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Abstract

The need for breeding does not appear to be highly significant in terms of raw materials requirements and cost for a moderately optimistic expanding nuclear power economy between 1960 and 2000. Since the expansion rate of the US nuclear economy is assumed to be high, at least 2/3 of the U-235 recovered from natural uranium is used to supply reactor inventory. It is the remaining 1/3 of the available U-235 that can be saved by breeder reactors. The significant variables in comparing two breeders or a breeder and converter are the doubling time and a parameter expressing the total fissile inventory per megawatt of electricity. In fact, the need for new raw material in any given year is reduced more by specific power than by changing from a converter to a breeder.

The cost of fuel inventory depends more on the value of total inventory per megawatt of electricity and the content and value of plutonium or U-233 than on raw material cost. The use of 12% vs 4% annual lease charge can change the inventory costs more significantly than either the Pu (or U-233)/U-235 value ratio or raw material cost. Net fuel burnup costs vary more with the product of net conversion ratio and Pu (or U-233)/U-235 value ratio than with the cost of raw material.

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REQUIREMENTS FOR RAW MATERIALS IN AN EXPANDING NUCLEAR POWER ECONOMY

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Abstract

The need for breeding does not appear to be highly significant in terms of raw materials requirements and cost for a moderately optimistic expanding nuclear power economy between 1960 and 2000. Since the expansion rate of the US nuclear economy is assumed to be high, at least $2/3$ of the U-235 recovered from natural uranium is used to supply reactor inventory. It is the remaining $1/3$ of the available U-235 that can be saved by breeder reactors. The significant variables in comparing two breeders or a breeder and converter are the doubling time and a parameter expressing the total fissile inventory per megawatt of electricity. In fact, the need for new raw material in any given year is reduced more by specific power than by changing from a converter to a breeder.

The cost of fuel inventory depends more on the value of total inventory per megawatt of electricity and the content and value of plutonium or U-233 than on raw material cost. The use of 12% vs 4% annual lease charge can change the inventory costs more significantly than either the Pu (or U-233)/U-235 value ratio or raw material cost. Net fuel burnup costs vary more with the product of net conversion ratio and Pu (or U-233)/U-235 value ratio than with the cost of raw material.

Introduction

In order to assess whether and when breeders are necessary, a study was made of the raw materials requirements of breeders and nonbreeders of various electrical specific power. The raw material requirements are compared to the quantities estimated available at various prices. The effect of increased raw material costs on nuclear power cost is examined as a function of net conversion ratio, electrical specific power, annual inventory charge and relative value of charged and discharged fissile material.

Summary

The use of breeding per se does not appear to be highly significant in terms of raw materials requirements and cost for an expanding nuclear power economy between 1960 and 2000. In this study the nuclear power industry was assumed to expand from 500 electrical megawatts in 1960 to over 1,000,000 in 2000. Since the expansion rate of the US nuclear power is assumed to be high, at least two-thirds of the U-235 recovered from natural uranium is used to supply reactor inventory. It is the remaining third of the available U-235 that can be saved by breeder reactors. If, for the reactor complex, we assume values of 0.8 or 4 Mw heat per kilogram of fissile material for the reactor specific power, values of 0.9 and 1.1 for the conversion ratio, a load factor of 0.8, an inventory ratio (total inventory/reactor inventory) of 2.00, a thermal efficiency of 0.250, and 1.3 tons of U-235 mined per ton recovered from diffusion plants, the mining requirements for 1960-2000 are:

<u>Conversion Ratio</u>	<u>Specific Power, Mw_t/kg U-235</u>	<u>Mining Requirements, 1960-2000</u>	
		<u>U-235, tons</u>	<u>Natural U, tons</u>
1.1	0.8	13,425	1,890,000
1.1	4	1,000	140,000
0.9	0.8	17,650	2,486,000
0.9	4	5,225	736,000

The ratio of raw material requirements for the 0.9 vs 1.1 conversion ratio is larger for higher specific power, but of more significance is the small constant difference in fissile raw material requirements for the breeder complex vs the converter complex and the large difference between the requirements for either breeders or converters when the specific power is increased. It is seen from this table that the new raw material needed in any given year is decreased more by increased specific power than by increased conversion ratio.

The fertile material requirements were also calculated for several reactors. In most cases the quantity of natural uranium that supplies fissile material also supplies the required fertile material. Additional U-238 is necessary for inventory if the doubling time of a breeder is less than the doubling time for the economy. The total raw material requirements for a homogeneous breeder (uranium + thorium) are approximately the same as the total natural uranium requirements for a high-specific-power fast breeder.

The exhaustion date for any given raw material supply depends on the assumed buildup curve. In this paper we have assumed a nuclear power buildup from 500 Mw electrical capability in 1960 to 1.2×10^6 Mw electrical capability in 2000.

The results of this study indicate that the US nuclear power economy will exhaust the 550,000 tons of uranium from known high-grade carnotite (recoverable at \$8 to \$10 per pound of U_3O_8) ore supply of the US and Canada between 1982 and 2000, depending on net conversion or breeding ratio if the reactor complex require a fissile inventory of 10 kg/Mw_e. This ore supply can be conserved beyond 2000 AD if the entire nuclear complex is operated with breeder reactors having an average doubling time of 7 years and a fissile inventory of 3 kg/Mw_e. If an additional 1,000,000 tons of lower grade carnotite cores (recoverable at \$15 to \$25 per pound of U_3O_8) is available, the raw material exhaustion dates for the reactor complex requiring a fissile inventory of 10 kg/Mw_e are extended an additional 10 years. The low-grade ores such as shales or the phosphoria formation will not have to be mined until somewhat beyond 1990.

The cost of fuel inventory depends more on the values of fuel inventory ratio (total inventory/reactor inventory), specific power, thermal efficiency, and content and value of bred or converted material discharged than on raw material cost. Fuel inventory costs can best be minimized by increased specific power and thermal efficiency and decreased fuel inventory ratio. Inventory cost computations are made for both 4% and 12% annual inventory charges. The 4% figure applies to the present or early buildup period when fuel is leased from the AEC. However, if, at some future date, fuel must be purchased by private utilities, a working capital charge greater than 4% will be more applicable. This paper assumes a value of 12% per year. The lease charge can change the inventory costs more significantly than either the Pu/U-235 value ratio or raw material costs.

Net fuel burnup costs vary more with the net conversion ratio times the Pu/U-235 value ratio (C_{rr}') than with the cost of raw material. Burnup costs increase with increased raw material costs for values of the net conversion ratio times the Pu/U-235 value ratio greater than 1 and decrease when the values of the same product are less than 1.

Thirteen reactors (5 homogeneous breeders, 5 fast breeders, and 3 heterogeneous converters) were compared in terms of raw material requirements and nuclear fuel costs. High-specific-power homogeneous or fast breeders minimize the amount of uranium mined. Fast or homogeneous breeders that operate with a high specific power and low external inventory are much better than their low-specific-power counterparts even though a decrease in conversion ratio probably accompanies the higher specific power. For an inventory charge of 4% per year, high-electrical-specific-power fast breeders give the lowest nuclear fuel cost. However, for a 12% per year inventory charge, high-specific-power two-region homogeneous breeders give the lowest nuclear fuel costs.

Utilization of Raw Material

The total amount of U-235 to be mined during an expanding nuclear power buildup period is given by the equation

$$M = \frac{RD}{ES} \left(P - \frac{G}{T} \right) \quad (1)$$

where M = total U-235 mined, kg

R = inventory ratio, total fissile material tied up per kilogram of initial fissile material in reactor

E = net thermal efficiency, fraction

S = specific power, thermal megawatts (Mwt) per kilogram of initial fissile material in reactor

G = total accumulated megawatt-years of electrical power generation

T = doubling time or its equivalent, years

D = U-235 recovery factor for gaseous diffusion process = kilograms of U-235 mined per kilogram of U-235 fed to system as inventory or makeup (taken = 1.3)

Equation 1 assumes that the nuclear properties of all fissile materials are identical. The allowable specific power and the recoverable heat per gram of fissile material burned are assumed to be the same regardless of the fissile material used.

The reactor doubling time, T, is given by

$$T = \frac{HR}{365(C-1)SL} \quad (1a)$$

where H = net megawatt-days of heat per kilogram of startup fissionable material burned (includes effect of burning part of the plutonium produced) (taken as 833)

C = net conversion ratio, grams of new fissile discharged per gram of starting fissile material consumed

L = load factor, fraction (taken as 0.8)

If the reactor is a converter rather than a breeder, the term (C-1) is negative, and the doubling time is negative. A negative doubling time is the time required to consume completely the original charge of fissionable material, including all external inventory.

The buildup of nuclear power assumed in this report (Fig. 1)* is based on an average of the predictions presented in the McKinney Panel Report.¹ The buildup curve used is somewhat less optimistic than the prediction of Davis and Roddis² but more optimistic than that presented by Lane.³ The buildup rate and the accumulated exposure derived from it in the years

* Figures appear at the end of this paper beginning on page 25.

1960 to 2000 are given in Table I.

Table I. Nuclear Electrical Expansion

Year	Installed Electrical Capacity, Mw (P)	Cumulative Electricity, Mwy (G)
1960	500	-
1961	975	763
1962	1,500	1,988
1963	2,200	3,875
1965	4,000	9,975
1968	7,625	27,000
1970	19,060	54,250
1975	59,650	199,950
1980	138,925	681,250
1985	270,875	1,696,250
1990	473,550	3,552,500
1995	769,850	6,664,000
2000	1,195,100	11,582,750

The equation for the assumed buildup rate is

$$P = 170,000 (1.065^{\theta} - 1)F + 500 \quad (2)$$

where P = installed nuclear power, Mw_e

θ = time, years since 1960 ($\theta = 0$ at 1960)

F = fraction of total additions since 1960 that have been nuclear

$$F = (0.04 + 0.003\theta) \int_{\theta=0}^{\theta=8.00} \frac{1}{\theta-8} (1-e^{-0.1\theta})^4 d\theta \quad (3)$$

Equation 3 represents the best mathematical fit of the average values of nuclear additions given on pages 27 and 117-118 of the McKinney Panel Report.¹ The equation for P may appear complex, but it has the desirable form of the product of a total electrical capacity buildup and the fraction of total additions that are nuclear.

The effect of the doubling time on the total U-235 that must be mined up to a given year (based on eq. 1 and the buildup curve of Fig. 1) is shown in Fig. 2, where the solid line plots a function proportional to the total quantity of U-235 mined while the dashed line plots a function proportional to the net quantity of U-235 used after allowing for breeding gain in excess of that required for the buildup curve. Since the average doubling time for the nuclear economy beyond 1980 is greater than seven years, reactors with a 7-year doubling time would produce more fissionable material than is required for burnup and inventory. In this case it would theoretically be possible to re-enrich some of the diffusion plant tails with the excess breeding gain.

We have assumed that there are three grades of uranium ore available for US nuclear power development. Conservative guesses by the authors of this study based on the literature⁴⁻⁷ for the quantities and recovery costs of these grades are:

Recoverable at	metric tons of uranium
\$8-10 per lb U ₃ O ₈	550,000
15-25	1,000,000
50-100	100,000,000

These guesses are based on the present known reserves of the US and Canada. The inferred reserves plus any new discoveries are assumed to compensate for the non-power industry uses and markets for the Canadian reserves other than the US.

Johnson⁸ has stated that ultimate production for high-grade uranium ore from the developed and adjacent areas in non-Communist countries may

reach or exceed 2,000,000 short tons of U_3O_8 . He further states that on the basis of present geological data and past discoveries, an additional 2,000,000 short tons of low-cost U_3O_8 should be developed in new areas within a reasonable period provided an aggressive exploration program is maintained. If it is assumed that $1/3$ of this U_3O_8 will be available to the US (on the basis that $1/3$ of the power of the non-Communist nations is generated in the US), the US will have 1,000,000 metric tons of low-cost uranium for stationary power and other uses. The authors' assumption of 550,000 metric tons low cost uranium for US stationary power may therefore be reasonable.

Preliminary estimates indicate that the recovery cost of uranium might vary inversely with the 0.5 power of the uranium content (Fig. 3). These estimates cannot be considered more than "ball park" numbers, but they show the trend in raw material recovery costs and may be used to estimate the cost of very lean raw materials.

From the above availability and power buildup assumptions, it can be established that each type of raw material will be exhausted by the dates listed in Table II. In every case the source of 100,000,000 tons of uranium will not be exhausted until some distant date beyond 2000. The buildup curve has not been extrapolated beyond 2000, and therefore raw material requirements beyond 2000 are not predicted. The exhaustion date of Table II depends on two parameters, the doubling time, T , and the term R/SE , i.e., the kilograms of fissile material per electrical megawatt. The requirements for raw materials are reduced by decreasing the value of this ratio.

Table II. Time to Exhaust Uranium Supply

<u>T, years</u>	<u>R/SE, kg U-235/Mw_e</u>	<u>Year</u>		
		<u>\$8-10/lb U₃O₈</u>	<u>\$15-25/lb U₃O₈</u>	<u>\$50-100/lb U₃O₈</u>
-10	3	1992	~2000	> 2000
	10	1982	1990	> 2000
-200	3	1997	~2000	> 2000
	10	1986	1995	> 2000
+15	3	~2000	> 2000	> 2000
	10	1993	~2000	> 2000
+7	3	> 2000	> 2000	> 2000
	10	> 2000	> 2000	> 2000

Unless reactors of very high specific power can be designed, an increase of a few tenths in the conversion or breeding ratio has a minor effect on the total U-235 requirements between 1960 and 2000 (Fig. 4). For typical power reactor conditions of RD/SE = 10 and L/E (load factor/thermal efficiency) = 3, 50 to 90% of the total U-235 mined is used to supply reactor system inventories. The change in U-235 requirements with a changed conversion ratio, i.e., the additional kilograms of U-235 required between 1960 and year in question for a given value of (C₂ - C₁) is given by

$$\Delta M = \frac{RDG}{SE} \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \quad (4)$$

With the previous definition of doubling time, eq. 4 reduces to

$$\Delta M = \frac{DGL}{EH} (C_2 - C_1) \quad (5)$$

If H is taken as 833 Mwd/kg burned (net) and D as 1.3,

$$\Delta M = \frac{0.57 GL}{E} (C_2 - C_1) \quad (6)$$

Effect of Raw Material Costs on Power Costs

The two cost items that vary with raw material costs are fuel inventory and burnup.

Inventory Costs.--The inventory cost, in mills per electrical kilowatt-hour (kwh_e) for a slightly enriched converter which sells plutonium is given by

$$\text{Inventory cost} = \frac{1000 V R_i}{8760 \text{ SEL}} (1 + f \bar{r} j), \quad (7)$$

where $R/\text{SE} = \text{kg U-235 total inventory}/\text{Mw}_e \text{ installed}$

V = dollars per gram of U-235 as slightly enriched uranium

i = annual inventory charge rate on initial loading, fraction

j = ratio of annual inventory charge rate fraction on converted or bred material (Pu or U-233) to charge rate on initial loading

f = ratio of fissile inventory that is plutonium to that which is U-235

L = load factor, fraction

$\bar{r}$ = ratio of plutonium value to slightly enriched U-235 value

The cost for fuel inventory increases as the cost of raw material increases. This increase, however, does not occur directly as the first power of the raw materials cost, since some of the cost for uranium of any enrichment different from natural is due to the cost of separative work in the gaseous diffusion cascade. Table III shows the cost per gram of U-235 in uranium of several enrichments as a function of natural uranium feed cost. The values listed in Table III assume a constant cost for separative work based on the unclassified AEC price schedule and do not consider any effects of future increased power cost or improved separation efficiency.

The value listed as "typical" was used in eq. 6 to calculate the inventory costs plotted in Fig. 5.

Table III. Variation in Cost of U-235 with Cost
Of Natural Uranium Feed

Enrichment, %	U-235 cost, \$/g for		
	Feed at \$10/lb U ^a	Feed at \$25/lb U ^a	Feed at \$50/lb U ^a
1.0	4.75	10.04	18.39
1.5	6.58	12.39	21.24
2.0	7.72	13.79	22.89
3.0	9.08	15.41	24.77
Typical	6.5	12.5	21.5

^aAs UF₆.

Figure 5 indicates that inventory costs for a slightly enriched converter vary much more significantly with the terms i , $\bar{f}r_j$, and R/SE than they do with the cost of raw material. The term $\bar{f}r_j$, the ratio of the cost of the plutonium inventory to that of the U-235 inventory, was used since a reactor burning U-235 in U-238 will produce plutonium as a by-product. The total charge for inventory depends not only on the initial value of U-235 and its lease charge but also on the quantity, value, and working capital charge for the plutonium present. The term $\bar{f}r_j$, which is taken for a range of values between 0.02 and 3.0, depends on the type of reactor, the plutonium value, and the accounting methods. For example: if, on an average, 20% of the fissile material present as inventory is plutonium, plutonium is valued at twice the U-235 in slightly enriched uranium, and U-235 is leased at 4% per year, but if the plutonium inventory is charged for at 12% per year, the value of $\bar{f}r_j$ is $0.2 \times 2 \times 3 = 1.2$. If a base charge of 12% per year is used for the U-235 inventory, the values

of Fig. 5 should be tripled for appropriate values of $\bar{f}r_j$.

By an equation similar to eq. 7, the fissile material inventory cost for a breeder at steady state is given by

$$\text{Inventory cost} = \frac{1000}{8760} \frac{r V' R' i}{\text{SEL}} (1 + f' r' j) \text{ mills/kwh}_e \quad (8)$$

where V' = dollars per gram of U-235 as 90% enriched uranium

r = ratio of fissile starting material value to U-235 value as 90% enriched

f' = ratio of excess fissile inventory held in reactor prior to processing to total fissile inventory after withdrawal for processing

r' = ratio of fissile product value to starting fissile value

$R'/S'E$ = kg total steady state fissile inventory/ Mw_e installed

Figure 6 is a plot of eq. 8 for $r = 1$, $L = 0.8$, and $R'/S'E = 1$ and 3 for various values of $f'r'j$, the ratio of the inventory cost of breeding gain holdup to the cost of steady state fissile holdup. The plot is for 4% annual charges on the steady state fissile holdup but can be used for 12% annual charge by using the appropriate $f'r'j$ and tripling the mills per electrical kilowatt-hour read.

The values of 90% enriched U-235 (V') were derived from the unclassified AEC price schedule by using the varying costs of natural uranium feed for constant unit cost of separation. The values are:

<u>\$/lb Natural U as UF₆</u>	<u>V', \$/g U-235 (90% enriched)</u>
10	13.3
25	20.2
50	30.0

Fertile material inventory costs are neglected in eq. 8. The fertile requirements for breeders are discussed in the section on Comparison of Selected Reactors.

Burnup Costs.--The cost of raw materials also affects the cost of fuel burnup. The cost of fuel burnup is determined partly by the cost of U-235 in uranium as a function of enrichment for various natural uranium feed costs. The burnup cost is also affected by the value ratio of plutonium to U-235. It is reasonable to assume that plutonium has a value in some ratio to U-235 rather than a fixed dollars per gram of plutonium value. Thus, as the cost per gram of U-235 increases, the value of plutonium also increases. If H Mwd of net heat is produced per kilogram of U-235 consumed, the burnup cost for a converter is given by

$$\text{Burnup cost} = \frac{1000 (\Delta\$ - Crr'V')}{24 EH} \text{ mills/kwh}_e \quad (9)$$

where $\Delta\$$ = dollars per gram of U-235 consumed

C = net conversion ratio, grams of plutonium discharged per gram of U-235 consumed

E = thermal efficiency, fraction

rr' = value ratio of fissile product to U-235 as 90% U-235

V' = value of 90% U-235, dollars per gram of U-235

Similarly, the burnup cost (or breeding credit) for a breeder, which supplies its own fissile fuel, neglecting the cost of fertile material burned, is given by

$$\text{Burnup cost} = \frac{1000 (1 - C') rr'V'}{24 EH} \text{ mills/kwh}_e \quad (10)$$

C' = net breeding ratio, g new Pu or U-233 discharged per g starting fissile consumed

The cost used for U-235 burnup in converters is an average value. Figure 7 shows the cost for U-235 burnup in dollars per gram of U-235 burned for enrichment changes during irradiation of 90-85%, 3.5-1.5%,

and 1.5-0.5% U-235 as a function of natural UF_6 cost. The assumed value lies about half way between the 0.5-1.5% and the 1.5-3.5% lines. This assumed line covers the full enrichment range to $\pm$ \$2 per gram of U-235 burned ($\pm$ 20% or less).

Figure 8 indicates that net burnup costs increase as the natural uranium feed cost increases if the product, Crr' , has a value between 0 and 1.0. For values of $Crr' > 1.0$ the net burnup costs decrease as the natural UF_6 cost increases. For $Crr' = 1.0$, the net burnup cost is zero and independent of feed cost. The important parameter does not appear to be the raw material costs but rather the product of conversion ratio and Pu/U-235 (as 90% U-235) value ratio.

Figure 9 is a plot of net burnup costs (actually negative) for a breeder reactor as a function of raw materials cost. This figure indicates that the breeding gain credit increases as the raw materials cost increases.

Comparison of Selected Reactors

How do several of the proposed future power reactors compare in terms of raw materials requirements and nuclear fuel costs? The best reactor, regardless of breeding or conversion ratio, is that reactor which will give the lowest total power cost over its entire lifetime. In many cases, especially in an economy that is expanding at a high rate, a reactor can startup with fuel which costs \$8 to \$10 per pound of uranium as natural uranium and begin to burn uranium at \$50 per pound near the end of its lifetime.

Inventory and Burnup Costs for Selected Reactors.--This study compares the raw material requirements for five homogeneous reactors, five fast reactors, and three heterogeneous converters. The homogeneous reactors vary in type, specific power, and conversion ratio. The fast reactors vary in inventory ratio, specific power, thermal efficiency, and conversion ratio. Table IV lists the important parameters for the reactors and gives the US net U-235 and natural uranium requirements for fissile material between 1960 and 2000 for each. Figure 10 is a plot of these requirements for 5 selected reactors from Table IV for the period 1965 to 2000.

The net U-235 requirements for fissile material can be defined as the amount of fissile material needed for inventory plus burnup in the case of converters or for inventory minus breeding gain in the case of breeders. The net requirements for a breeder can become negative if the doubling time for breeders is less than the doubling time for the US nuclear power economy. A negative value for U-235 requirements indicates that excess fissile material has been produced which can be exported, stockpiled, or used to enrich diffusion plant tails.

The fertile material requirements for each of the 13 reactors are shown in Table V, and the fertile material requirements of five of the reactors are plotted in Fig. 11. The fertile material required for homogeneous reactors is assumed to be thorium.

The inventory and burnup costs for fertile material were neglected in the section on Effect of Raw Material Costs on Power Costs since in most cases inclusion of fertile material costs add less than 10% to the fissile inventory cost. For example, at a fertile/fissile inventory ratio of 50/1 and a specific cost ratio of 1/1000, the fertile/fissile inventory cost ratio would be 5/100.

Table IV. Net Raw Materials Required by 2000 to Supply Fissile Material
to Various Reactor Types

Reactor Type	R	E	S, Mw/kg fissile	R/SE*	C	Doubling Time, years	U-235, tons	Natural U, tons
Aq Homo (SR-1)	1.5	0.26	1.5	3.85	1.0	∞	5,975	836,000
Aq Homo (SR-2)	1.5	0.26	3.0	1.93	1.0	∞	2,990	418,000
Aq Homo (SR-3)	1.5	0.26	6.0	0.96	1.0	∞	1,495	209,000
Aq Homo (TR-1)	1.5	0.26	3.0	1.93	1.1	14.3	960	134,000
Aq Homo (TR-2)	1.5	0.26	6.0	0.96	1.1	7.1	-536 (55**)	-75,000 (7700**)
Fast Reactor (1)	3	0.35	0.5	17.15	1.85	20	13,800	1,934,000
Fast Reactor (2)	2.5	0.35	1.5	4.76	1.60	8	-1,650 (362**)	-231,000 (50,700**)
Fast Reactor (3)	2.5	0.35	1.5	4.76	1.45	10.6	612 (890**)	85,700 (125,000**)
Fast Reactor (4)	2.5	0.35	2.0	3.57	1.45	8	-1,238 (272**)	-173,300 (38,100**)
Fast Reactor (5)	1.75	0.35	2.0	2.50	1.25	10	114 (385**)	16,000 (54,000**)
Hetero (1) (H ₂ O)	1.75	0.30	1.0	5.84	0.75	-20	13,460	1,885,000
Hetero (2) (HiQ)	1.65	0.30	2.5	2.20	0.625	-5	10,000	1,402,000
Hetero (3) (GCR)	1.25	0.35	0.5	7.15	0.75	-28.6	14,870	2,081,000

*R'/S'E for breeders

**Peak value.

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019

Table V. Net Raw Materials Required by 2000 to Supply Fertile Material to Various Reactor Types

Reactor Type	R	S, Mw/kg fissile	Fertile Fissile	Mw Reactor Heat Ton fertile	Natural U Req'd, tons	Th Req'd, tons
Aq Homo (SR-1)	1.5	1.5	50	30	-	230,000
Aq Homo (SR-2)	1.5	3.0	50	60	-	115,000
Aq Homo (SR-3)	1.5	6.0	50	120	-	57,500
Aq Homo (TR-1)	1.5	3.0	150	20	-	345,000
Aq Homo (TR-2)	1.5	6.0	300	20	-	345,000
Fast Reactor (1)	3.0	0.5	75	6.7	1,529,000	
Fast Reactor (2)	2.5	1.5	50	30	285,000	
Fast Reactor (3)	2.5	1.5	50	30	285,000	
Fast Reactor (4)	2.5	2.0	50	40	213,000	
Fast Reactor (5)	1.75	2.0	50	40	150,000	
Hetero (1) (H ₂ O)	1.75	1.0	50	20	1,269,000	
Hetero (2) (HiQ)	1.65	2.5	50	50	478,000	
Hetero (3) (GCR)	1.25	0.5	50	10	1,554,000	

Table VI Total Raw Materials Required by 2000 to Supply Various Reactor Types

Reactor Type	Natural U Required, tons		Th Req'd, tons	Total Raw Materials, tons
	For fertile	For fissile		
Aq Homo (SR-1)	-	836,000	230,000	1,066,000
Aq Homo (SR-2)	-	418,000	115,000	533,000
Aq Homo (SR-3)	-	209,000	57,000	266,000
Aq Homo (TR-1)	-	134,000	345,000	479,000
Aq Homo (TR-2)	-	7,700	345,000	353,000
Fast Reactor (1)	1,529,000	1,934,000	-	1,934,000*
Fast Reactor (2)	285,000	50,700	-	285,000**
Fast Reactor (3)	285,000	125,000	-	285,000**
Fast Reactor (4)	213,000	38,100	-	213,000**
Fast Reactor (5)	150,000	53,900	-	150,000**
Hetero (1) (H ₂ O)	349,000	1,885,000	-	1,885,000*
Hetero (2) (HiQ)	139,000	1,402,000	-	1,402,000*
Hetero (3) (GCR)	598,000	2,081,000	-	2,081,000*

* Fertile material used supplied at same time and from same source as fissile material.

** Fertile material determines total natural uranium requirements since fissile material production rate (at some date prior to 2000) is greater than the fissile inventory addition rate. (Turnover point of fissile requirement curve reached before 2000.)

The total raw material requirements for both fertile and fissile materials for each of the 13 reactors are shown in Table VI. Figure 12 is a plot of the total raw materials required for each of the five selected reactors. Homogeneous reactors use both uranium and thorium and the total raw material (uranium plus thorium) they require is very little different from that required for fast breeders of comparable degrees of optimism. The total raw material requirement for the heterogeneous converters is dictated by the fissile needs since the fertile material used is supplied at the same time and from the same sources as the fissile material required for reactor inventory. The fissile material needs dictate the total raw material requirements for fast reactors up to the time at which the new fissile production rate exceeds the new inventory requirements. After this time the total requirements are dictated by fertile inventory needs.

The preceding tables and figures indicate that the breeding ratio is not the most important quality of a breeder. For example, fast reactor F-1, which has the highest breeding ratio (a hypothetical 1.85), uses almost as much uranium as any of the others listed since reactors of this type would require almost 2,000,000 tons of natural uranium between 1960 and 2000 to supply the entire nuclear economy. The high uranium requirements are due to the low specific power and high inventory ratio. Fast reactors that operate at a high specific power and with a low external inventory look more attractive than F-1 even though the breeding ratio may be 1.25-1.45. A two-region homogeneous breeder that operates at 6 Mw_t per kilogram of U-233 also looks attractive even

Table VII. Burnup and Inventory Costs for Various Reactors as a Function of Raw Materials Costs*

	Inventory Costs, mills/kwh _e									Total Nuclear Fuel Costs (Inventory and Burnup), mills/kwh _e					
	Burnup Costs, mills/kwh _e for Raw Materials (as normal UF ₆) at			i = 4%/yr			i = 12%/yr			i = 4%/yr			i = 12%/yr		
				For Raw Materials (as normal UF ₆) at			For Raw Materials (as normal UF ₆) at			For Raw Materials (as normal UF ₆) at			For Raw Materials (as normal UF ₆) at		
	\$10/lb U	\$25/lb U	\$50/lb U	\$10/lb U	\$25/lb U	\$50/lb U	\$10/lb U	\$25/lb U	\$50/lb U	\$10/lb U	\$25/lb U	\$50/lb U	\$10/lb U	\$25/lb U	\$50/lb U
Homogeneous:															
SR-1	0	0	0	0.26	0.40	0.59	0.78	1.20	1.77	0.26	0.40	0.59	0.78	1.20	1.77
SR-2	0	0	0	0.13	0.20	0.30	0.39	0.60	0.90	0.13	0.20	0.30	0.39	0.60	0.90
SR-3	0	0	0	0.07	0.10	0.15	0.21	0.30	0.45	0.07	0.10	0.15	0.15	0.30	0.45
TR-1	-0.22	-0.34	-0.52	0.14	0.21	0.32	0.42	0.63	0.96	-0.09	-0.13	-0.20	0.20	0.29	0.44
TR-2	-0.22	-0.34	-0.52	0.07	0.11	0.16	0.21	0.33	0.48	-0.16	-0.23	-0.36	-0.01	-0.01	-0.04
Fast Reactors:															
F-1	-1.62	-2.46	-3.65	1.56	2.37	3.53	4.68	7.11	10.59	-0.06	-0.09	-0.12	3.06	4.65	6.94
F-2	-1.14	-1.74	-2.57	0.43	0.66	0.97	1.29	1.98	2.91	-0.71	-1.08	-1.60	0.15	0.24	0.34
F-3	-0.85	-1.30	-1.93	0.43	0.66	0.97	1.29	1.98	2.91	-0.42	-0.64	-0.96	0.44	0.68	0.98
F-4	-0.85	-1.30	-1.93	0.33	0.50	0.73	0.99	1.50	2.19	-0.52	-0.80	-1.20	0.14	0.20	0.26
F-5	-0.48	-0.72	-1.07	0.23	0.34	0.51	0.69	1.02	1.53	-0.25	-0.38	-0.56	0.21	0.30	0.46
Heterogeneous Converters:															
H-1	0.67	1.15	1.98	0.55	0.83	1.24	1.65	2.49	3.72	1.22	1.98	3.22	2.32	3.64	5.70
H-2	0.87	1.45	2.42	0.21	0.31	0.47	0.63	0.93	1.41	1.08	1.76	2.89	1.50	2.38	3.83
H-3	0.57	0.99	1.70	0.67	1.01	1.56	2.01	3.03	4.68	1.24	2.00	3.26	2.58	4.02	6.38

*Assumptions: H = 833 Mwd net heat/kg initial fissile material burned

L = 0.8 load factor

r = ratio fissile starting material value/25 value ($r_{23} = 0.9$, $r_{49} = 0.7$ for converters, $r_{49} = 1.0$ for fast reactors)

r' = ratio fissile product value/starting fissile value = 1.0 in all cases

f' = average fraction of fissile inventory above steady state due to holdup of breeding gain in reactor
(f' = 0.05 for homogeneous breeders, f' = 0.20 for fast breeders)

f = average fraction of fissile inventory in a converter which is Pu (f = 0.3 for all cases)

j = ratio of annual inventory charges rate fraction on Pu or U-233 to $i_{25} = 1.0$ for all cases $v'_{25} = \$13.3/g$ U-235 (\$10/lb U), \$20.2/g U-235 (\$25/lb U), \$30.0/g U-235 (\$50/lb U)

though the breeding ratio is 1.1. Even a single-region homogeneous reactor with a conversion ratio of 1 and a specific power of 6 Mw_t per kilogram of U-233 looks attractive if compared to a low-specific-power fast breeder.

Burnup charges (or credits), inventory costs for 4% and 12% annual lease charge, and total nuclear fuel costs for all 13 reactors are given in Table VII. For 4% annual lease charge the high-specific-power fast reactors have the lowest nuclear fuel cost. For 12% annual lease charge a two-region homogeneous breeder which operates at $6 \text{ Mw}_t/\text{kg}$ U-233 has the lowest nuclear fuel charge. Table VII indicates that at 4% annual lease charge the nuclear fuel costs for all listed breeders are negative, while at 12% annual lease charge all breeders, with the exception of the 6 Mw/kg U-233 two-region homogeneous reactor, have positive nuclear fuel costs.

Nomenclature

C = conversion ratio

C' = breeding ratio

D = U-235 recovery factor for gaseous diffusion process

E = net thermal efficiency

F = fraction of total additions since 1960 which have been nuclear

f = ratio of fissile inventory which is Pu to that which is U-235

f' = ratio of average fissile inventory above steady state (due to holdup of breeding gain in reactor) to steady state fissile inventory

G = total accumulated megawatt-years of electrical power generation

H = net Mwd heat per kg of startup fissionable material burned

i = annual inventory charge rate on initial loading, fraction per year

j = ratio of annual inventory charge rate fraction on converted or bred material Pu or U-233 to i

L = load factor, fraction

M = total kgs U-235 mined

P = total installed electrical nuclear power at any period in question

R = inventory ratio, total fissile tied up, kg initial fissile material in reactor (R' for steady state breeder)

r = ratio fissile starting material value/25 value

$\bar{r}$ = value ratio Pu to slightly enriched U-235 value

r' = ratio fissile product value/starting fissile value

S = specific power, Mw_t/kg initial fissile in reactor (S' = specific power for steady state breeder)

T = doubling time, years

$\Delta\$$ = $\$/g$ U-235 consumed

V = $\$/g$ U-235 as slightly enriched U

V' = value 90% U-235, $\$/g$ U-235

θ = time, years

Subscripts

B = breeder

C = converter

e = electric

t = thermal

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Fig. 1. Buildup curves for growth of nuclear power in the United States. For 1960 $\theta = 0$.

Fig. 2. Plot of P - G/T vs. time for US nuclear power.

Fig. 3. Effect of concentration of uranium in ore on recovery cost.

Fig. 4. Effect of conversion ratio on U-235 mined in an expanding US nuclear power economy.

Fig. 5. Effect of natural UF_6 value, inventory ratio, specific power, and efficiency and Pu content and value on slightly enriched converter inventory cost. Uranium lease charge 4% per year; $L = 0.8$; all lines interest at 0 cost and UF_6 at $-\$8/\text{lb U}$.

Fig. 6. Effect of natural UF₆ value, inventory ratio, specific power, efficiency, and breeding gain holdup and value on breeder inventory cost. Uranium lease charge = 4% per year; L = 0.8.

Fig. 7. Effect of natural uranium feed cost on U-235 burnup cost.
Separative work cost = \$37.29 per kilogram of uranium.

Fig. 8. Effect of natural uranium feed cost and Pu/U-235 value ratio on net burnup cost for slightly enriched converter. Separative work cost = \$37.29 per kilogram of uranium; $E = 29\%$; U-235 burnup cost from Fig. 7; 0.833 Mwd net heat per gram of fissile material consumed. All lines intersect at 0 cost and UF_6 at $-\$22/\text{lb U}$.

Fig. 9. Effect of natural uranium feed cost, breeding ratio, and fissile value ratios on breeding gain credit. Separative work cost = \$37.29 per kilogram of uranium; $E = 29\%$; 0.833 Mwd net heat per gram of fissile material consumed. All lines intersect at 0 cost and UF_6 at $-\$22/\text{lb U}$.

Fig. 10. Effect of reactor type and year on raw materials required to supply fissile material for US nuclear power economy.

Fig. 11. Effect of reactor type and year on raw materials required to supply only fertile material for US nuclear power economy.

Fig. 12. Effect of reactor type and year on raw materials required for US nuclear power economy.

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