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STARTUP OF FAST REACTORS ON ²³⁵U FUEL

R. S. Carlsmith

J. G. Delene

L. Jung

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STARTUP OF FAST REACTORS ON ^{235}U FUEL

R. S. Carlsmith J. G. Delene
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ABSTRACT

It is usually assumed that plutonium for the initial inventory of fast breeders will be produced in thermal reactors. A possible alternative is the use of "fast converters," fueled with partially enriched uranium. We have studied the fuel cycles of several types of fast converters with regard to inventories, conversion ratios, fuel-cycle costs, and uranium ore utilization. The fast converter was found to have a performance potential considerably superior to that of the light-water-moderated thermal reactor, while the comparison with a heavy-water-moderated "advanced converter" depended on the design of the fast converter and on the economic assumptions that were made.

INTRODUCTION

It is well known that the requirements for initial inventory of fissionable plutonium can be a significant consideration in a rapid, large-scale introduction of fast breeder reactors. Roughly speaking, the inventory requirements cannot be produced by the breeders themselves if the construction of new breeders is characterized by a doubling time that is shorter than the doubling time for fissionable material by the reactor type. That a plutonium shortage may quite possibly arise is seen from the fact that some of the fast reactor designs under active consideration have doubling times as long as 15 to 20 years,¹ while estimates of the doubling time for the United States nuclear power capacity^{2,3,4} tend to be in the 5 to 10 year range. If these estimates are correct, the alternative possibilities may conveniently be expressed as some combination of the following:

1. The growth rate of the nuclear power industry might be limited by the plutonium production from fast breeders to a doubling time of 15 to 20 years, with the remaining demand coming from non-nuclear power stations.

2. A portion of the nuclear power growth might be supplied by thorium cycle converters and/or breeders.

3. A portion of the plutonium required for fast breeder inventories might come from thermal reactors of the current light-water-moderated types. This alternative obviously implies a continuing construction of LWR's after the introduction of fast breeders since those installed earlier would soon yield only a very small fraction of the required plutonium production.

4. A portion of the plutonium required for fast breeder inventories might come from thermal reactors of an "advanced converter" type.

5. Some fast reactors might be fueled initially with partially enriched uranium instead of plutonium.

In this report we examine in some detail the fifth alternative - the use of ^{235}U to start up fast reactors. We also make some comparisons with the third and fourth alternatives - the use of thermal reactors to produce plutonium. The first two alternatives are omitted from the scope of what we have considered, but may nevertheless turn out to be significant.

There has been a considerable number of reports and papers in the last couple of years on the general topic of fissionable material requirements. A few recent examples are noted here in Refs. 5 through 9. Most of these authors have treated the fuel cycles of the thermal reactors quite carefully, by taking the mass balances and inventories from detailed depletion calculations. However, the fuel cycles of ^{235}U fueled fast reactors have often been either neglected completely or treated by inexact assumptions. In the current investigation we have attempted to do reasonably careful calculations of 30-year reactor histories for several typical fast reactor designs with several different fuel management procedures. We then compared the resulting mass balances with regard to the implied economics (fuel-cycle costs) and also the uranium resource requirements.

This study was conducted as a part of the ORNL program to identify areas of technology that are most promising in the development of large-scale water desalination.

FAST REACTOR FUEL CYCLES

Fast Reactor Design Characteristics

The fast reactors for which we made fuel-cycle calculations are based on three of the General Electric 1000 Mw(e), sodium-cooled fast breeder concepts described in GEAP-4418.¹⁰ These three designs are the 2-ft-high, BeO-moderated (soft spectrum) reactor used as the reference design in the General Electric report, the hard-spectrum (without BeO) version of the reference reactor, and the 4-ft-high internal breeder. All three use an oxide fuel. A summary of the characteristics of the reactors is given in Table 1.

Table 1. Reactor Characteristics

	Soft-Spectrum Reactor	2-ft Core Hard-Spectrum Reactor	4-ft Core Hard-Spectrum Reactor
Reactor power, Mw(t)	2500	2500	2500
Mw(e)	1000	1000	1000
Fuel burnup, Mwd/T	100,000	100,000	100,000
Core height, ft	2	2	4
Core diameter, ft	11.65	10.0	6
Core volume fractions			
Fuel	0.220	0.290	0.400
Sodium	0.459	0.470	0.350
Steel	0.188	0.190	0.200
BeO	0.071	--	--
Void	0.062	0.050	0.050
Axial blanket thickness, ft	1.5	1.5	1.5
Radial blanket thickness, ft	1.26	1.26	1.26
Radial blanket height, ft	5.0	5.0	7.0
Radial blanket volume fractions			
Fuel	0.439	0.439	0.439
Sodium	0.321	0.321	0.321
Steel	0.172	0.172	0.172
Void	0.068	0.068	0.068

These three designs were selected with the idea of covering a fairly wide range in performance. We recognized that still higher breeding ratios are possible, by the use of gas-cooling or metal fuel, and that still lower system specific inventories are possible with the use of carbide fuel and on-site reprocessing. There have also been suggestions for fast reactors with lower breeding ratios, using steam cooling. However, the performance of the reactors selected seems representative of the most likely developments of the next few years.

For consistency and in order to simplify our fuel-cycle calculations, the General Electric designs were modified slightly. The blanket thicknesses and radial blanket volume fractions in all of the calculations were assumed to be the same as those used by G. E. for the soft spectrum reactor. The reactor plant factor was 0.8 in all calculations. A uniform core was used for all designs instead of the three zones specified by G. E. for the soft spectrum design. The final core fuel burnup was assumed to be ~100,000 Mwd/MT. The radial blanket as well as the axial blanket cycle time was assumed to be the same as that of the core.

Fast Reactor Fuel-Cycle Types

Thirty-year fuel-cycle depletion calculations were done on the three reactor designs for various initial fuel and recycle assumptions. Initial fuel was assumed to be either partially enriched ^{235}U from a diffusion plant or plutonium from a PWR. The PWR discharge plutonium composition was taken from ORNL-3686¹¹ and has a $^{239}\text{Pu}:^{240}\text{Pu}:^{241}\text{Pu}:^{242}\text{Pu}$ ratio of 0.5603:0.2374:0.1493:0.0530. At each refueling one-fifth of the core and blanket inventories were removed and replaced with fresh fuel. No delay was assumed for the initial refueling; hence the first four batches of core fuel removed had a burnup of less than 100,000 Mwd/T. A one-cycle delay was assumed from fuel purchase to fuel loading, and an additional cycle for cooling, shipping and reprocessing the fuel before sale. For recycled fuel there was a two-cycle delay from the time the discharged fuel was removed from the core until it was recycled back into the core of the same reactor or another reactor. (A cycle is defined here as the time between refuelings, about 280 calendar days.)

Depletion calculations were made with the following four types of fuel management:

1. Pu-Feed, Pu-Recycle. The initial fuel consisted of PWR plutonium. The plutonium produced in the core and both blankets was mixed and recycled back into the core. Excess plutonium over that needed for criticality was sold. If the available recycle plutonium at the beginning of any cycle was insufficient, the additional fuel for criticality was assumed to be of the PWR discharge composition. Depleted uranium was used as fertile material in both core and blankets. Thirty-year fuel-cycle calculations of this type were done for the soft-spectrum design and for the 2-ft-high core hard-spectrum design.

2. U-Feed, U-Pu Recycle. The initial fuel consisted of uranium, enriched sufficiently for criticality. All of the uranium was recycled, along with sufficient plutonium to maintain criticality. If there was any excess plutonium from a cycle, it was sold. If additional fuel was needed, it was supplied in the form of partially enriched uranium. As the uranium was recycled through many successive cycles, there was an increasing buildup of ^{236}U . Eventually the ^{236}U content became so high that the ^{235}U plus ^{236}U was absorbing more neutrons than it produced. At this point we assumed that all of the uranium discharged at the end of a cycle would be discarded. Thirty-year fuel-cycle calculations of this type were done for the soft-spectrum design and for the 2-ft-high core hard-spectrum design.

3. U-Feed, U-Recycle. The initial fuel consisted of partially enriched uranium as in the preceding type of fuel cycle. All of the uranium was recycled, along with sufficient enriched uranium to provide makeup. The plutonium was sold. The ^{236}U buildup in the recycled uranium penalized the neutron economy so severely that this type of fuel cycle is clearly not of interest. A few indicative results are given in Appendix B; otherwise, this fuel cycle is not included in the subsequent discussion.

4. U-Feed, No Recycle. The initial and makeup fuel consisted of partially enriched uranium. The uranium discharged from the core was returned to the diffusion plant for re-enrichment (as light-water-thermal reactors do). The plutonium recovered from core and blankets was sold.

Thirty-year fuel-cycle calculations of this type were done for all three reactor designs.

We will refer generally to U-feed cases as "fast converters" and to Pu-feed cases as "fast breeders."

Fast Reactor Fuel-Cycle Results

The major results of the depletion calculations are given in Table 2. This table summarizes the fissile masses bought and sold during the 30-year history for each of the seven variations in reactor type and fueling scheme carried through the complete history. The masses of ^{235}U and fissile plutonium are separated in this table and broken down into initial inventory, final inventory and net amount bought or sold during the history other than the initial and final inventories. Equilibrium fissile inventories and the breeding ratios at start of life and at equilibrium are also tabulated in Table 2.

The various fissile masses discounted to startup at 6% per year are tabulated in Table 3. These masses are important in the comparative economic evaluation of the different systems and in determining the value of fissile plutonium relative to ^{235}U . Actually it is the value of the material which is discounted but since the unit price is an unknown in this study it is convenient to express the results in terms of discounted mass.

The lifetime-averaged present-value cost associated with the sale, purchase and interest charges for fissile material are given in Table 4 for each of the seven fuel cycles. Here the value of ^{235}U and fissile plutonium are unknowns in units of \$/g. Fuel-cycle cost is in units of mills/kwhr(e). A capital charge rate of 10% per year and a discount rate of 6% compounded semiannually were used. (The discounting method is discussed in Appendix D.)

The reactivity change upon sodium loss and the Doppler coefficients are tabulated in Table 5. For these calculations the compositions were taken from the end of a cycle near the end of the 30-year history. The ^{235}U -feed cases with U-Pu recycle are not included since their compositions approach the plutonium fueled, plutonium recycle cases at equilibrium.

Table 2. Thirty-Year History Results

	Soft-Spectrum Reactor			Hard-Spectrum, 2-ft Core, Reactor			Hard-Spectrum, 4-ft Core, Reactor
	Type of Initial Fuel			Type of Initial Fuel			Initial Fuel
	Pu with Recycle	²³⁵ U with Pu Recycle	²³⁵ U without Recycle	Pu with Recycle	²³⁵ U with Pu Recycle	²³⁵ U without Recycle	²³⁵ U without Recycle
Breeding ratio at start of life	1.27	0.77	0.77	1.48	0.89	0.89	0.98
Average equilibrium breeding ratio	1.18	1.18	0.79	1.34	1.34	0.93	1.04
²³⁵ U inventories, kg							
Initial inventory	--	3,010	3,010	--	2,700	2,700	1,790
Net purchases during 30-year history	--	1,590	23,600	--	1,180	21,100	18,000
30-year final inventory	--	--	2,500	--	--	2,010	1,070
Total net ²³⁵ U purchases	--	4,600	24,100	--	3,880	21,800	18,700
²³⁹ Pu+ ²⁴¹ Pu inventories, kg							
Initial inventory	2,060	--	--	1,680	--	--	--
Net sales during 30-year history	4,770	4,580	18,200	8,540	8,470	19,900	19,700
30-year final inventory	2,490	2,510	621	2,230	2,220	750	792
Total net ²³⁹ Pu+ ²⁴¹ Pu sales	5,200	7,090	18,800	9,090	10,700	20,600	20,500
Equilibrium fissile inventories, kg							
²³⁵ U inventories							
Core + blankets	--	--	2,460	--	--	2,060	1,180
Out-of-pile	--	--	1,020	--	--	850	510
Total ²³⁵ U inventory	--	--	3,480	--	--	2,910	1,690
²³⁹ Pu+ ²⁴¹ Pu inventories							
Core + blankets	2,510	2,510	656	2,200	2,200	700	673
Out-of-pile	1,000	1,000	244	870	870	260	243
Total ²³⁹ Pu+ ²⁴¹ Pu inventory	3,510	3,510	900	3,070	3,070	960	916

Table 3. Mass Discounted to Startup

	Masses Discounted to Startup	
	²³⁵ U Purchases (kg)	²³⁹ Pu+ ²⁴¹ Pu Sales (kg)
Soft-Spectrum Reactor		
Pu feed, Pu recycle	--	-478 ^a
U feed, U-Pu recycle	4680	1830
U feed, no recycle	14,600	8040
Hard-Spectrum 2-ft Core Reactor		
Pu feed, Pu recycle	--	1720
U feed, U-Pu recycle	3960	3620
U feed, no recycle	12,990	8830
Hard-Spectrum 4-ft Core Reactor		
U feed, no recycle	10,400	8770

^a Negative sales means that there was a net purchase of material.

Table 4. Thirty-Year Lifetime Averaged
Fissile Material Costs

Fuel Cycle	Fissile Material Cost [mills/kwhr(e)]
Soft-Spectrum Reactor	
Pu feed, Pu recycle	$+ 0.0250 V_{Pu}^b$
U feed, U-Pu recycle	$0.0659 V_U^a - 0.0089 V_{Pu}^b$
U feed, no recycle	$0.1758 V_U - 0.0785 V_{Pu}$
Hard-Spectrum 2-ft Core Reactor	
Pu feed, Pu recycle	$+ 0.0007 V_{Pu}$
U feed, U-Pu recycle	$0.0558 V_U - 0.0283 V_{Pu}$
U feed, no recycle	$0.1542 V_U - 0.0865 V_{Pu}$
Hard-Spectrum 4-ft Core Reactor	
U feed, no recycle	$0.1199 V_U - 0.0858 V_{Pu}$

^a V_U $\equiv$ value of ²³⁵U in \$/g.

^b V_{Pu} $\equiv$ value of ²³⁹Pu+²⁴¹Pu in \$/g.

Table 5. Reactivity Change Upon Sodium Loss
and Doppler Coefficients

Fuel Cycle	Sodium-Loss Reactivity Change (% Δk)	Doppler Coefficient ($T \cdot \frac{dk}{dT}$)
Pu feed, Pu recycle, soft-spectrum reactor	-0.02	-0.014
U feed, no recycle, soft-spectrum reactor	-2.27	-0.028
Pu feed, Pu recycle, hard-spectrum 2-ft core reactor	+0.45	-0.006
U feed, no recycle, hard-spectrum 2-ft core reactor	-2.15	-0.008
U feed, no recycle, hard-spectrum 4-ft core reactor	-0.50	-0.008

FUEL-CYCLE COSTS

It is important to recognize that the uranium-feed fast reactors and the plutonium-feed fast reactors would not be competitors. Instead, a uranium-feed fast reactor, or some other type of plutonium producer, is likely to be a necessary adjunct to the rapid construction of large numbers of plutonium-feed fast breeders. Another way of expressing the relationship is to say that there is always some price for plutonium which would make the total power costs for a particular uranium-feed fast reactor equal to those for a particular plutonium-feed fast reactor. If a combination of uranium and plutonium-feed fast reactors were built at the same time, plutonium would tend to adjust to this price under the pressure of supply and demand. Even if there is not a well established market for the buying and selling of plutonium, the concept of a plutonium value which would equalize the power production cost between plutonium-producing reactors and plutonium-consuming reactors is useful in comparing alternatives.

In this section we will fix the plutonium price such that the fuel-cycle cost for a uranium-feed fast reactor is equal to that for a plutonium-feed fast reactor, assuming that the capital costs and operating costs for the two fast reactors are the same. We will then compare the uranium-feed fast reactors with two typical plutonium-producing thermal reactors. The characteristics assumed for the thermal reactor are given in Table 6, along with a summary of the same quantities from our fast reactor calculations. For the light-water-moderated reactor (LWR) we used the calculations reported in Ref. 11 at a burnup of 22,000 Mwd/T. We recognize that LWR's are currently being designed for somewhat higher fuel burnup. However, it appears that a strong future demand for plutonium coupled with increasing uranium ore costs and decreasing fuel fabrication costs would cause optimum burnups to be reduced -- perhaps even below 22,000 Mwd/T. The characteristics of the HWR are those calculated by AI/CE^{1,2} for a heavy-water-moderated and organic-cooled reactor using natural uranium carbide fuel.

Comparative fuel-cycle costs are given in Table 7 for the soft-spectrum, no-recycle fast converter and the two thermal reactors supplying plutonium to the soft-spectrum fast breeder.

A plutonium price of \$19.09/g fissile was required in this case to give the same total fuel-cycle costs for the fast converter and the fast breeder. Other cost bases used in the calculation were: uranium ore at \$8.00/lb U₃O₈, separative work at \$30.00/kg U, fuel inventory cost at 10% per year, and reprocessing and fabrication in 10-tonne per-day centrally located plants. Further discussion of the fabrication, shipping, and reprocessing cost estimates is given in Appendix C. The fuel purchase, sale, and inventory costs were determined on a levelized-cost basis (6% per year discount rate) from the 30-year history mass balances as described in Appendix D. Heavy-water inventory costs were not included in the fuel-cycle costs. All of the reactors were assumed to operate at a constant load factor of 0.8 throughout life. The large difference in total fuel-cycle cost between the fast converter and the HWR means that this fast converter could not compete with an HWR under the stated economic conditions. If both reactor types were fully developed, the HWR's

Table 6. Summary of Reactor and Performance Characteristics

Reactor Type	U-Feed, No-Recycle, Fast Converters			Thermal Converters	
	Soft Spectrum	Hard-Spectrum, 2-ft Core	Hard-Spectrum, 4-ft Core	LWR	HWR
Fuel material	UO ₂	UO ₂	UO ₂	UO ₂	UC
Clad material	SS	SS	SS	Zr-4	SAP
Fuel pin diameter, in.					
Core	0.22	0.22	a		
Blanket	0.45	0.45	a	0.338	0.695
Equilibrium core fuel burnup, Mwd(t)/kg	100	100	100	21	7.8
Equilibrium conversion ratio	0.79	0.93	1.04	0.60	0.78
Equilibrium core feed enrichment (fissile U/total U)	0.259	0.227	0.146	0.022	0.00711
Equilibrium system specific inventory (fissile), kg/Mw(e)	4.38	3.88	2.60	1.96	1.31
Equilibrium system specific inventory (total U+Pu), kg/Mw(e)	87	80	63	132	312
Initial equivalent core specific inventory, short tons natural U ₃ O ₈ /Mw(e) ^b	0.845	0.757	0.501	0.499	0.272
Equilibrium fissile Pu discharge rate, kg/Mw(e)-yr	0.622	0.683	0.679	0.200	0.316
Equilibrium fissile Pu discharged/natural U ₃ O ₈ consumed, kg/short ton ^b	2.75	3.36	3.88	0.99	2.21

^aNot applicable.

^bThroughout this report the enrichment of natural uranium was assumed to be 0.711% and that of diffusion plant tails was 0.251%.

Table 7. Fuel-Cycle Costs - No Recycle, Soft-Spectrum
Fast Converter and Soft-Spectrum Fast Breeder

	Costs in mills/kwhr(e)			
	Fast Breeder	Fast Converter	LWR	HWR
Processing, shipping, and fabrication	0.481	0.442	0.338	0.558
Uranium purchase and inventory	0	2.015	1.215	0.488
Plutonium purchase and inventory	0.478	-1.498	-0.481	-0.857
Total	0.959	0.959	1.072	0.189

would be the preferred type of plutonium producer. The plutonium price would then adjust so that the power cost of the HWR was equal to that of the fast breeder. This would give a plutonium price of \$8.08/g fissile if the capital costs of the two reactor types were the same.

Similar results were obtained for the case of the Pu-recycle soft-spectrum fast converter supplying its excess plutonium to the soft-spectrum fast breeder as shown in Table 8.

Table 8. Fuel-Cycle Costs - Pu Recycle, Soft-Spectrum Fast
Converter and Soft-Spectrum Fast Breeder

	Costs in mills/kwhr(e)	
	Fast Breeder	Fast Converter
Processing, shipping, and fabrication	0.481	0.481
Uranium purchase and inventory	0.0	0.753
Plutonium purchase and inventory	0.555	-0.198
Total	1.036	1.036

The unit costs bases were the same here as in the previous case except that the fabrication for the fast converter fuel was assumed to be remote, and thus as expensive as for the fast breeder. The plutonium price was adjusted to \$22.19/g fissile to equalize the fuel-cycle costs between the fast converter and fast breeder.

Up to this point we have assumed tacitly that fast converters, if they were built, would be of the same design as the fast breeders to which they were supplying plutonium. Actually, this may not be the case. The lowered performance of the soft-spectrum and pancake-shaped cores is associated with efforts to obtain more negative Doppler and sodium-void coefficients. But we can see from the numbers in Table 5 that the change from plutonium to uranium feed also improves the sodium-void coefficient and, to a smaller extent, the Doppler coefficient. A much more detailed analysis of potential accident conditions will be required to establish which designs are actually acceptable. However it appears reasonable that plutonium-feed fuel cycles may require a reactor with a soft-spectrum and high-leakage core, while uranium feed would permit a hard-spectrum and a relatively square core.

The use of the higher performance designs in the fast converters makes a considerable difference in the fuel-cycle costs as shown in Tables 9 and 10.

Table 9. Fuel-Cycle Costs - No Recycle, Hard-Spectrum, 2-ft Core, Fast Converter and Soft-Spectrum Fast Breeder

	Fast Breeder	Fast Converter	LWR	HWR
Processing, shipping, and fabrication	0.481	0.442	0.338	0.558
Uranium purchase and inventory	0.0	1.764	1.215	0.488
Plutonium purchase and in- ventory	0.387	-1.338	-0.391	-0.694
Total	0.868	0.868	1.162	0.352

The plutonium price used in Table 9 to give equal fuel-cycle costs for the fast breeder and fast converter was \$15.47/g.

Table 10. Fuel-Cycle Costs - No Recycle, Hard-Spectrum, 4-ft Core, Fast Converter and Soft-Spectrum Fast Breeder

	Fast Breeder	Fast Converter	LWR	HWR
Processing, shipping, and fabrication	0.481	0.442	0.338	0.558
Uranium purchase and inventory	0.0	1.319	1.215	0.488
Plutonium purchase and inventory	0.289	-0.991	-0.278	-0.517
Total	0.770	0.770	1.275	0.529

The plutonium price used in Table 10 was \$11.54/g.

In this last case, the fuel cycle of the fast converter appears to be distinctly more economical than that of the LWR but still not quite as favorable as the HWR.

There are of course large uncertainties in determining the appropriate economic ground rules for such calculations. Two of the most important questions of this type are the size of the fuel fabrication and reprocessing plants and the cost of uranium ore. We chose to use a fuel plant size corresponding to a throughput of 10 tonnes of heavy metal per day on the basis that plants that large are likely to be built before the end of the century. For comparison, a set of fuel-cycle cost estimates is given in Table 11 on the basis of 1 tonne/day fabrication and processing plants, which should be more typical of the early years of fast reactor use.

The plutonium price used in Table 11 was \$9.88/g. The comparison is more favorable to the fast converter than in Table 10, in which the same reactors were compared in the context of a large fuel processing industry.

Table 11. Fuel-Cycle Costs - No Recycle, Hard-Spectrum, 4-ft
Core Fast Converter and Soft-Spectrum Fast Breeder
with 1 Tonne Per Day Reprocessing

	Fast Breeder	Fast Converter	LWR	HWR
Reprocessing, shipping, and fabrication	1.080	0.856	0.678	1.342
Uranium purchase and inventory	0.0	1.319	1.215	0.488
Plutonium purchase and in- ventory	0.247	-0.848	-0.232	-0.443
Total	1.327	1.327	1.661	1.387

In all of the preceding tables the uranium ore price was assumed to be the current \$8.00/lb U_3O_8 . However, the principal reason for development of breeders and advanced converters is apprehension over the possibility that depletion of the most available uranium reserves may cause a large increase in price. The effect of changing uranium price on the reactors of Table 10 is shown in Fig. 1. It can be seen that a rise in uranium price produces a very rapid increase in LWR fuel-cycle cost, a more gradual increase in HWR fuel cost, and a still more gradual increase in fuel cost of the high-performance fast converters. The indication is that the fast converter surpasses the HWR if uranium ore prices are above \$25.00/lb.

Similar sets of curves for the other two, lower-performance, fast converters are given in Figs. 2 and 3. The soft-spectrum fast converter is less able to withstand uranium ore price increases than the HWR, while the cost curve of the hard-spectrum, 2-ft core, fast converter has about the same slope as that of the HWR.

FUEL UTILIZATION

When different fuel cycles are evaluated by comparing the fuel-cycle costs under a fixed set of economic assumptions, as in the preceding

Fig. 1. Fuel-Cycle Cost of Hard-Spectrum, 4-ft Core, Fast Converter Compared to Thermal Converters.

Fig. 2. Fuel-Cycle Cost of Hard-Spectrum, 2-ft Core, Fast Converter Compared to Thermal Converters.

Fig. 3. Fuel-Cycle Cost of Soft-Spectrum Fast Converter Compared to Thermal Converters.

section, one ignores the fact that the introduction of one type of reactor rather than another may strongly affect the unit costs. This is particularly true of uranium ore costs where the use of a reactor type which requires more uranium may also cause the price of uranium to rise.

The amount of uranium to be mined as a function of time for the various reactor types we are considering can be estimated if we first make assumptions regarding the rate of increase in nuclear power plant capacity and the dates of introduction of the various reactor types. Our estimate of nuclear generating capacity is given in Fig. 4. This curve approximately parallels other recent estimates,³ but is somewhat higher throughout so as to reflect firm construction commitments through 1970. We assume that the fast breeder, fast converter, and advanced converter such as an HWR would all be commercially available to go on the line by 1985. (Though a few reactors of these types might be built earlier.) We assume that all nuclear power generation prior to 1985 is to be by LWR's. Plutonium produced before 1982 is recycled to the LWR's. Subsequent to that time plutonium is to be reserved as needed for use in fast reactors, since construction commitments would have already been made. We assume that all reactors, once built, will continue to operate for 30 years at a constant 0.8 load factor.

The very large difference in ultimate uranium ore consumption between using only LWR's and introducing high-performance fast breeders at an early date is well known. Figure 5 shows these extremes under our assumptions. The use of LWR's alone required 8.9 million tons of uranium through the year 2020. The construction of LWR's to 1985 and HWR's thereafter reduced the ore consumption to 5.7 million tons. The construction of LWR's to 1985 and hard-spectrum fast breeders thereafter required only 1.4 million tons of uranium. These uranium requirements were calculated from the detailed 30-year history mass balances for each of the reactor types, and thus include initial inventories, refueling requirements, and release of material upon final shutdown. Requirements for enriched uranium were based on the assumption of a constant diffusion plant tails enrichment of 0.251%.

Fig. 4. Estimate of Cumulative Installed Capacity of U.S. Nuclear Power Plants.

Fig. 5. Cumulative Ore Requirements Without the Use of Converter Fast Breeder Combinations.

Estimates of uranium reserves are, of course, very uncertain because of the incompleteness of geologic data. However, Table 12 may give some idea of the amounts available at various prices. The indication from these estimates is that the use of LWR's alone would result in the uranium price increases above \$30.00/lb before the end of the century, and thus (as shown in Fig. 1) prohibitively high fuel-cycle costs. The early development of the hard-spectrum fast breeder, on the other hand, would keep the uranium price below \$30.00/lb indefinitely.

Table 12. Estimates of Possible United States Ore Reserves

Price (\$/lb U_3O_8)	Cummulative Total - Million of Tons U_3O_8		
	ENEA ¹³ Estimate	FPC ¹⁴ Estimate	AEC ³ Estimate
Less than 10	0.52	1.08	0.80
Less than 30	1.48	1.83	1.70
Less than 50			9.70
Less than 100		39.91	

The hard-spectrum fast breeder had a short enough doubling time so that concurrent construction of plutonium-producing converter reactors was not required in order to meet our assumed power growth rate. The doubling time of the soft-spectrum fast breeder, on the other hand, was too long to supply all of the plutonium inventory needs for additional reactors of the same type. Figures 6, 7, and 8 show the uranium requirements for the soft-spectrum fast breeder built in conjunction with a sufficient number of converters to supply the required plutonium. The uranium requirement using the soft-spectrum fast converter was about the same as the HWR, while the hard-spectrum fast converter was somewhat better. There was little difference between the soft-spectrum, no-recycle fast converter and the soft-spectrum, Pu-recycle, fast converter. All of the fast converters and the HWR had much lower uranium requirements than the LWR.

Fig. 6. Cumulative Ore Requirements with Thermal Converters and Soft-Spectrum Fast Breeders.

Fig. 7. Cumulative Ore Requirements with No-Recycle Fast Converters and Soft-Spectrum Fast Breeders.

Fig. 8. Cumulative Ore Requirements with Recycle Fast Converters and Soft-Spectrum Fast Breeders.

SUMMARY AND CONCLUSIONS

Some of the principal performance features of the fast converters investigated in this study are summarized in Table 13. Conclusions from the study are summarized below:

1. There is essentially no difference in either fuel-cycle cost or uranium ore requirements between a fast converter, initially fueled with uranium, which recycles plutonium and one of the same design which does not recycle but sells the plutonium.

2. A distinct advantage to the no-recycle fast converter is that safety considerations may allow a higher-performance design in the case of a reactor which is fueled with ^{235}U .

3. A high-performance fast converter had fuel-cycle costs either above or below those of natural uranium HWR, depending on economic assumptions. The fuel-cycle costs for a low-performance fast converter were always higher than those of an HWR.

4. The fuel utilization characteristics of the fast converters ranged from about the same as an HWR to slightly better.

5. Both the fuel-cycle costs and fuel utilization characteristics of all of the fast converters were better than those of the LWR. The difference in fuel-cycle cost increased with increasing uranium cost.

6. As has been noted by previous investigators, the fuel utilization characteristics of a high performance (i.e., short doubling time) fast breeder provide a strong incentive for its development. If a fast breeder with a doubling time of about 7 years can be introduced economically at an early date, there will be no need for the development of either fast or thermal converters.

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Appreciation is expressed to J. T. Roberts, T. N. Washburn, and R. Salmon for permission to use unpublished calculations of fuel-cycle component costs.

Table 13. Summary of Fast Converters

	Soft-Spectrum Fast Converter U-Feed, U-Pu Recycle	Soft-Spectrum Fast Converter U-Feed, No- Recycle	Hard-Spectrum, 2-ft Core, Fast Converter U-Feed, No-Recycle	Hard-Spectrum, 4-ft Core, Fast Converter U-Feed, No-Recycle
Initial conversion ratio	0.77	0.77	0.89	0.98
Equilibrium conversion ratio	1.18	0.79	0.93	1.04
Initial fissile specific inventory, kg/Mw(e)	3.01	3.01	2.70	1.79
Equilibrium system specific inventory, kg/Mw(e)	3.51	4.38	3.87	2.61
Equilibrium core en- richment	0.17	0.26	0.23	0.15
Fuel-cycle cost, mills/kwhr(e) ^a	1.04	0.96	0.87	0.77
Plutonium value, \$/g ^b	22.19	19.09	15.47	11.54

^aWith \$8.00/lb U₃O₈, 10 tonne/day fabrication and reprocessing plants, 10% per year interest on inventory, \$30.00/kg U separative work cost.

^bWhen used to supply plutonium to a soft-spectrum, Pu-feed, Pu-recycle fast breeder.

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APPENDIX A

Calculational Procedure

A basic GAM-II¹⁵ cross section library was used for all calculations. Cross sections were reduced from 99 groups to 20 groups with the zero-dimensional GAM-II code. Five sets of 20-group cross sections were generated for use in the depletion calculations: one each for the three reactor designs fueled with ²³⁵U and one each for the two reactor designs fueled with plutonium.

The one-dimensional MODRIC¹⁶ and MERC¹⁷ codes were then used to obtain one-group microscopic reaction rates for each region of the reactors. In each of the MODRIC and MERC calculations a two-dimensional synthesis was obtained by iterating between successive one-dimensional radial and axial calculations. The transverse buckling terms were adjusted until the leakage from the core for each group in the radial calculation matched the corresponding term in the axial calculation and vice versa. Since the neutron spectra and flux levels in a region vary with time during the reactor history, it was necessary to use several sets of one-group reaction rates to represent successive stages in the thirty-year history.

One-group fuel-cycle calculations were performed with the TONG¹⁸ point-depletion code for each type of fuel management under consideration. This code was used to follow the isotopic compositions in the five fuel streams in each of the three regions: the core, radial blanket, and axial blanket. In this way one-fifth of the core and blankets could be removed and replaced at each refueling, after the proper irradiation exposure. It was assumed that each fuel stream within a single region was exposed to the same spectrum and flux level at any one time. The changes in spectra and flux levels with time were followed by frequent recalculation of reaction rates as indicated above. The size of the perturbations to critical enrichment and breeding ratio upon introducing a new set of reaction rates was used to determine how frequently this change was required. A uniform poison was used to maintain criticality throughout burnup, and the enrichment at the start of each cycle was adjusted so as to give the desired reactivity lifetime. In the cycles which involved recycle of uranium

and/or plutonium there was a delay of two cycles from discharge of the material until it was reintroduced to the core. Mass balances and breeding ratios for the equilibrium cycle were also obtained from MERC calculations as a check on the accuracy of the TONG calculations for each fuel cycle.

For the calculations of Doppler coefficients and sodium-loss reactivity coefficients, fuel compositions were taken from the end of a cycle near the end of the thirty-year history. The higher relative plutonium concentrations at the end of cycle give the most positive (least favorable) value for the sodium-void coefficient. The reactivity coefficients were then obtained by comparing k for MODRIC calculations with and without sodium and at an elevated fuel temperature. Doppler-broadened 20-group cross sections were obtained for this purpose by additional GAM-II calculations for each reactor composition, fuel temperature, and sodium content condition.

APPENDIX B

 ^{235}U Feed With ^{236}U Recycle

The third series of depletion calculations used ^{235}U as the initial and makeup fuel with the recycle of ^{235}U plus ^{236}U removed from the core back into the core after a two-cycle delay. All plutonium produced in the core and blankets was sold. These depletion calculations were carried through eleven calendar years of operation for both the soft- and hard-spectrum reactors.

Figures B.1 through B.3 plot the ^{236}U core inventory, fissile inventory, and conversion ratio for the soft-spectrum reactor as a function of time since startup. The values plotted are all for the beginning of cycle, that is, after the old fuel had been replaced by fresh fuel.

The nearly linear increase of ^{236}U inventory (Fig. B.1) caused the fissile inventory (Fig. B.2) to rise and the conversion ratio (Fig. B.3) to fall. Similar results were obtained for the hard-spectrum reactor. The steady increase of the ^{236}U poison would prove disastrous to the economics of such a fuel cycle. These calculations were therefore discontinued.

Fig. B.1. Mass of ^{236}U in Reactor Core as a Function of Time Since Startup (Soft-Spectrum Reactor, ^{235}U Feed, U Recycle).

Fig. B.2. Fissile Inventory as a Function of Time Since Startup (Soft-Spectrum Reactor, ^{235}U Feed, U Recycle).

Fig. B.3. Conversion Ratio as a Function of Time Since Startup (Soft-Spectrum Reactor, ^{235}U Feed, U Recycle).

APPENDIX C

Cost Estimates for Fuel Fabrication,
Reprocessing, and Shipping

The unit costs for fabrication, reprocessing, and shipping were taken from unpublished calculations by T. N. Washburn, J. T. Roberts, and R. Salmon of ORNL. The calculational procedures are described in some detail in an earlier report,¹¹ though some revisions have been made to the estimates since that time. The fabrication and reprocessing were assumed to be done in separate, central plants located 1000 miles from the reactor site. A fixed charge of 22% per year of the plant capital cost was used, and the plant was assumed to operate 260 days/year. Principal variables affecting the calculational results were the design of the fuel elements and the size of the fabrication and reprocessing plants.

The resulting unit costs for reprocessing can be expressed as a single set of equations for each type of fuel element as follows:

1. LWR

The capital investment is

$$C_c = 29 P_c^{0.35} \quad (\$10^6) ,$$

where P_c is plant capacity in MT/day, and operating cost is

$$C_o = 0.084 C_c + 0.13 P_c \quad (\$10^6/\text{yr}) .$$

2. HWR

The capital investment is

$$C_c = 31 P_c^{0.35} ,$$

and operating cost is

$$C_o = 0.084 C_c + 0.13 P_c .$$

3. Fast Reactors

The capital investment is

$$C_c = 39.5 P_c^{0.35} ,$$

and operating cost is

$$C_o = 0.084 C_c + 0.26 P_c$$

Fabrication costs are shown in Fig. C.1, also as a function of plant size. There are two curves for fast reactors depending on whether the fuel would be fabricated directly, as in the case of uranium feed, or remotely, as would be required for plutonium. We assumed that the unit costs for the 4-ft-high core fast reactor, for which the fuel element design is somewhat different, were the same as those for the 2-ft-high core reactors. Other related items which must be included in the fuel-cycle cost calculation are chemical conversion, shipping, and ultimate waste disposal. The unit costs for all of those items are given in Table C.1 for a plant size of 1 tonne/day and in Table C.2 for a plant size of 10 tonnes/day.

Table C.1. Unit Costs at 1 Tonne/Day
(\$/kg heavy metal)

	LWR	HWR	Fast Reactor (Direct)	Fast Reactor (Remote)
Processing	34.41	36.73	47.18	47.18
Conversion	6.51	4.45	17.00	17.00
Waste disposal	3.50	3.50	3.50	3.50
Shipping				
Core and axial blanket	3.60	3.03	12.00	12.00
Radial blanket			6.00	6.00
Fabrication				
Core and axial blanket	58.10	34.51	173.40	269.20
Radial blanket			56.00	56.00
Total	106.12	82.22	253.08 ^a	348.88 ^a

^aTotals do not include radial blanket.

Fig. C.1. Unit Fabrication Costs.

Table C.2. Unit Costs at 10 Tonnes/Day
(\$/kg heavy metal)

	LWR	HWR	Fast Reactor (Direct)	Fast Reactor (Remote)
Processing	8.09	8.47	11.34	11.34
Conversion	3.62	2.59	9.05	9.05
Waste disposal	2.40	2.40	2.40	2.40
Shipping				
Core and axial blanket	3.60	3.03	12.00	12.00
Radial blanket			6.00	6.00
Fabrication				
Core and axial blanket	35.42	17.71	108.00	124.70
Radial blanket			24.20	24.20
Total	53.13	34.20	142.79 ^a	159.49 ^a

^aTotals do not include radial blanket.

APPENDIX D

Calculation of Lifetime Average Fuel-Cycle Costs

The thirty-year lifetime averaged fuel-cycle costs calculated in this study were based on present value discounting techniques. The average or levelized fuel cost was determined by computing the present value (value discounted to reactor startup) of all future costs and dividing it by the discounted amount of the energy sold during the thirty-year life of the plant. The advantage of present value discounting is that it implicitly includes the effect of time displacements between investments and returns. The levelized cost includes applicable interest charges caused by these time displacements.

The fuel-cycle cost is made up of two components, the direct cost and the interest charges associated with an item of cost. The direct cost contribution is obtained by summing up all costs or credits for an item during the reactor history and dividing this by the total energy sold with no discounting.

To calculate the interest charges associated with an item of cost, we determine the total discounted present value of all direct costs and credits for an item over the reactor lifetime and divide this by the discounted amount of energy delivered. The result is the total cost for an item, including interest charges if the interest rate is equal to the discount rate. The interest charge is the difference between this total cost and the direct cost, multiplied by the ratio of the capital charge rate to the discount rate.

A capital charge rate of 10% per year was used in this study. Capital items include fuel purchase and fuel fabrication. Non-capital items such as fuel shipping and reprocessing have a charge rate equal to the net cost of borrowing money, that is, 6% per year in this study. A 6% per year semiannual compounded discounting was used to calculate the present value of an item of cost. For calculational purposes we assumed that income from energy generated or fissile material sold during a six month accounting period is received at the end of the period. Costs from the purchase of fissile material were charged at the beginning of the period in which

they were purchased. Thus, the initial core inventory which is purchased approximately 5 months or one cycle before startup is treated as if purchased 6 months before startup. All items are discounted to actual reactor startup.

APPENDIX E

Fissile Inventories and Conversion Ratios

Results from the TONG depletion calculations are shown in Figs. E.1 through E.14. Fissile inventories and conversion ratios are plotted as a function of time for each of the seven fuel management calculations carried through the thirty-year history.

The values plotted in these figures represent those for the beginning of cycle, that is, after fresh fuel has replaced the discharged fuel, but before power operation. Discontinuities in the TONG results due to changes in cross section sets have been smoothed out. These discontinuities were relatively minor and were at most about $\pm 1\%$ of the values plotted.

The removal of ^{235}U and ^{236}U from the reactor caused the sharp change in the shape of the curves in Figs. E.4 and E.10 at 13-1/2 and 14-1/2 years respectively. When the $^{235}\text{U} + ^{236}\text{U}$ became a net poison they were removed from the reactor as they came up for reprocessing. After five cycles the removal was complete and the reactors were approximately at equilibrium.

Fig. E.1. Fissile Inventory as a Function of Time Since Startup (Soft-Spectrum Reactor, Pu Feed, with Recycle).

Fig. E.2. Breeding Ratio as a Function of Time Since Startup (Soft-Spectrum Reactor, Pu Feed, with Recycle).

Fig. E.3. Fissile Inventory as a Function of Time Since Startup (Soft-Spectrum Reactor, ^{235}U Feed, U + Pu Recycle).

Fig. E.4. Breeding Ratio as a Function of Time Since Startup (Soft-Spectrum Reactor, ^{235}U Feed, U + Pu Recycle).

Fig. E.5. Fissile Inventory as a Function of Time Since Startup (Soft-Spectrum Reactor, ^{235}U Feed, No Recycle).

Fig. E.6. Conversion Ratio as a Function of Time Since Startup (Soft-Spectrum Reactor, ^{235}U Feed, No Recycle).

Fig. E.7. Fissile Inventory as a Function of Time Since Startup (Hard-Spectrum, 2-ft Core, Reactor Pu Feed with Recycle).

Fig. E.8. Breeding Ratio as a Function of Time Since Startup (Hard-Spectrum, 2-ft Core, Reactor Pu Feed with Recycle).

Fig. E.9. Fissile Inventory as a Function of Time Since Startup (Hard-Spectrum, 2-ft Core, Reactor ^{235}U Feed, U + Pu Recycle).

Fig. E.10. Breeding Ratio as a Function of Time Since Startup (Hard-Spectrum, 2-ft Core, Reactor ^{235}U Feed, U + Pu Recycle).

Fig. E.11. Fissile Inventory as a Function of Time Since Startup (Hard-Spectrum, 2-ft Core, Reactor ^{235}U Feed, No Recycle).

Fig. E.12. Conversion Ratio as a Function of Time Since Startup (Hard-Spectrum, 2-ft Core, Reactor ^{235}U Feed, No Recycle).

Fig. E.13. Fissile Inventory as a Function of Time Since Startup (Hard-Spectrum, 4-ft Core, Reactor ^{235}U Feed, No Recycle).

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Fig. E.14. Conversion Ratio as a Function of Time Since Startup (Hard-Spectrum, 4-ft Core, Reactor ^{235}U Feed, No Recycle).

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