,26,26
   26 IF(A(J)-YMAX) 40,40,30
   28 YMIN=A(J)
      GO TO 40
   30 YMAX=A(J)
   40 CONTINUE
      GO TO 201
  110 YMAX=YLAX
      YMIN=YLIN
C     GET SCALE SIZE AND END POINTS
  201 YSCAL = (YMAX - YMIN ) / 50.
      CALL SCALS(YSCAL,YMAX,YMIN)
C     PRINT TOP SCALE
      XPR(1) = XMIN
      DO 200 JP=1,10
      XPR(JP+1) = XPR(JP) + XSCAL * 10.
C     TO MAKE SURE THAT ZERO REALLY PRINTS AS ZERO, NOT A SMALL NUMBER
C          CAUSED BY ROUNGING ERRORS.
      IF (ABS(XPR(JP+1) - .5 * XSCAL)) 240,240,200
  240 XPR(JP+1) = 0.
  200 CONTINUE
C     THE FOLLOWING WRITE STATEMENT IS COMMENTED OUT TO SUPPRESS SCALE
C     PRINT ON TOP LINE
C     WRITE(6,8) (XPR(JP),JP=1,11)
      WRITE(6,7)
C     IF CALCULATED CURVE WANTED GET VALUES BETWEEN XMIN AND XMAX
      IF (NFUNC) 210,210,211
  211 F = XMIN
      JP = 1
  213 CALL FUNC(F,CALC(JP))
      IF (F - XMAX) 212,210,210
  212 F = F + XSCAL
      JP = JP + 1
      IF(JP.GT.102)  XSCAL=XSCAL+.02*XSCAL
      IF(JP.GT.102) GO TO 211
      GO TO 213
  210 CONTINUE
```

```
      C      START PRINT AT MAXIMUM Y
             YPR = YMAX
      C      CLEAR PRINT LINE
         230 DO 55 JP = 1,101
          55 IOUT(JP) = 0
      C      IF CALCULATED CURVE WANTED SET UP POINTS
             IF (NFUNC) 214,214,215
         215 F = XMIN
      C      SCAN ALL VALUES OF Y FOR X BETWEEN XMIN AND XMAX
             JP = 1
      C      IS POINT WITHIN HALF A SCALE OF PRINT POSITION
         220 IF (ABS(YPR-CALC(JP)) - .5 * YSCAL) 216,217,218
      C      IF EXACTLY  BETWEEN PRINT POSITIONS ONLY PRINT IT ONCE
         217 IF (YPR - CALC (JP)) 218,216,216
      C      BELIEVE IT OR NOT THIS IS AN ASTERISK (NUMBER TOO LARGE TO WRITE
      C           AS ONE NUMBER)
         216 IOUT(JP) = 92*16777216
         218 IF (F - XMAX) 219,214,214
         219 JP = JP +1
             F = F + XSCAL
             GO TO 220
      C      RUN DOWN EACH SET OF DEPENDENT VARIABLES
      C      IF NO POINTS WANTED
         214 IF (N) 70,70,300
         300 DO 221 J = 2,M
             DO 222 L = 1,N
      C      CALCULATE SUBSCRIPT FOR A
             LL = (J - 1) * N + L
      C      IS IT WITHIN HALF A SCALE OF PRINT POSITION
             IF (ABS(YPR - A(LL)) - .5 * YSCAL) 223,224,225
      C      IF EXACTLY HALFWAY BETWEEN, PRINT ONLY ONCE
         224 IF (YPR - A(LL)) 225,223,223
      C      FIND HORIZONTAL POSITION
         223 JP = (A(L) -XMIN) / XSCAL + 1.5
      C      IF OFF GRAPH, FORGET IT
             IF (JP - 1) 225,226,226
         226 IF (JP - 101) 227,227,225
      C      THIS GIVES 1,2,3 ETC. FOR J=2,3,4 ETC
         227 IOUT (JP) = (J - 17) * 16777216
         225 CONTINUE
         222 CONTINUE
         221 CONTINUE
          70 ICOUNT = ICOUNT +1
      C      PRINT VALUE ON VERTICAL AXIS EVERY FIVE POSITIONS
             IF (ICOUNT - 5) 120,119,120
         120 WRITE(6,118) (IOUT(JP),JP=1,101)
             GO TO 80
      C      MAKE ZERO PRINT AS ZERO, NOT SMALL NUMBER
         119 IF (ABS(YPR )-.5 * YSCAL)  232,232,233
         232 F= 0.
             GO TO 234
         233 F = YPR
         234 WRITE(6,2) F,(IOUT(JP),JP=1,101),F
```

```
0096            ICOUNT = 0
          C     IF REACHED YMIN, STOP
0097         80 IF (YPR - YMIN) 86,86,45
          C     ELSE DECREMENT Y
0098         45 YPR = YPR - YSCAL
0099            GO TO 230
0100         86 WRITE(6,7)
          C     PRINT BOTTOM SCALE
0101            XPR(1) = XMIN
0102            DO 90 JP =1,10
0103            XPR(JP+1)=XPR(JP)+XSCAL*10.
0104            IF (ABS(XPR(JP+1) - .5*XSCAL)) 231,231,90
0105        231 XPR(JP+1) = 0.
0106         90 CONTINUE
0107            WRITE(6,8) (XPR(JP),JP=1,11)
0108            RETURN
0109            END
```

SUBPROGRAMS CALLED

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
IBCLM#	228	SCALS	22C	FUNC	230				

EQUIVALENCE DATA MAP

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
IOLT	268	XPR	268						

SCALAR MAP

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
NO	3FC	ICOUNT	40C	XLAX	404	XLIN	408	XMIN	40C
XMAX	410	J	414	N	418	XSCAL	41C	YLAX	420
YLIN	424	L	428	YMIN	42C	YMAX	430	LL	434
M	438	YSCAL	43C	JP	440	NFUNC	444	F	448
YPR	44C								

ARRAY MAP

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
A	450	CALC	454						

FORMAT STATEMENT MAP

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
1	5EC	118	5FE	2	610	7	626	8	63F

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FORTRAN IV G LEVEL  19                 SCALS              DATE = 71158         22/51/17              PAGE 0001

 0001                  SUBROUTINE SCALS(XSCAL,XMAX,XMIN)
                 C     PURPOSE. GIVEN RAW SCALE AND END POINTS, GET ROUNDED VALUES.
 0002                  F=ALOG10(XSCAL)
                 C     FIND NEXT LOWEST POWER OF 10.
 0003                  IF (F) 1,2,2
                 C     IF NEGATIVE, STOP FORTRAN FROM ROUNDING UP
 0004                1 JP=F-1
 0005                  GO TC 20
 0006                2 JP=F
                 C     FIND VALUE JUST LARGER THAN TAW YSCAL, OF FORM 1,2,2.5,2,OR 10
                 C          TIMES 10 TO AN INTEGRAL POWER
 0007               20 F=10.**JP
 0008                6 IF (F-XSCAL) 3,4,4
 0009                3 F=F+F
 0010                  IF (F-XSCAL) 5,4,4
 0011                5 F=1.25*F
 0012                  IF (F-XSCAL) 7,4,4
 0013                7 F=F+F
 0014                  IF (F-XSCAL) 30,4,4
 0015               30 F=F+F
 0016                  GO TC 6
                 C     SET EQUAL TO SCALE
 0017                4 XSCAL=F
 0018                  JP=XMAX/XSCAL
                 C     MAKE END POINTS INTEGRAL MULTIPLES OF SCALE
 0019               12 F=JP*XSCAL
 0020                  IF (F-XMAX) 10,11,11
 0021               10 JP=JP+1
 0022                  GO TO 12
 0023               11 XMAX=F
 0024                  JP=XMIN/XSCAL
 0025               13 F=JP*XSCAL
 0026                  IF (F-XMIN) 14,14,15
 0027               15 JP=JP-1
 0028                  GO TC 13
 0029               14 XMIN=F
 0030                  RETURN
 0031                  END


FORTRAN IV G LEVEL  19                 SCALS              DATE = 71158         22/51/17              PAGE 0002

                                SUBPROGRAMS CALLED
SYMBOL     LOCATION        SYMBOL    LOCATION       SYMBOL    LOCATION       SYMBOL    LOCATION       SYMBOL    LOCATION
FRXPI#        108          ALOG10       10C

                                SCALAR MAP
SYMBOL     LOCATION        SYMBOL    LOCATION       SYMBOL    LOCATION       SYMBOL    LOCATION       SYMBOL    LOCATION
F             11C          XSCAL        120         JP           124         XMAX         128         XMIN         12C
```

```
             C      SUBROUTINE PLOTS(NO,A,N,M,NFUNC,FUNC,XLAX,XLIN,YLAX,YLIN)
             C      PURPOSE - TO PLOT A GRAPH WITH ONE INDEPENDENT VARIABLE AND UP
             C      TO 9 DEPENDENT VARIABLES, WITH THE ADDITIONAL ABILITY TO PLOT A
             C      CALCULATED CURVE. THE INDEPENDENT VARIABLE IS PLOTTED ON A
             C      HORIZONTAL AXIS, THE DEPENDENT ONES ON A VERTICAL AXIS. WIDTH
             C      IS 100 PRINT POSITIONS, HEIGHT IS 50. EVERY POINT OF EACH
             C      DEPENDENT VARIABLE IS INDICATED BY A NUMBER (1-9), WHILE THE
             C      CALCULATED POINTS ARE DENOTED BY ASTERISKS.
             C      PARAMETER USAGE.
             C          NO    A FIXED POINT NUMBER, UP TO 3 DIGITS, PRINTED AS THE
             C                    CHART NUMBER
             C          A     A VECTOR WHOSE FIRST N POSITIONS CONTAIN THE INDEPENDENT
             C                    VARIABLE, AND WHOSE NEXT M SETS OF N POSITIONS CONTAIN
             C                    THE DEPENDENT VARIABLES
             C          N     NUMBER OF OBSERVATIONS
             C          M     NUMBER OF VARIABLES (INDEPENDENT & DEPENDENT)
             C          NFUNC GREATER THAN ZERO IF A CALCULATED CURVE IS TO BE
             C                    PRINTED
             C          FUNC  SUBROUTINE TO GENERATE CALCULATED CURVE. IF ONE WANTED.
             C                    ELSE IS A DUMMY. PROGRAM CALLING PLOT MUST HAVE AN
             C                    'EXTERNAL FUNC'. SUBROUTINE CALLED BY CALL FUNC (X,Y),
             C                    WHERE X IS GIVEN TO SUBROUTINE AND Y RETURNED.
             C          XLAX,XLIN,YLAX,YLIN  MAXIMUM AND MINIMUM VALUES OF THE
             C                    INDEPENDENT AND DEPENDENT VARIABLES TO BE USED IN THE
             C                    PLOT IF XLAX = XLIN, THE PROGRAM CALCULATES ITS OWN
             C                    MAXIMUM AND MINIMUM FOR THE INDEPENDENT VARIABLE.
             C                    SIMILARLY FOR YLAX = YLIN
             C      REQUIRED SUBROUTINES. FUNC (IF USED), AND SCAL.
             C      CALC IS 1 LARGER THAN NEEDED IN CASE XMIN + 100*XSCAL
             C      SHOULD BE LARGER THAN XMAX.  THIS PREVENTS SLOPOOVER INTO
             C      NEXT LOCATION.       LOOK AROUND CARD #950 TO SEE WHAT I MEAN.
             C      CALC IS WHERE CALCULATED FUNCTION GOES.
0001                SUBROUTINE PLOTS(NO,A,N,M,NFUNC,FUNC,XLAX,XLIN,YLAX,YLIN)
0002                DATA MISVAL,FLMISV/2*ZFFFF0000/
0003                DATA L1,L2,L3,L4,L5,L6,L7,L8,L9,L0,L11,L12,LA,LB,LC,LD,LE,LAS/'.',
                   1':','3','4','5','6','7','8','9','0','1','2','A','B','C','D','E',
                   2'*'/
0004                DATA  BLN2,LF/' ','F'/
0005                DIMENSION IOUT(101),XPR(11),CALC(102),A(1)
0006                DIMENSION ICNT(101)
0007                NN=0
0008              1 FORMAT(1H1,60X,7H CHART ,I3)
0009            118 FORMAT (1H ,12X,2H- ,101A1,'-')
             C    2 FORMAT (1H ,E12.3,'+ ',101A1,'+',E12.3)
0010              2 FORMAT (1H ,F12.3,'+ ',101A1,'+',F12.3)
0011              7 FORMAT (1H ,14X,10('+.........'),1H+)
             C    8 FORMAT%1H0,9X,11E10.3<
0012              8 FORMAT(1H0,9X,11F10.3)
             C      PRINT CHART NO.
0013                WRITE(6,1) NO
             C      IF NO EXTREMES OF X GIVEN, FIND THEM
0014                ICOUNT = 4
0015                IF (XLAX - XLIN) 20,10,20
```

```
0016          10 XMIN = A(1)
0017             XMAX = XMIN
0018             DO 15 J = 1,N
0019             IF (A(J) - XMIN) 11,12,12
0020          12 IF (A(J) - XMAX) 15,15,14
0021          11 XMIN = A(J)
0022             GO TO 15
0023          14 XMAX = A(J)
0024          15 CONTINUE
0025             GO TO 202
0026          20 XMAX=XLAX
0027             XMIN=XLIN
           C     CALCULATE RAW SCALE SIZE
0028         202 XSCAL=(XMAX-XMIN)/100.
           C     ROUTINE TO CALCULATE EXACT SCALE SIZE AND END POINTS
0029             CALL SCALS(XSCAL,XMAX,XMIN)
           C     IF NO EXTREMES OF Y GIVEN, FIND THEM
0030             IF (YLAX - YLIN) 110,112,110
0031         112 L  = N + 1
0032             YMIN = A(L)
0033             YMAX=YMIN
0034             LL = M*N
0035             DO 40 J = L,LL
0036             IF(A(J).EQ.FLMISV) GO TO 40
0037             IF(A(J)-YMIN) 28,26,26
0038          26 IF(A(J)-YMAX) 40,40,30
0039          28 YMIN=A(J)
0040             GO TO 40
0041          30 YMAX=A(J)
0042          40 CONTINUE
0043             GO TO 201
0044         110 YMAX=YLAX
0045             YMIN=YLIN
           C     GET SCALE SIZE AND END POINTS
0046         201 YSCAL = (YMAX - YMIN ) / 50.
0047             CALL SCALS(YSCAL,YMAX,YMIN)
0048                   IF((YMAX-50.0*YSCAL).GE.YMIN) GO TO 2011
0049             YMIN=YMAX-50.0*YSCAL
0050        2011 XPR(1)=XMIN
           C     PRINT TOP SCALE
0051             XPR(1) = XMIN
0052             DO 200 JP=1,10
0053             XPR(JP+1) = XPR(JP) + XSCAL * 10.
           C     TO MAKE SURE THAT ZERO REALLY PRINTS AS ZERO, NOT A SMALL NUMBER
           C         CAUSED BY ROUNGING ERRORS.
0054             IF( ABS(XPR(JP+1)-.5*XSCAL)) 240,240,200
0055         240 XPR(JP+1) = 0.
0056         200 CONTINUE
           C     THE FOLLOWING WRITE STATEMENT IS COMMENTED OUT TO SUPPRESS SCALE
           C     PRINT ON TOP LINE
           C     WRITE(6,8) (XPR(JP),JP=1,11)
0057             WRITE(6,7)
           C     IF CALCULATED CURVE WANTED GET VALUES BETWEEN XMIN AND XMAX
```

```
            IF (NFUNC) 210,210,211
        211 F = XMIN
            JP = 1
        213 CALL FUNC(F,CALC(JP))
            IF (F - XMAX) 212,210,210
        212 F = F + XSCAL
            JP = JP + 1
            IF(JP.GT.102)  XSCAL=XSCAL+.02*XSCAL
            IF(JP.GT.102) GO TO 211
            GO TO 213
        210 CONTINUE
C           START PRINT AT MAXIMUM Y
            YPR = YMAX
C           CLEAR PRINT LINE
        230 DO 55 JP=1,101
            IOUT(JP)=BLN2
         55 ICNT(JP)=0
C           IF CALCULATED CURVE WANTED SET UP POINTS
            IF (NFUNC) 214,214,215
        215 F = XMIN
C           SCAN ALL VALUES OF Y FOR X BETWEEN XMIN AND XMAX
            JP = 1
C           IS POINT WITHIN HALF A SCALE OF PRINT POSITION
        220 IF( ABS(YPR-CALC(JP))-.5*YSCAL) 216,217,218
C           IF EXACTLY  BETWEEN PRINT POSITIONS ONLY PRINT IT ONCE
        217 IF (YPR - CALC (JP)) 218,216,216
C           BELIEVE IT OR NOT THIS IS AN ASTERISK (NUMBER TOO LARGE TO WRITE
C                 AS ONE NUMBER)
        216 IOUT(JP)=LAS
            ICNT(JP)=-1
        218 IF (F - XMAX) 219,214,214
        219 JP = JP +1
            F = F + XSCAL
            GO TO 220
C           RUN DOWN EACH SET OF DEPENDENT VARIABLES
C           IF NO POINTS WANTED
        214 IF (N) 70,70,300
        300 DO 221 J = 2,M
            DO 222 L = 1,N
C           CALCULATE SUBSCRIPT FOR A
            LL = (J - 1) * N + L
C           IS IT WITHIN HALF A SCALE OF PRINT POSITION
            IF(A(LL).EQ.FLMISV) GO TO 225
            IF( ABS(YPR-A(LL))-.5*YSCAL) 223,224,225
C           IF EXACTLY HALFWAY BETWEEN, PRINT ONLY ONCE
        224 IF (YPR - A(LL)) 225,223,223
C           FIND HORIZONTAL POSITION
        223 JP = (A(L) -XMIN) / XSCAL + 1.5
C           IF OFF GRAPH, FORGET IT
            IF (JP-1) 425,226,226
        226 IF (JP-101) 227,227,425
        425 NN=NN+1
            GO TO 225
```

```
      C      THIS GIVES 1,2,3 ETC. FOR J=2,3,4 ETC
        227  ICNT(JP)=ICNT(JP)+1
             IF (ICNT(JP).GT.0) GO TO 401
             GO TO 225
        401  IF (ICNT(JP).GT.1) GO TO 402
             IOUT(JP)=L1
             GO TO 225
        402  IF (ICNT(JP).GT.2) GO TO 403
             IOUT(JP)=L2
             GO TO 225
        403  IF (ICNT(JP).GT.3) GO TO 404
             IOUT(JP)=L3
             GO TO 225
        404  IF (ICNT(JP).GT.4) GO TO 405
             IOUT(JP)=L4
             GO TO 225
        405  IF (ICNT(JP).GT.5) GO TO 406
             IOUT(JP)=L5
             GO TO 225
        406  IF (ICNT(JP).GT.6) GO TO 407
             IOUT(JP)=L6
             GO TO 225
        407  IF (ICNT(JP).GT.7) GO TO 408
             IOUT(JP)=L7
             GO TO 225
        408  IF (ICNT(JP).GT.8) GO TO 409
             IOUT(JP)=L8
             GO TO 225
        409  IF (ICNT(JP).GT.9) GO TO 410
             IOUT(JP)=L9
             GO TO 225
        410  IF (ICNT(JP).GT.10) GO TO 411
             IOUT(JP)=LC
             GO TO 225
        411  IF (ICNT(JP).GT.11) GO TO 412
             IOUT(JP)=L11
             GO TO 225
        412  IF (ICNT(JP).GT.12) GO TO 413
             IOUT(JP)=L12
             GO TO 225
        413  IF (ICNT(JP).GT.16) GO TO 414
             IOUT(JP)=LA
             GO TO 225
        414  IF (ICNT(JP).GT.32) GO TO 415
             IOUT(JP)=LB
             GO TO 225
        415  IF (ICNT(JP).GT.64) GO TO 416
             IOUT(JP)=LC
             GO TO 225
        416  IF (ICNT(JP).GT.128) GO TO 417
             IOUT(JP)=LD
             GO TO 225
        417  IF (ICNT(JP).GT.256) GO TO 418
```

```
0148              IOUT(JP)=LE
0149              GO TO 225
0150        418   IOUT(JP)=LF
0151          225 CONTINUE
0152          222 CONTINUE
0153          221 CONTINUE
0154           70 ICOUNT = ICOUNT +1
           C      PRINT VALUE ON VERTICAL AXIS EVERY FIVE POSITIONS
0155              IF (ICOUNT - 5) 120,119,120
0156          120 WRITE(6,118) (IOUT(JP),JP=1,101)
0157              GO TO 80
           C      MAKE ZERO PRINT AS ZERO, NOT SMALL NUMBER
0158          119 IF( ABS(YPR)-.5*YSCAL) 232,232,233
0159          232 F= 0.
0160              GO TO 234
0161          233 F = YPR
0162          234 WRITE(6,2) F,(IOUT(JP),JP=1,101),F
0163              ICOUNT = 0
           C      IF REACHED YMIN, STOP
0164           80 IF (YPR - YMIN) 86,86,45
           C      ELSE DECREMENT Y
0165           45 YPR = YPR - YSCAL
0166              GO TO 230
0167           86 WRITE(6,7)
           C      PRINT BOTTOM SCALE
0168              XPR(1) = XMIN
0169              DO 90 JP =1,10
0170              XPR(JP+1)=XPR(JP)+XSCAL*10.
0171              IF( ABS(XPR(JP+1)-.5*XSCAL)) 231,231,90
0172          231 XPR(JP+1) = 0.
0173           90 CONTINUE
0174              WRITE(6,8) (XPR(JP),JP=1,11)
0175              WRITE(6,9) N,NN
0176        9     FORMAT(1H0,'NUMBER OF POINTS ENTERED ',I5/1H ,'NUMBER OF POINTS RE
                 1JECTED ',I5)
0177              RETURN
0178              END
```

SUBPROGRAMS CALLED

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
IBCOM#	31C	SCALS	320	FUNC	324				

SCALAR MAP

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
MISVAL	35C	FLMISV	360	L1	364	L2	368	L3	36C
L4	370	L5	374	L6	378	L7	37C	L8	380
L9	384	L0	388	L11	38C	L12	390	LA	394
LB	398	LC	39C	LD	3A0	LE	3A4	LAS	3A8
BLN2	3AC	LF	3B0	NN	3B4	NO	3B8	ICOUNT	3BC
XLAX	3C0	XLIN	3C4	XMIN	3C8	XMAX	3CC	J	3D0
N	3D4	XSCAL	3D8	YLAX	3DC	YLIN	3E0	L	3E4
YMIN	3E8	YMAX	3EC	LL	3F0	M	3F4	YSCAL	3F8
JP	3FC	NFUNC	400	F	404	YPR	408		

ARRAY MAP

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
IOUT	4CC	XPR	5AC	CALC	5CC	A	764	ICNT	758

FORMAT STATEMENT MAP

SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION	SYMBOL	LOCATION
1	8FC	118	9CE	2	920	7	936	8	94F
9	958								

```
FORTRAN IV G LEVEL  19                FUNC              DATE = 71158          22/51/17            PAGE 0001

 0001          SUBROUTINE FUNC(XX,YY)                                          SCAL 390
 0002          COMMON A,B,C                                                    SCAL 400
 0003          YY=A*EXP(B*XX)+C                                                SCAL 410
 0004          RETURN                                                          SCAL 420
 0005          END                                                             SCAL 430
```

```
FORTRAN IV G LEVEL  19                FUNC              DATE = 71158          22/51/17            PAGE 0002

                              COMMON BLOCK /        / MAP SIZE        C
SYMBOL    LOCATION      SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
A               0       B                4     C                8

                              SUBPROGRAMS CALLED
SYMBOL    LOCATION      SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
EXP            94

                              SCALAR MAP
SYMBOL    LOCATION      SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION     SYMBOL    LOCATION
YY             9C       XX              AC
```

```
FORTRAN IV G LEVEL  19            FUNC1            DATE = 71158          22/51/17            PAGE 0001

 0001          SUBROUTINE FUNC1(XX,YY)                                       SCAL 440
 0002          COMMON A,B,C                                                  SCAL 450
 0003          YY=0.0                                                        SCAL 460
 0004          RETURN                                                        SCAL 470
 0005          END                                                           SCAL 480
```

```
FORTRAN IV G LEVEL  19            FUNC1            DATE = 71158          22/51/17            PAGE 0002

                        COMMON BLOCK /        / MAP SIZE        C
SYMBOL    LOCATION      SYMBOL    LOCATION    SYMBOL    LOCATION    SYMBOL    LOCATION    SYMBOL    LOCATION
A                0      B                4    C                8

                            SCALAR MAP
SYMBOL    LOCATION      SYMBOL    LOCATION    SYMBOL    LOCATION    SYMBOL    LOCATION    SYMBOL    LOCATION
YY              94      XX              98
```

```
F88-LEVEL LINKAGE EDITOR OPTIONS SPECIFIED XREF,LET,LIST
          VARIABLE OPTIONS USED -  SIZE=(112640,10240)-          DEFAULT OPTION(S) USED
****MAIN      NOW REPLACED IN DATA SET
```

CROSS REFERENCE TABLE

CONTROL SECTION			ENTRY							
NAME	ORIGIN	LENGTH	NAME	LOCATION	NAME	LOCATION	NAME	LOCATION	NAME	LOCATION
MAIN	00	2294								
PULA	2298	BE0								
ENRGCT	2E78	BA2								
ECNTOL	3A20	CC2								
PLOT9	4628	E44								
SCALS	5470	3C6								
PLOTS	5838	14F8								
FUNC	6D30	164								
FUNC1	6E98	136								
IHCSLOG *	6FD0	1B6								
			ALOG10	6FD0	ALOG	6FE8				
IHCDBUG *	7188	7F9								
			DEBUG#	71E8						
IHCSEXP *	7988	192								
			EXP	7988						
IHCFRXPI*	7B2C	141								
			FRXPI#	7B2C						
IHCFRXPR*	7C68	183								
			FRXPR#	7C68						
IHCECOMH*	7DF0	F39								
			IBCOM#	7DF0	FDIOCS#	7EAC	INTSWTCH	8D0E		
IHCCOMH2*	8D30	651								
			SEQDASD	9C9C						
IHCFCVTH*	9388	119D								
			ADCON#	9388	FCVAOUTP	9432	FCVLOUTP	94C2	FCVZOUTP	9612
			FCVIOUTP	99CC	FCVEOUTP	9EC2	FCVCOUTP	A0DC	INT6SWCH	A3C3
IHCEFNTH*	A528	512								
			ARITH#	A528	ADJSWTCH	A894				
IHCEFIOS*	AA40	131C								
			FIOCS#	AA40	FIOCSBEP	AA46				
IHCERRM *	BD60	5BC								
			ERRMON	BD60	IHCERRE	BD78				
IHCUATBL*	C320	638								
IHCUOPT *	C958	300								
IHCETRCH*	CC58	28E								
			IHCTRCH	CC58	ERRTRA	CC60				
$BLANKCOM	CEE8	D88								
GNE	DCA0	4								

LOCATION	REFERS TO SYMBOL	IN CONTROL SECTION	LOCATION	REFERS TO SYMBOL	IN CONTROL SECTION
78			7C	ONE	ONE
2B4			1FC	IBCOM#	IHCECOMH
20C	PUBA	PUBA	204	ENRGCT	ENRGCT
208	ECNIDL	ECNIDL	20C	PLOTS	PLOTS
21C	PLOTS	PLOTS	12AC		
2310			2378		
237C			2380		
2364			236C	FRXPR#	IHCFRXPR
2370	IBCOM#	IHCECOMH	2374	FXP	IHCSFXP
2EF0			2F3C	FRXPI#	IHCFRXPI
2F34	IBCOM#	IHCECOMH	3A9C	ONE	ONE
3A98			485C	IBCOM#	IHCECOMH
4854	SCALS	SCALS	5578	FRXPI#	IHCFRXPI
557C	ALOG10	IHCSLOG	5854	IBCOM#	IHCECOMH
5858	SCALS	SCALS	5DC4	FXP	IHCSFXP
6DA8			6F1C		
70F8	IBCOM#	IHCECOMH	7134	IHCERRM	IHCERRM
791C	ADCON#	IHCFCVTH	79C8	IHCUATBL	IHCUATBL
7918	FIOCS#	IHCEFIOS	7914	IBCOM#	IHCECOMH
7A9C	IBCOM#	IHCECOMH	7A8C	IHCERRM	IHCERRM
7BF0	IBCOM#	IHCECOMH	7BF4	IHCERRM	IHCERRM
7D78	IBCOM#	IHCECOMH	7D7C	IHCERRM	IHCERRM
7D7C	ALOG	IHCSLOG	7D74	FXP	IHCSFXP
7EAC	SEQDASD	IHCCOMH2	8C14	ADCON#	IHCFCVTH
8C0C	FIOCS#	IHCEFIOS	8C18	ARITH#	IHCEFNTH
8C38	ADJSWTCH	IHCEFNTH	8BCC	IHCUOPT	IHCUOPT
8C34	IHCUOPT	IHCUOPT	8C1C	FCVEOUTP	IHCFCVTH
8C2C	FCVLOUTP	IHCFCVTH	8C24	FCVIOUTP	IHCFCVTH
8C28	FCVCOUTP	IHCFCVTH	8C2C	FCVAOUTP	IHCFCVTH
8C30	FCVZOUTP	IHCFCVTH	8FBC	IHCERRE	IHCERRM
8BEC	IHCCOMH2	IHCCOMH2	8BFC	IHCERRM	IHCERRM
8BC4	IHCCOMH2	IHCCOMH2	8BC8	IHCCOMH2	IHCCOMH2
8BCC	IHCCOMH2	IHCCOMH2	8BD0	IHCCOMH2	IHCCOMH2
8FC1	IHCECOMH	IHCECOMH	8FC4	IHCECOMH	IHCECOMH
8D74	IHCERRM	IHCERRM	8E70	IBCOM#	IHCECOMH
91E1	IHCECOMH	IHCECOMH	91F1	IHCECOMH	IHCECOMH
9201	IHCECOMH	IHCECOMH	A384	IBCOM#	IHCECOMH
A380	IHCERRM	IHCERRM	A8F4	IBCOM#	IHCECOMH
A8E8	INTSWTCH	IHCECOMH	A890	INT6SWCH	IHCFCVTH
A88C	IHCUOPT	IHCUOPT	A8FC	ADCON#	IHCFCVTH
A8EC	FIOCS#	IHCEFIOS	A95C	IHCERRM	IHCERRM
ABAC	IHCERRM	IHCERRM	B994	IHCUATBL	IHCUATBL
B99C	IBCOM#	IHCECOMH	C30C	IHCUOPT	IHCUOPT
C310	IBCOM#	IHCECOMH	C314	IHCTRCH	IHCFTRCH
C318	FIOCSBEP	IHCEFIOS	CCCC	IBCOM#	IHCECOMH
CDD0	ADCON#	IHCFCVTH	CDD4	FIOCSBEP	IHCEFIOS

ENTRY ADDRESS C0
TOTAL LENGTH DCA8

CAPITAL CASE I-D

YEAR	NUCLEAR GENERATING CAPACITY (MWE)	LWR CAPITAL COSTS (MPKWH)	OPERATING & MAINT. COSTS (MPKWH)	LIABILITY INSURANCE COSTS (MPKWH)	LWR FUEL COSTS AT PUPR = 0 (MPKWH)	FBR FUEL COSTS AT PUPR = 0 (MPKWH)
1965	2000.00	2.40000	0.18700	0.13080	1.96000	1.35000
1966	2800.00	2.45000	0.18500	0.12920	1.96000	1.35000
1967	3700.00	2.50500	0.18350	0.12770	1.96000	1.35000
1968	4000.00	2.56000	0.18000	0.12600	1.96000	1.35000
1969	7000.00	2.62000	0.17800	0.12430	1.96000	1.35000
1970	14000.00	2.67000	0.17530	0.12280	1.68850	1.01000
1971	23000.00	2.73500	0.17300	0.12120	1.68850	1.01000
1972	33000.00	2.80500	0.17100	0.11950	1.68850	1.01000
1973	44000.00	2.87000	0.16850	0.11800	1.68850	1.01000
1974	56000.00	2.94000	0.16600	0.11650	1.68850	1.01000
1975	67000.00	3.00000	0.16380	0.11500	1.54500	0.86000
1976	80000.00	2.90000	0.16150	0.11320	1.54500	0.86000
1977	95000.00	2.82000	0.15900	0.11150	1.54500	0.86000
1978	110000.00	2.74000	0.15650	0.11000	1.54500	0.86000
1979	130000.00	2.67000	0.15400	0.10850	1.54500	0.86000
1980	150000.00	2.60500	0.15200	0.10680	1.42400	0.71000
1981	180000.00	2.55500	0.14930	0.10500	1.42400	0.71000
1982	220000.00	2.51500	0.14700	0.10350	1.42400	0.71000
1983	250000.00	2.48500	0.14470	0.10200	1.42400	0.71000
1984	290000.00	2.46000	0.14250	0.10050	1.42400	0.71000
1985	320000.00	2.43500	0.14000	0.09900	1.57000	0.56200
1986	360000.00	2.41700	0.13780	0.09710	1.57000	0.56200
1987	390000.00	2.40000	0.13520	0.09570	1.57000	0.56200
1988	420000.00	2.38500	0.13300	0.09400	1.57000	0.56200
1989	460000.00	2.37000	0.13070	0.09230	1.57000	0.56200
1990	500000.00	2.36000	0.12840	0.09080	1.57000	0.56200
1991	545000.00	2.34500	0.12600	0.08920	1.62000	0.40800
1992	590000.00	2.33300	0.12360	0.08760	1.62000	0.40800
1993	650000.00	2.32000	0.12120	0.08600	1.62000	0.40800
1994	705000.00	2.31300	0.11900	0.08440	1.62000	0.40800
1995	750000.00	2.30000	0.11650	0.08280	1.62000	0.40800
1996	815000.00	2.29000	0.11420	0.08130	1.67000	0.36500
1997	880000.00	2.28200	0.11180	0.07970	1.67000	0.36500
1998	950000.00	2.27500	0.10950	0.07800	1.67000	0.36500
1999	1025000.00	2.26800	0.10710	0.07650	1.67000	0.36500
2000	1100000.00	2.26000	0.10500	0.07500	1.67000	0.36500
2001	1175000.00	2.25200	0.10250	0.07320	1.80000	0.30900
2002	1250000.00	2.24800	0.10000	0.07170	1.80000	0.30900
2003	1345000.00	2.24000	0.09780	0.07000	1.80000	0.30900
2004	1430000.00	2.23500	0.09530	0.06850	1.80000	0.30900
2005	1540000.00	2.23000	0.09400	0.06680	1.80000	0.30900
2006	1650000.00	2.22200	0.09080	0.06520	1.86800	0.28500
2007	1730000.00	2.21800	0.08820	0.06370	1.86800	0.28500
2008	1850000.00	2.21000	0.08600	0.06210	1.86800	0.28500
2009	1990000.00	2.20500	0.08360	0.06050	1.86800	0.28500
2010	2100000.00	2.20000	0.08120	0.05900	1.86800	0.28500

INPUT DATA

SPINV	=	2187.00000
XCOR	=	1.50000
PUPF	=	1386.22998
CEFFF	=	0.40000
CEFFL	=	0.33333
BURNL	=	30.00000
EXPL	=	0.47100
UCHG	=	103814.37500
AVLWR	=	0.80000
AVFBR	=	0.80000
XCRR	=	1.50000
FABLOS	=	1.02000
REPLOS	=	0.98000
DISRAT	=	0.10000
F	=	0.85595

YEAR	NUCLEAR GENERATING CAPACITY (MWE)	LWR GENERATING CAPACITY (MWE)	LWR FRAC-TION	LWR PLUTONIUM PRODUCTION (KG)	FBR GENERATING CAPACITY (MWE)	FBR FRAC-TION	FBR PLUTONIUM REQUIREMENTS (KG)	FBR PLUTONIUM PRODUCTION (KG)	PLUTONIUM BALANCE (KG)
1965	2000.	2000.	1.000	0.0	0.	0.0	0.0	0.0	0.0
1966	2800.	2800.	1.000	1009.8035	0.	0.0	0.0	0.0	1002.9998
1967	3700.	3700.	1.000	1413.7239	0.	0.0	0.0	0.0	2400.4409
1968	4000.	4000.	1.000	1868.1362	0.	0.0	0.0	0.0	4239.8125
1969	7000.	7000.	1.000	2019.6069	0.	0.0	0.0	0.0	6217.2422
1970	14000.	14000.	1.000	3534.3125	0.	0.0	0.0	0.0	9685.8516
1971	23000.	23000.	1.000	7068.6211	0.	0.0	0.0	0.0	16641.5859
1972	33000.	33000.	1.000	11612.7383	0.	0.0	0.0	0.0	28063.9609
1973	44000.	44000.	1.000	16661.7500	0.	0.0	0.0	0.0	44424.3711
1974	56000.	56000.	1.000	22215.6680	0.	0.0	0.0	0.0	66191.0000
1975	67000.	67000.	1.000	28274.4961	0.	0.0	0.0	0.0	93828.9375
1976	80000.	80000.	1.000	33828.4180	0.	0.0	0.0	0.0	126797.1875
1977	95000.	95000.	1.000	40392.1445	0.	0.0	0.0	0.0	166062.8750
1978	110000.	109000.	0.991	47965.6602	1000.	0.009	3346.1074	0.0	209262.8750
1979	130000.	128000.	0.985	55034.2969	2000.	0.015	5019.1563	1358.5039	258880.3750
1980	150000.	147000.	0.980	64627.3828	3000.	0.020	6692.2070	2717.0093	317379.6250
1981	180000.	176000.	0.978	74220.5000	4000.	0.022	8365.2617	4075.5134	384700.8125
1982	220000.	215000.	0.977	88862.6250	5000.	0.023	10038.3164	5434.0156	465799.4375
1983	250000.	244000.	0.976	108553.8125	6000.	0.024	11711.3711	6792.5234	565597.8125
1984	290000.	283000.	0.976	123196.0000	7000.	0.024	13384.4219	8151.0234	678954.8750
1985	320000.	283000.	0.884	142887.1250	37000.	0.116	112094.4375	9509.5313	714411.0625
1986	360000.	283000.	0.786	142887.1250	77000.	0.214	195747.1250	50264.6797	707019.8750
1987	390000.	273000.	0.700	142887.1250	117000.	0.300	262669.3125	104604.8750	687181.3125
1988	420000.	263000.	0.626	137838.1250	157000.	0.374	329591.4375	158945.0625	649964.2500
1989	460000.	263000.	0.572	132789.1250	197000.	0.428	396513.6250	213285.2500	595485.6875
1990	500000.	263000.	0.526	132789.1250	237000.	0.474	463435.5625	267625.3750	528877.1250
1991	545000.	263000.	0.483	132789.1250	282000.	0.517	547088.2500	321965.5000	433602.3125
1992	590000.	263000.	0.446	132789.1250	327000.	0.554	622375.4375	383098.1875	324910.2500
1993	650000.	263000.	0.405	132789.1250	387000.	0.595	747854.3125	444231.0625	153038.0000
1994	705000.	269000.	0.382	132789.1250	436000.	0.618	811430.3750	525741.2500	137.0702
1995	750000.	315000.	0.420	135818.5000	435000.	0.580	726104.4375	592307.9375	2144.5159
1996	815000.	373000.	0.458	159044.0625	442000.	0.542	751200.5000	590949.5000	931.2456
1997	880000.	424000.	0.482	188328.3125	456000.	0.518	786334.3750	600459.0625	3361.3867
1998	950000.	472000.	0.497	214078.3125	478000.	0.503	836526.0000	619478.2500	389.2966
1999	1025000.	521000.	0.508	238313.6250	504000.	0.492	886717.6250	649365.3125	1341.4631
2000	1100000.	565000.	0.514	263053.8125	535000.	0.486	946947.5000	684686.5000	2119.8704
2001	1175000.	605000.	0.515	285269.2500	570000.	0.485	1012196.8750	726800.1875	1978.9514
2002	1250000.	642000.	0.514	305465.3125	608000.	0.486	1080791.0000	774347.7500	994.2559
2003	1345000.	698000.	0.519	324146.8750	647000.	0.481	1147713.0000	825971.0625	3376.0994
2004	1430000.	738000.	0.516	352421.3125	692000.	0.484	1233039.0000	878952.6250	1699.4722
2005	1540000.	802000.	0.521	372617.3750	738000.	0.479	1311672.0000	940085.3125	2711.6067
2006	1650000.	860000.	0.521	404931.0000	790000.	0.479	1408709.0000	1002576.8125	1499.8264
2007	1730000.	885000.	0.512	434215.5000	845000.	0.488	1505746.0000	1073218.0000	3165.5278
2008	1850000.	950000.	0.514	446838.0000	900000.	0.486	1597764.0000	1147936.0000	173.8209
2009	1990000.	1032000.	0.519	479656.6250	958000.	0.481	1699821.0000	1222653.0000	2644.0649
2010	2100000.	1076000.	0.512	521058.6250	1024000.	0.488	1823626.0000	1301447.0000	1512.7388

MINIMUM GENERATING COSTS

YEAR	MINIMUM ANNUAL NUCLEAR GENERATING COSTS ($ BIL)	MINIMUM DISCOUNTED NUCLEAR GENERATING COSTS ($ BIL)	MINIMUM CUMULATIVE DISCOUNTED GENERATING COSTS ($ BIL)	PLUTONIUM PRICE YIELDING MINIMUM GENERATING COSTS
1965	0.05577	0.37519	0.37519	30.50
1966	0.07899	0.48308	0.85827	30.50
1967	0.10573	0.58783	1.44609	30.50
1968	0.11570	0.58478	2.03087	30.50
1969	0.20523	0.94303	2.97390	30.50
1970	0.38831	1.62204	4.59593	30.50
1971	0.64779	2.45995	7.05588	30.50
1972	0.94478	3.26160	10.31748	30.50
1973	1.27853	4.01253	14.33001	30.50
1974	1.65314	4.71655	19.04655	30.50
1975	1.93689	5.02375	24.07030	30.50
1976	2.25430	5.31548	29.38577	30.50
1977	2.62089	5.61807	35.00383	30.50
1978	2.96991	5.78749	40.79131	30.50
1979	3.44243	6.09845	46.88976	30.50
1980	3.77249	6.07561	52.96536	30.50
1981	4.45820	6.52722	59.49258	30.50
1982	5.38133	7.16253	66.65511	30.50
1983	6.05589	7.32762	73.98271	30.50
1984	6.96646	7.66311	81.64581	30.50
1985	7.94970	7.94970	89.59550	30.50
1986	8.88761	8.07965	97.67514	30.50
1987	9.57081	7.90977	105.58490	30.50
1988	10.25136	7.70202	113.28691	30.50
1989	11.16639	7.62682	120.91373	30.50
1990	12.08900	7.50635	128.42006	30.50
1991	13.29548	7.50499	135.92505	30.50
1992	14.32707	7.35210	143.27715	30.50
1993	15.70658	7.32729	150.60443	30.50
1994	16.98219	7.20216	157.80659	30.50
1995	17.97623	6.93067	164.73726	30.50
1996	19.74106	6.91919	171.65643	30.50
1997	21.24142	6.76824	178.42467	30.50
1998	22.85780	6.62116	185.04582	30.50
1999	24.58403	6.47382	191.51964	30.50
2000	26.29338	6.29451	197.81415	30.50
2001	28.07784	6.11064	203.92477	0.0
2002	29.68028	5.87217	209.79694	0.0
2003	31.68475	5.69887	215.49580	0.0
2004	33.46822	5.47241	220.96822	0.0
2005	35.83360	5.32653	226.29474	0.0
2006	37.85651	5.11566	231.41040	0.0
2007	39.45132	4.84653	236.25693	0.0
2008	41.87900	4.67706	240.93399	0.0
2009	44.74463	4.54282	245.47681	0.0
2010	47.05962	4.34351	249.82031	0.0

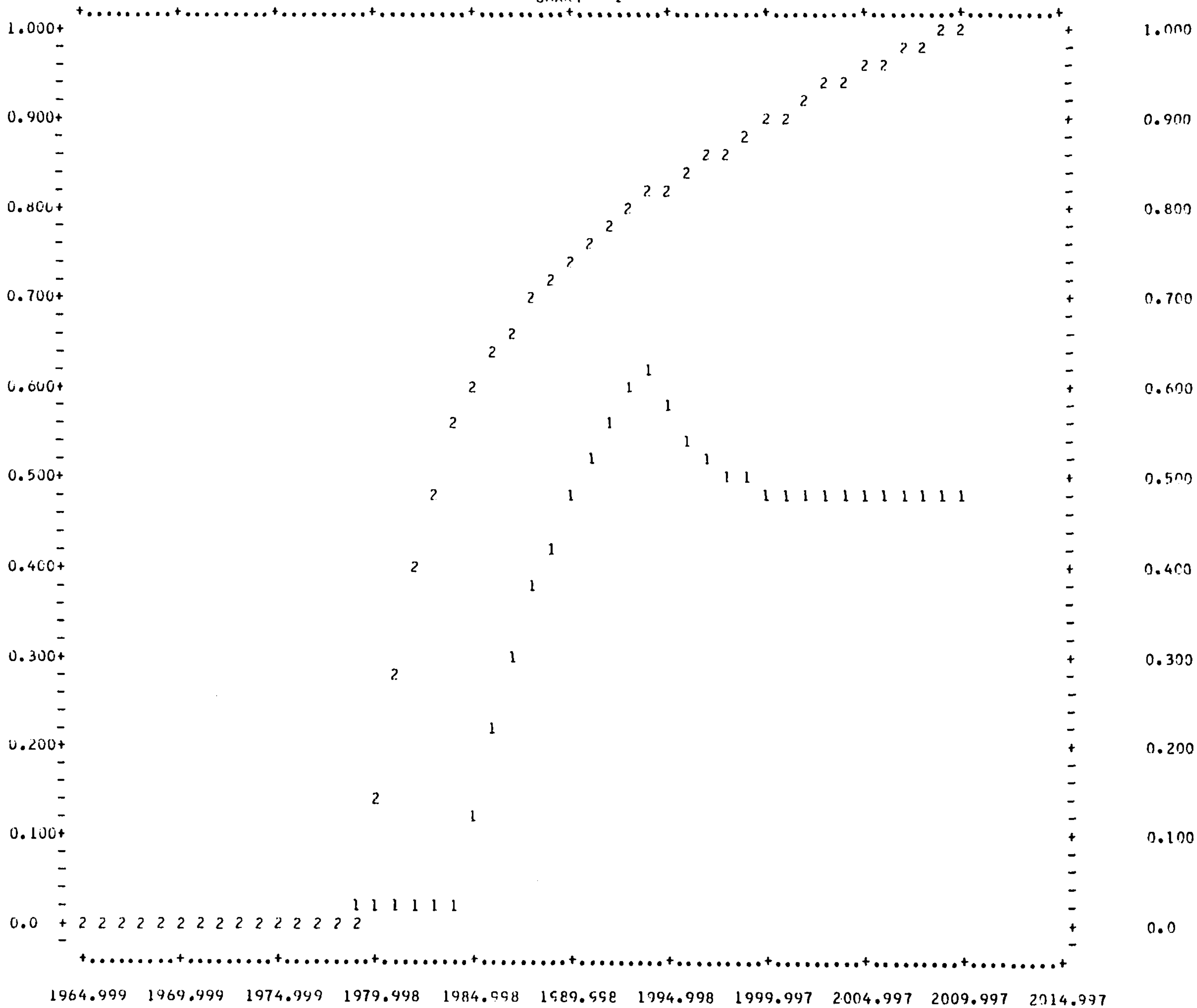
PUPR = 0.0

YEAR	ANNUAL NUCLEAR GENERATING COSTS ($ BIL)	PLUTONIUM INVENTORY COSTS ($ BIL)	PRESENT WORTH FACTOR	DISCOUNTED NUCLEAR GENERATING COSTS ($ BIL)	CUMULATIVE NUCLEAR GENERATING COSTS ($ BIL)	ECON LWR FRAC-TION	ECON FBR FRAC-TION	ANN NUCLEAR GENERATING COSTS ($ BIL)	DISCOUNTED ECONOMIC GENERATING COSTS ($ BIL)	CUMULATIVE ECONOMIC GENERATING COSTS ($ BIL)	ADDITIONAL NUCLEAR GENERATING COSTS ($ BIL)
1965	0.06561	0.0	6.727362	0.44138	0.44138	1.000	0.0	0.06561	0.44138	0.44138	0.05619
1966	0.09276	0.0	6.115806	0.56732	1.00870	1.000	0.0	0.09276	0.56732	1.00870	0.15043
1967	0.12393	0.0	5.559830	0.68903	1.69772	1.000	0.0	0.12393	0.68903	1.69772	0.25163
1968	0.13537	0.0	5.054397	0.68424	2.38196	1.000	0.0	0.13537	0.68424	2.38196	0.35109
1969	0.23967	0.0	4.594909	1.10126	3.48322	1.000	0.0	0.23967	1.10126	3.48322	0.50932
1970	0.45718	0.0	4.177192	1.90973	5.39295	1.000	0.0	0.45718	1.90973	5.39295	0.79702
1971	0.76094	0.0	3.797452	2.88962	8.28257	1.000	0.0	0.76094	2.88962	8.28257	1.22669
1972	1.10712	0.0	3.452232	3.82204	12.10461	1.000	0.0	1.10712	3.82204	12.10461	1.78713
1973	1.49499	0.0	3.138395	4.69186	16.79646	1.000	0.0	1.49499	4.69186	16.79646	2.46645
1974	1.92863	0.0	2.853088	5.50255	22.29900	1.000	0.0	1.92863	5.50255	22.29900	3.25244
1975	2.26649	0.0	2.593719	5.87865	28.17764	1.000	0.0	2.26649	5.87865	28.17764	4.10735
1976	2.64786	0.0	2.357929	6.24347	34.42110	1.000	0.0	2.64786	6.24347	34.42110	5.03532
1977	3.08824	0.0	2.143574	6.61987	41.04095	1.000	0.0	3.08824	6.61987	41.04095	6.03712
1978	3.51133	0.0	1.948705	6.84255	47.88350	1.000	0.0	3.51196	6.84201	47.88297	7.09219
1979	4.08226	0.0	1.771552	7.23194	55.11543	1.000	0.0	4.08197	7.23142	55.11438	8.22568
1980	4.50989	0.0	1.610503	7.26320	62.37862	0.867	0.133	4.50694	7.25844	62.37282	9.41325
1981	5.34263	0.0	1.464095	7.82212	70.20073	0.722	0.278	5.33040	7.80421	70.17702	10.70815
1982	6.46191	0.0	1.330997	8.60078	78.80150	0.591	0.409	6.43300	8.56230	78.73930	12.14639
1983	7.28337	0.0	1.209996	8.81287	87.61436	0.520	0.480	7.23815	8.75814	87.49744	13.63165
1984	8.39000	0.0	1.099999	9.22899	96.84335	0.448	0.552	8.32200	9.15419	96.65163	15.19754
1985	9.42941	0.0	1.000000	9.42941	106.27275	0.406	0.594	9.03858	9.03858	105.69020	16.67725
1986	10.45920	0.0	0.909091	9.50837	115.73111	0.361	0.639	10.06296	9.14815	114.83835	18.10597
1987	11.18237	0.0	0.826448	9.24165	125.02275	0.333	0.667	10.80711	8.93151	123.76985	19.43785
1988	11.90060	0.0	0.751317	8.94127	133.96402	0.310	0.690	11.54777	8.67603	132.44588	20.67711
1989	12.90047	0.0	0.683016	8.81122	142.77524	0.283	0.717	12.54340	8.56734	141.01321	21.86151
1990	13.90735	0.0	0.620924	8.63540	151.41063	0.260	0.740	13.54742	8.41191	149.42513	22.99057
1991	14.80139	0.0	0.564477	8.35504	159.76567	0.239	0.761	14.24713	8.04217	157.46729	23.84062
1992	15.85857	0.0	0.513161	8.13801	167.90367	0.220	0.780	15.30095	7.85186	165.31914	24.62653
1993	17.27122	0.0	0.466511	8.05721	175.96088	0.200	0.800	16.71002	7.79540	173.11453	25.35645
1994	18.60362	0.0	0.424101	7.88981	183.85068	0.184	0.816	18.01486	7.64012	180.75464	26.04408
1995	19.81145	0.0	0.385547	7.63824	191.48891	0.171	0.829	19.01428	7.33089	188.08553	26.75165
1996	21.56841	0.0	0.350497	7.55967	199.04857	0.156	0.844	20.35497	7.13436	195.21988	27.39214
1997	23.31113	0.0	0.318634	7.42772	206.47629	0.144	0.856	21.83606	6.95771	202.17758	28.05162
1998	25.15506	0.0	0.289668	7.28661	213.76289	0.133	0.867	23.43501	6.78836	208.96594	28.71707
1999	27.11270	0.0	0.263334	7.13971	220.90259	0.120	0.880	25.12759	6.61696	215.58290	29.38295
2000	29.02692	0.0	0.239395	6.94891	227.85149	0.105	0.895	26.77948	6.41088	221.99377	30.03734
2001	31.22929	0.0	0.217632	6.79650	234.64798	0.091	0.909	28.07784	6.11064	228.10440	30.72321
2002	33.13533	0.0	0.197848	6.55574	241.20372	0.078	0.922	29.68028	5.87217	233.97656	31.40678
2003	35.57553	0.0	0.179862	6.39867	247.60239	0.064	0.936	31.68475	5.69887	239.67543	32.10658
2004	37.69827	0.0	0.163511	6.16407	253.76645	0.052	0.948	33.46822	5.47241	245.14784	32.79823
2005	40.54967	0.0	0.148646	6.02755	259.79395	0.041	0.959	35.83360	5.32653	250.47437	33.49921
2006	43.56416	0.0	0.135133	5.88696	265.68066	0.030	0.970	37.85651	5.11566	255.59003	34.27026
2007	45.45065	0.0	0.122848	5.58354	271.26416	0.020	0.980	39.45132	4.84653	260.43652	35.00723
2008	48.45959	0.0	0.111680	5.41199	276.67603	0.011	0.989	41.87900	4.67706	265.11353	35.74203
2009	52.06033	0.0	0.101528	5.28557	281.96143	0.0	1.000	44.74463	4.54282	269.65625	36.48462
2010	54.70120	0.0	0.092298	5.04881	287.01001	0.0	1.000	47.05962	4.34351	273.99976	37.18970

GENERATING AND FUEL CYCLE COSTS (MILS/KWH)

YEAR	UCLWR	LWRFCC	UCFBR	FBRFCC
1965	4.67780	1.96000	4.71455	1.35000
1966	4.72420	1.96000	4.77295	1.35000
1967	4.77620	1.96000	4.83832	1.35000
1968	4.82600	1.96000	4.90100	1.35000
1969	4.88230	1.96000	4.97180	1.35000
1970	4.65660	1.68850	4.68942	1.01000
1971	4.71770	1.68850	4.76620	1.01000
1972	4.78400	1.68850	4.84950	1.01000
1973	4.84500	1.68850	4.92612	1.01000
1974	4.91100	1.68850	5.00900	1.01000
1975	4.82380	1.54500	4.92975	0.86000
1976	4.71970	1.54500	4.80007	0.86000
1977	4.63550	1.54500	4.69525	0.86000
1978	4.55150	1.54500	4.59062	0.86000
1979	4.47750	1.54500	4.49850	0.86000
1980	4.28780	1.42400	4.26305	0.71000
1981	4.23330	1.42400	4.19537	0.71000
1982	4.18950	1.42400	4.14100	0.71000
1983	4.15570	1.42400	4.09912	0.71000
1984	4.12700	1.42400	4.06362	0.71000
1985	4.24400	1.57000	3.87975	0.56200
1986	4.22190	1.57000	3.85260	0.56200
1987	4.20090	1.57000	3.82670	0.56200
1988	4.18200	1.57000	3.80350	0.56200
1989	4.16300	1.57000	3.78017	0.56200
1990	4.14920	1.57000	3.76330	0.56200
1991	4.18020	1.62000	3.58595	0.40800
1992	4.16420	1.62000	3.56635	0.40800
1993	4.14720	1.62000	3.54550	0.40800
1994	4.13640	1.62000	3.53240	0.40800
1995	4.11930	1.62000	3.51142	0.40800
1996	4.15550	1.67000	3.45155	0.36500
1997	4.14350	1.67000	3.43695	0.36500
1998	4.13250	1.67000	3.42362	0.36500
1999	4.12160	1.67000	3.41037	0.36500
2000	4.11000	1.67000	3.39625	0.36500
2001	4.22770	1.80000	3.32532	0.30900
2002	4.21970	1.80000	3.31570	0.30900
2003	4.20780	1.80000	3.30125	0.30900
2004	4.19880	1.80000	3.29037	0.30900
2005	4.19080	1.80000	3.28080	0.30900
2006	4.24600	1.86800	3.24120	0.28500
2007	4.23790	1.86800	3.23145	0.28500
2008	4.22610	1.86800	3.21710	0.28500
2009	4.21710	1.86800	3.20625	0.28500
2010	4.20820	1.86800	3.19550	0.28500

CHART 1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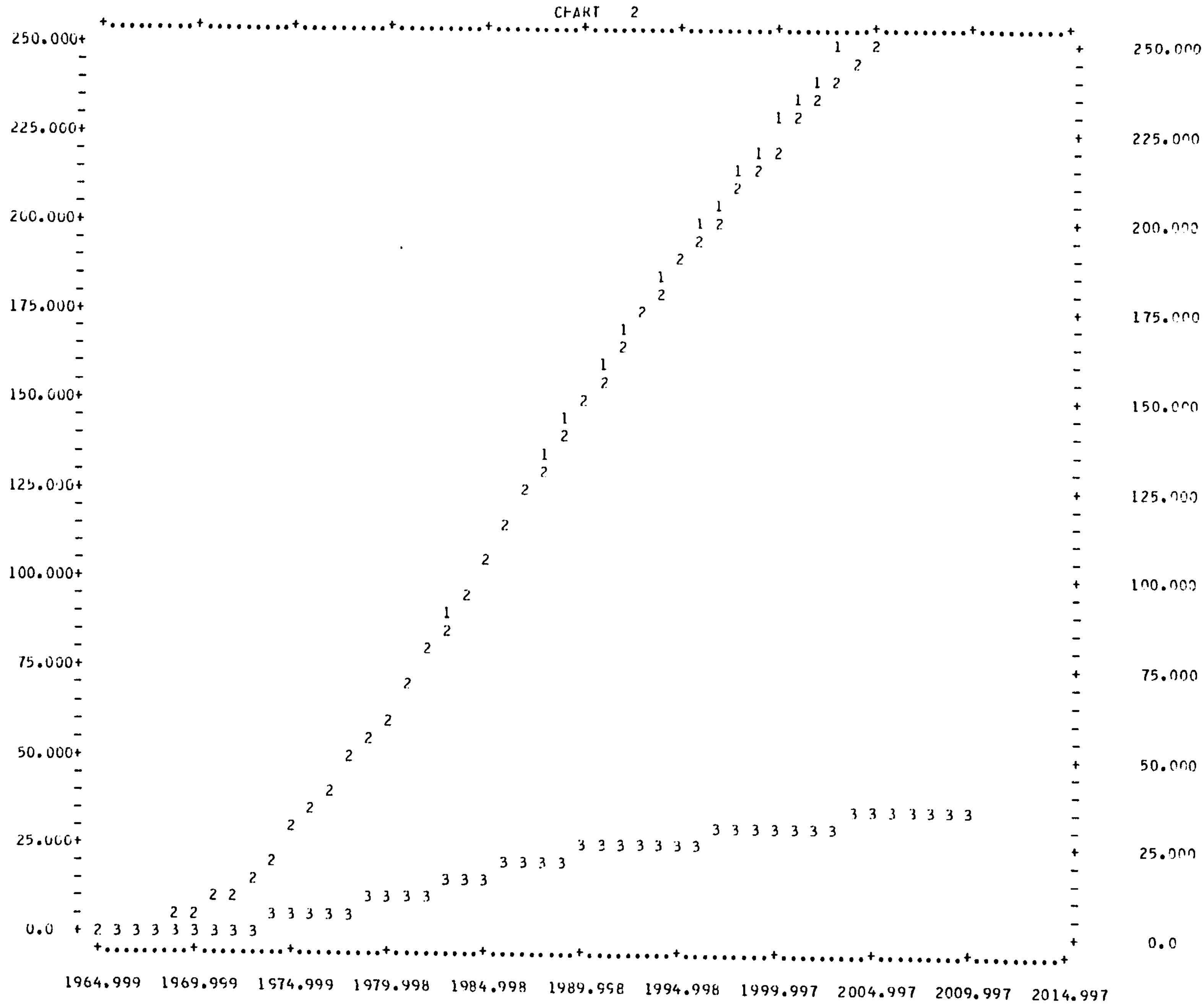
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150.000
125.000
100.000
75.000
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25.000
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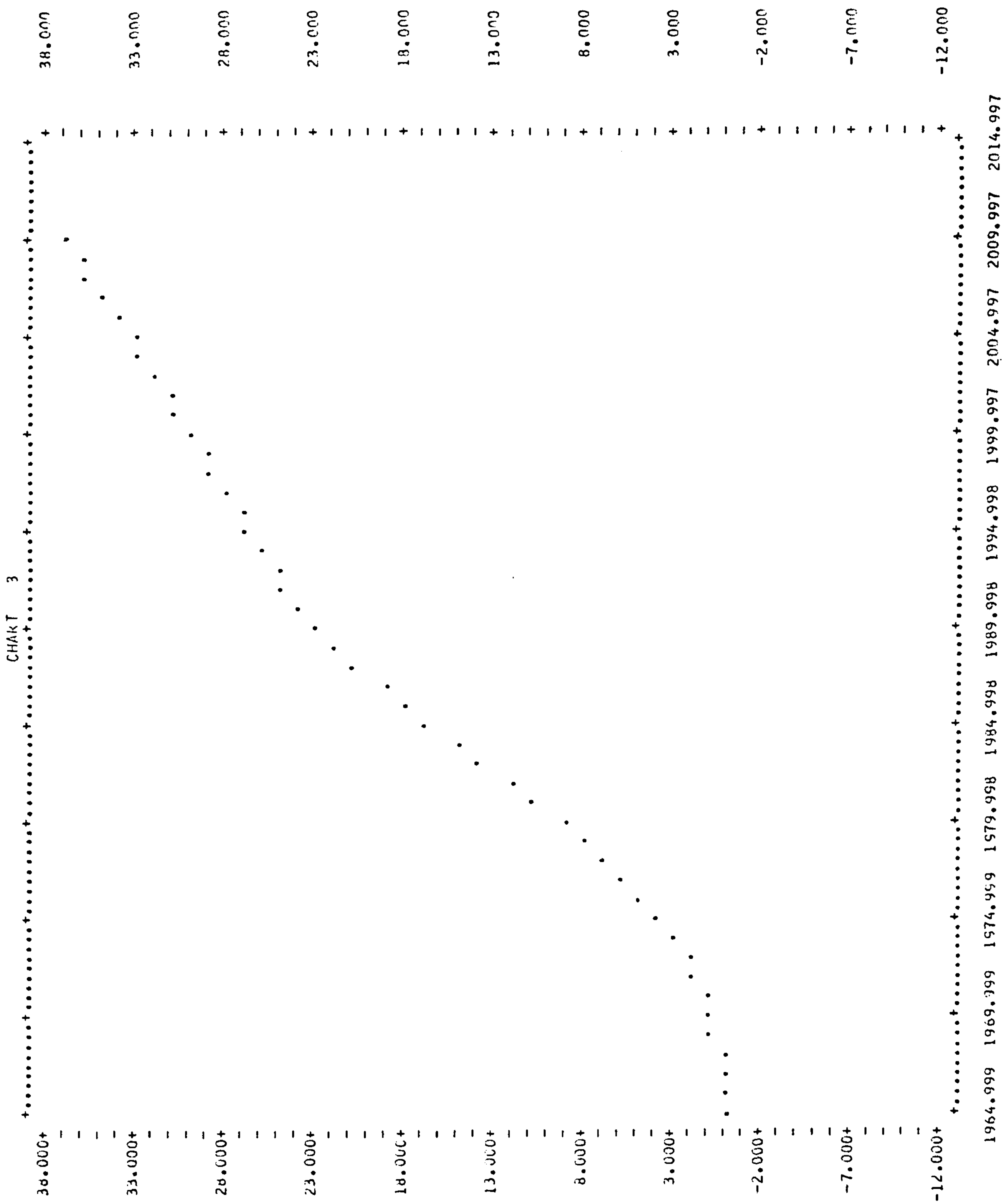

NUMBER OF POINTS ENTERED 46
NUMBER OF POINTS REJECTED 0