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ALTERNATIVE FUEL CYCLE OPTIONS:
Performance Characteristics and Impact on
Nuclear Power Growth Potential

by

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ABSTRACT

The fuel utilization characteristics for LWR, SSCR, CANDU and LMFBR reactor concepts are quantified for various fuel cycle options, including once-through cycles, thorium cycles and denatured cycles. The implications of various alternative reactor deployment strategies on the long-term nuclear power growth potential are then quantified in terms of the maximum nuclear capacity that can be achieved and the growth pattern over time, subject to the constraint of a fixed uranium resource base.

The overall objective of this study is to shed light on any large differences in the long-term potential that exist between various alternative reactor/fuel cycle deployment strategies.

I. INTRODUCTION

The recent resurgence of nuclear arms proliferation concerns has prompted a reevaluation of various reactor concepts and fuel cycle options as alternatives to the baseline strategy of LWR-Recycle-LMFBR evolution. A balanced evaluation of proliferation-resistant alternatives should address the following four issues:

1. Technological feasibility
2. Economic feasibility
3. Effectiveness as a non-proliferation measure
4. Implications on uranium resource utilization and longer-term energy supply.

This report limits its scope to the last of these issues. The longer-term energy supply potential defines ultimate incentives in the choice of the next generation reactor types. This report has two objectives: (1) to provide a consistent quantitative basis for the fuel utilization characteristics, and (2) to illuminate differences in longer-term potential among various reactor deployment strategies so that the least promising options can be discarded in the early planning stages and the most promising options can be evaluated in more detail.

A consistent normalized set of reactor performance characteristics is a requirement for realistic conclusions from reactor strategy studies involving a large number of alternative reactor/fuel cycle options. This work attempts to accomplish this, even though in a preliminary way, and the performance characteristics for various reactor concepts and fuel cycle options are presented in Section II. Various fuel cycle options were analyzed for the following reactor types, in addition to the reference LWR: the Spectral Shift Control Reactor, the CANDU Heavy Water Reactor, and the LMFBR.

Based on the reactor performance characteristics presented in Section II, the longer-term power growth potential is analyzed in Section III for various deployment strategies. The maximum nuclear capacity achievable and the growth pattern over time are determined subject to two main constraints:

1. Cumulative U_3O_8 consumption of 3.7 million ST.
2. Fissile material availability at each point in time.

The viewpoint in this work differs somewhat from the usual way of looking at system studies: Normally an energy demand is imposed and the output is cumulative U_3O_8 consumption as a function of time. The form of the energy demand function, the growth rate as well as the magnitude, can make a significant difference in the total U_3O_8 requirements shown by various reactor deployment strategies for a given time period. In this work, with the U_3O_8 resource fixed at 3.7 million ST, the shape of the demand curve is allowed to vary to maximize the amount of electrical energy produced for each of the various reactor deployment scenarios. In this way, we hope to be fair to each reactor type and deployment scenario by allowing it to maximize capacity and in this way to shed light on any large differences in the longer-term potential that may exist between the various reactor types and deployment strategies.

II. PERFORMANCE CHARACTERISTICS OF VARIOUS REACTOR CONCEPTS AND FUEL CYCLE ALTERNATIVES

A. Light Water Reactor (LWR)

The Westinghouse PWR with standard 17 x 17 fuel design¹ was taken as the model LWR for this study. The mechanical fuel design features were unaltered, with the exception of the heavy metal loading, for the comparison of various fuel cycle options listed below.

1. Uranium cycle once-through
2. Uranium cycle with U recycle
3. Thorium cycle with 93% enriched ^{235}U startup and annual makeup
4. Denatured thorium cycle with 20% enriched ^{235}U startup and annual makeup
5. Denatured thorium cycle with externally supplied ^{233}U (12% ^{233}U in U) startup and annual makeup
6. Denatured uranium cycle with externally supplied ^{233}U startup and annual makeup.

The analysis of the fuel utilization characteristics for the various fuel cycle options was based on lattice calculations performed with the EPRI-CELL code.² The EPRI-CELL code consists of modified versions of the GAM, THERMOS and CINDER codes. The original GAM resonance treatment has been replaced by a parameterization of group-wise resonance integral shielding factors tabulated as functions of the effective potential scattering cross section and temperature. For the isotopes in the thorium chain, the resonance shielding factors were generated by the RABANL module of MC²-2 code package³ (an improved version of RABBLE⁴). The ^{232}Th resonance integrals calculated by the EPRI-CELL procedure are in good agreement with the measured data,^{5,6} as illustrated in Fig. 1.

Fig. 1

Comparison of EPRI-CELL Calculations of Th Resonance Integrals with Measured Data. ANL Neg. No. 116-77-764.

Even though detailed core analyses have not been performed, the EPRI-CELL calculations should provide adequate estimates of fuel utilization characteristics. The results are summarized in Table I for the various fuel cycle options in the LWR.

1. Uranium Once-Through Cycle: This is the reference cycle with no recycle allowed. The 30-year uranium requirements are 5,985 ST U_3O_8 /GWe. The lifetime U_3O_8 requirements are calculated as the initial core requirements plus 29 annual reloads at 75% capacity factor and assuming a 0.2% tails assay.

2. Uranium Cycle With U Recycle: The mass flow characteristics are identical to the reference U cycle. With the uranium recycle credit, the U_3O_8 requirements are reduced by ~20%. With the plutonium recycle the U_3O_8 requirements could be further reduced by additional 20%.⁷

3. Thorium Cycle: In this option, the initial core is fueled with 93% ^{235}U enriched uranium, and self-generated ^{233}U recycle is assumed for the equilibrium cycles, again with 93% ^{235}U enriched uranium makeup. The initial U_3O_8 requirements are about 30% higher for the thorium cycle than the uranium cycle. Because of the high conversion ratio possible with ^{233}U fueling, the equilibrium cycle U_3O_8 requirements are about 20% less for this cycle than for the comparable uranium cycle with full uranium and plutonium recycle. The breakeven cumulative uranium consumption between the two cycles occurs in about 10 years and the net savings for a 30-year lifetime is in the order of 15%.

The uranium isotopic composition for self-generated recycle in the thorium cycle is presented in Fig. 2 as a function of the recycle generation. All uranium isotopes were recycled continuously, mixed with 93% ^{235}U enriched uranium makeup fuel at each recycle generation. Each recycle generation represents a 36,000 MWD/T discharge burnup (about a 3-year in-core irradiation). The ^{233}U concentration saturates rapidly, within 3-4 recycle generations. However, the parasitic ^{234}U and ^{236}U isotopes continue to build up even after 15 recycle generations. After 15 recycles, the uranium isotopic composition is as follows:

<u>Isotope</u>	<u>% Composition</u>
^{233}U	28
^{234}U	14
^{235}U	18
^{236}U	29
^{238}U	11

The fissile enrichment ($^{233}U + ^{235}U$) in uranium drops below 50% after 8 recycle generations. As ^{234}U and ^{236}U build up the fissile loading requirements increase as shown in Fig. 3. Also shown in Fig. 3 is the net ^{235}U makeup requirement as a function of the recycle generation. For a more complete thorium cycle assessment, more careful attention should be given to the neutronics of continued recycling and the implications of ^{232}U buildup on fuel cycle facility requirements.

4. Denatured Thorium Cycle With ^{235}U Makeup: The standard thorium cycle described above probably should be assigned a similar proliferation risk to the Pu cycle because both the fresh fuel and the discharge fuel contain highly enriched uranium that can be separated from thorium by chemical processes.

TABLE 1. FUEL UTILIZATION CHARACTERISTICS FOR LWRs UNDER VARIOUS FUEL CYCLE OPTIONS

	Uranium Cycle		Th Cycle	Denatured Th		Denatured U
	Throwaway	U Recycle	93% ^{235}U	^{235}U Makeup	^{233}U Makeup	^{233}U Makeup
Discharge Burnup, MWD/kg	33	33	36	35.3	35.3	33
Equilibrium Fissile Enrichment, ^a XEM	3.2	3.2	4.1 (93% in U)	4.4 (20% in U)	3.0 (12% in U)	2.4
Initial Core Loading, kg/GWe						
^{235}U (ST U_3O_8)	1800(417)	1800(417)	2124(539)	2319(584)	33	159
^{233}U	-	-	-	-	1582	1210
Equilibrium Loading, ^b kg/GWe-yr						
^{235}U (ST U_3O_8)	804(192)	804(192)	583	774	d	d
^{233}U	-	-	390	342	722	570
Equilibrium Discharge, ^b kg/GWe-yr						
^{235}U (ST U_3O_8)	216(N.C.)	216(42)	206	318	d	d
^{233}U	-	-	390	342	435	107
Fissile Pu	163	163	6	61	57	154
Annual Net Requirements, ^b kg/GWe-yr						
^{235}U (ST U_3O_8)	588(192)	588(150)	377(96)	456(116)	0	0
^{233}U	0	0	0	0	287	463
Fissile Pu	-163	-163	-6	-61	-57	-154
Lifetime Requirements ^c						
ST U_3O_8	5985	4767	3323	3948	0	0
kg ^{233}U	0	0	0	0	9905	14637
kg Fissile Pu	-4890	-4890	-180	-1830	-1710	-4620

^aFor Fresh Fuel

^bAt 75% Capacity Factor, Tails Assay = 0.2%

^cInitial Core +29 Equilibrium Reloads.
Transition period requirements not included.

^dSelf-generated Recycle.

Fig. 2. Uranium Isotopic Composition as a Function of Continuous Recycle for the LWR Thorium Cycle with Highly Enriched Uranium Makeup. ANL Neg. No. 116-77-761.

Fig. 3. Fissile Loading and Net ^{235}U Makeup Requirements as a Function of Continuous Recycle for the LWR Thorium Cycle with Highly Enriched Uranium Makeup. ANL Neg. No. 116-77-771.

To circumvent this and at the same time to take advantage of the improved fuel utilization characteristics of the thorium cycle, the concept of an isotopically denatured cycle has been proposed.^{8,9} In the present work the enrichment constraint for the denatured thorium cycle was assumed to be 12% ^{233}U or 20% ^{235}U of total uranium, or a weighted average for a mixture. It is a separate issue in itself whether or not isotopic denaturing to the enrichment level indicated would be an adequate proliferation deterrent. As shown in Table I, the uranium requirements for the ^{235}U makeup denatured thorium cycle are about 20% higher than for the reference thorium cycle, giving no credit for the increased plutonium production.

5. Denatured Thorium Cycle With ^{233}U Makeup: In this cycle option, externally supplied ^{233}U is used as the makeup fuel in addition to the self-generated ^{233}U . The plutonium is discarded after discharge. The annual makeup requirements for ^{233}U are 287 kg/GWe, with initial core requirements of about 1600 kg of ^{233}U .

6. Denatured Uranium Cycle With ^{233}U Makeup: In this cycle option, externally supplied ^{233}U is mixed with depleted uranium. Discharge uranium is recycled but plutonium is not. The disadvantage of this cycle compared to the denatured thorium cycle is that the conversion ratio is lower because plutonium is produced instead of high- η ^{233}U . The advantages are that the initial core ^{233}U inventory is reduced by about 25%, and if ^{233}U is produced in plutonium-fueled LMFBRs in a symbiotic system, the effect of the increment in conversion ratio lost in the LWR is counter-balanced by the LWR-produced plutonium available to the breeder system.

B. Spectral Shift Control Reactor (SSCR)

The SSCR, developed by B&W in early 1960's,^{10,11} is a variation on the conventional PWR. In the SSCR the excess reactivity is controlled by a spectrum shift produced by varying the D_2O/H_2O ratio of the coolant. At the beginning of a cycle the concentration of heavy water is highest, resulting in a hard spectrum. The hardened spectrum increases the resonance absorption in the fertile material and reduces reactivity. Because the excess neutrons which ordinarily would be lost to the hold-down poison material in the PWR are captured by the fertile material in the SSCR, an improved conversion ratio results.

Fuel utilization characteristics for selected fuel cycle options in the SSCR are summarized in Table II and compared with the standard LWR. For the SSCR analysis, the same fuel design features and fuel management assumptions were employed as for the standard LWR with the exception of the D_2O concentration.

1. Uranium Once-Through Cycle: As shown in Table II the fissile loading requirements for the SSCR are reduced by ~10% from those of the LWR, and the saving in U_3O_8 consumption for the once-through cycle is therefore of the order of 10% as well. Annual refueling is assumed for both cases. The D_2O concentration for the SSCR is decreased linearly from 40% at BOC to 2% at EOL. With the annual refueling, the reactivity swing over the cycle for the standard LWR is about 10% Δk , which can be controlled by only 40% initial D_2O concentration. Hence, full spectrum shift cannot be utilized with annual refueling. The reactivity worth of the D_2O is shown in Fig. 4 as a function of the D_2O concentration in the coolant.

2. Uranium Cycle With Uranium Recycle: Since the initial fissile loading for the SSCR is less than for the LWR, the discharge ^{235}U content is also less for the SSCR. Hence, the U_3O_8 saving for the U recycle case is about the same as the throwaway cycle, i.e., of the order of 10%. However, the Pu discharge is increased by 15%. The net fissile (^{235}U + fissile Pu) consumption is reduced by about 20% for the SSCR. This apparent rather marginal improvement in the fuel utilization is due to the fact that only partial spectrum shift is compatible with annual refueling. A more extreme spectrum shift can be achieved in a cycle with one continuous burnup without annual partial refueling. If the same discharge burnup is assumed as for the annual refueling case, then the continuous burnup case (full core replaced every 33,000 MWD/T) requires an initial D_2O concentration of 73%. Preliminary calculations indicate, however, that the fissile loading requirements are increased and the U_3O_8 net consumption is also increased even though the plutonium production is increased significantly compared to the annual refueling case. The overall conversion ratio is about the same between the two cases. The reactivity changes with burnup for the SSCR equilibrium batches are plotted in Fig. 5 compared with the equivalent LWR case.

3. Denatured Thorium Cycle With ^{233}U Makeup: As shown in Table II the initial core ^{233}U inventory is reduced by 10% and the annual makeup requirements by 20% for the SSCR as compared to the LWR. In this cycle option, the makeup fuel (^{233}U) is same as the bred fuel. In the standard thorium cycle or the denatured thorium cycle with ^{235}U makeup, the fuel utilization improvements achieved by the SSCR are expected to be higher than those for the ^{233}U makeup case because the conversion ratio will be further enhanced by the better quality of the bred fuel.

TABLE II. FUEL UTILIZATION CHARACTERISTICS FOR SSCR COMPARED WITH LWR

	U Cycle-Throwaway		U Cycle - U Recycle		Dematured Th- ²³³ U Makeup	
	LWR	SSCR	LWR	SSCR	LWR	SSCR
Discharge Burnup, MWD/kg	33	33	33	33	35.3	35.3
Equilibrium Fissile Enrichment, ^a %HM	3.2	2.9	3.2	2.9	3.0 (12% in U)	2.8 (12% in U)
Initial Core Loading, kg/GWe						
²³⁵ U (ST U ₃ O ₈)	1800(417)	1609(369)	1800(417)	1609(369)	33	30
²³³ U	-	-	-	-	1582	1439
Equilibrium Loading, ^b kg/GWe-yr						
²³⁵ U (ST U ₃ O ₈)	804(192)	719(170)	804(192)	719(170)	d	d
²³³ U	-	-	-	-	722	657
Equilibrium Discharge, ^b kg/GWe-yr						
²³⁵ U (ST U ₃ O ₈)	216(N.C.)	190(N.C.)	216(42)	190(35)	d	d
²³³ U	-	-	-	-	435	427
Fissile Pu	163	188	163	188	57	60
Annual Net Requirements, ^b kg/GWe-yr						
²³⁵ U (ST U ₃ O ₈)	588(192)	529(170)	588(150)	529(135)	0	0
²³³ U	0	0	0	0	287	230
Fissile Pu	-163	-188	-163	-188	-57	-60
Lifetime Requirements ^c						
ST U ₃ O ₈	5985	5299	4767	4284	0	0
kg ²³³ U	0	0	0	0	9905	8109
kg Fissile Pu	-4890	-5640	-4890	-5640	-1710	-1800

^aFor Fresh Fuel^bAt 75% Capacity Factor, Tails Assay = 0.2%.^cInitial Core +29 Equilibrium Reloads. Transition period requirements not included.^dSelf-generated recycle.

Fig. 4

D₂O Reactivity Worth as a Function of D₂O Concentration for Uranium Cycle SSCR. ANL Neg. No. 116-77-747.

Fig. 5
Reactivity Variations with Burnup for the Uranium Cycle in SSCR and PWR. ANL Neg. No. 116-77-746.

C. CANDU Heavy Water Reactor

Heavy water moderated reactors start with a small advantage over other moderators in the conversion ratio theoretically achievable because of the very low neutron absorption in the deuteron, were there no other differences in the neutron absorption of other necessary reactor components. As a practical matter, however, absorption in the structural materials in both HWRs and LWRs, and in fission products due to burnup differences, makes the conversion efficiency more dependent on reactor design than on moderator type.

In this study the current generation CANDU reactor was chosen as the model heavy water reactor. In the development of the CANDU reactor concept, neutron economy was given high priority to take maximum advantage of the D_2O properties. The on-line refueling scheme was introduced to minimize the excess reactivity requirements. Unlike most other reactor systems, in the natural uranium- D_2O system, the payoff in reducing parasitic absorption and excess reactivity requirements is direct and substantial in the achievable burnup. However, these same considerations make CANDU an efficient converter when the natural uranium restriction is removed and recycle fueling schemes are introduced.

Penalties associated with the CANDU neutron economy include the large inventory of the moderator (the D_2O inventory cost is a significant portion of the plant capital cost) and the large fuel mass flow through the fuel cycle. In enriched fuel cycles, with the reactivity constraint removed, the CANDU design can be reoptimized for the prevailing economic and resource conditions. However, scoping calculations performed indicate marginal economic incentives, if any, for any substantial design modifications from the current commercial CANDU design.¹²⁻¹⁶

In this study, where only the fuel utilization aspect is addressed, the current generation CANDU fuel design is assumed with a minor modification for the thorium cycle. A discharge burnup of 16,000 MWD/T and the on-line refueling capability were assumed for all enriched fuel cycles. Fuel utilization characteristics are summarized in Table III.

1. Natural Uranium Once-Through Cycle: The 30-year U_3O_8 requirements are about 4,700 ST/GWe, which is 22% less than the LWR once-through cycle. Even though the fissile plutonium concentration in the spent fuel is low ($\sim 0.27\%$), the total quantity of fissile plutonium discharged annually is twice that from the LWR.

2. Enriched Uranium Once-Through Cycle: With slightly enriched uranium ($1\% \text{ }^{235}\text{U}$) a 16,000 MWD/T burnup can be achieved and the U_3O_8 consumption is reduced by 25% from the natural uranium cycle. As shown in Fig. 6 the optimum enrichment is in the area of 1.2%, which corresponds to about 20,000 MWD/T burnup.

3. Plutonium Cycle: In this cycle option the natural uranium fuel is "topped" with 0.3% fissile plutonium. A discharge burnup of 16,000 MWD/T can be achieved and the plutonium content in the discharge is sufficient to keep the system going with only the natural uranium makeup. The U_3O_8 requirements are reduced to about one half of the natural uranium cycle. (Smaller plutonium toppings decrease the burnup and make the system a net plutonium producer, larger toppings increase the burnup and make the system a net plutonium burner.)

TABLE III. Fuel Utilization Characteristics for CANDU Reactors under Various Fuel Cycle Options

	Natural Uranium	Enriched Uranium	Pu Cycle	Th Cycle	Denatured Th Cycle		
					²³³ U Makeup	²³⁵ U Makeup	Once-Through
Discharge Burnup, MWD/kg	7.5	←————— 16 —————→					
Equilibrium Fissile Enrichment, ^a % HM	0.711	1.0	NU+0.3	1.91 (93% in U)	1.46 (12% in U)	1.65 (13% in U)	1.88 (20% in U)
Initial Core Loading, kg/GWe							
²³⁵ U (ST U ₃ O ₈)	897(164)	1261(257)	897(164)	2159(548)	-	2121(538)	2121(538)
Fissile Pu	-	-	378	-	-	-	-
²³³ U	-	-	-	-	1648	-	-
Equilibrium Loading, ^b kg/GWe-yr							
²³⁵ U (ST U ₃ O ₈)	852(156)	561(114)	399(73)	191(48)	-	250(63)	1052(267)
Fissile Pu	-	-	168	-	-	-	-
²³³ U	-	-	-	750	831	685	-
Equilibrium Discharge, ^b kg/GWe-yr							
²³⁵ U (ST U ₃ O ₈)	249(N.C.)	59(N.C.)	61(N.C.)	86(21)	-	99(25)	336(N.C.)
Fissile Pu	340	183	197	2	32	30	25
²³³ U	-	-	-	750	729	685	476
Annual Net Requirements, ^b kg/GWe-yr							
²³⁵ U (ST U ₃ O ₈)	603(156)	502(114)	338(73)	105(27)	0	151(38)	716(267)
Fissile Pu	-340	-183	-29	-2	-32	-30	-25
²³³ U	0	0	0	0	102	0	-476
Lifetime Requirements (IC+29 yr)							
ST U ₃ O ₈	4688	3563	2281	1331 ^c	0	1640 ^c	8281
kg Fissile Pu	-10200	-5490	-870	-60	-960	-900	-750
kg ²³³ U	0	0	0	0	4606	0	-14280

^aFor fresh fuel.^bAt 75% capacity factor.^cSelf-generated recycle. Excludes transition requirements and out-of-core inventories.

Fig. 6

Fuel Utilization Characteristics
for Enriched Uranium Fueled CANDU.
ANL Neg. No. 116-77-763.

4. Thorium Cycle: With 93% ^{235}U enriched uranium startup and makeup, the annual U_3O_8 makeup requirements at near-equilibrium are about 27 ST/GWe for the 16,000 MWD/T burnup case. This net consumption of U_3O_8 is only 14% of the LWR once-through cycle or 28% of the LWR thorium cycle. However, the initial core U_3O_8 requirements are more than double those of the CANDU slightly enriched uranium cycle. In addition, the transition to equilibrium and the out-of-core inventory requirements, depending on the recycle turn-around time, can be very significant.

5. Denatured Thorium Cycle With ^{235}U Makeup: The initial core requirements are about the same as the standard thorium cycle, however, the equilibrium net U_3O_8 consumption is slightly increased.

6. Denatured Thorium Cycle With ^{233}U Makeup: The initial core ^{233}U inventory requirement is about 1,650 kg/GWe, with the annual net requirements of about 100 kg ^{233}U /GWe.

7. Denatured Thorium Cycle - 20% ^{235}U Once-Through: This cycle option is included to indicate that self-generated ^{233}U recycle is mandatory for the denatured thorium cycle. As shown in Table III, the lifetime U_3O_8 requirements for the once-through denatured thorium cycle are about 8,300 ST, which is a factor of 2.3 higher than those for the once-through enriched uranium cycle in CANDU reactors.

D. Liquid Metal Fast Breeder Reactor (LMFBR)

For the converter reactor characteristics presented in earlier sections, commercially developed reactor designs were used as the reference point in comparing various fuel cycle options.

Since a large size commercial LMFBR design has not yet been developed the reference oxide-fueled LMFBR design parameters were selected to be very conservative, representing only a minor extrapolation from CRBR technology: a slightly higher linear heat rating and a larger fuel pin diameter. A more conservative burnup (average discharge burnup of ~50,000 MWD/T) than is normally assumed was also selected to reduce the fast neutron fluence. The design parameters and assumptions are listed in Table IV. Also shown in Table IV are the design assumptions for two advanced fuel types; carbide fuel and metal fuel.

TABLE IV. Design Parameters for Reference LMFBRs

	Oxide	Carbide	Metal
<u>Pin Design</u>			
Pin Outer Diameter, in	0.29	0.35	0.35
Cladding Thickness, in.	0.015	0.015	0.015
Pitch/Diameter Ratio	1.193	1.238	1.188
Smear Fuel Density, % T.D.	88	86	75 (U) 85 (Th)
<u>Assembly Design</u>			
Structural Material	SS316	SS316	SS316
No. of Pins Per Assembly	271	169	169
Assembly Pitch, in	6.300	6.489	6.074
Assembly Wall Thickness, in	0.140	0.139	0.136
Inter-Assembly Gap, in	0.226	0.441	0.279
<u>Core Design and Performance</u>			
Reactor Power, MWe	1200	1200	1200
Core Height, in	40	40	40
Axial Blanket Thickness, in	15	15	15
Radial Blanket, No. of Rows	3	3	3
Core Volume Fractions			
Fuel (Smear)	0.4186	0.3727	0.4254
Structure	0.2052	0.1764	0.1849
Sodium	0.3762	0.4849	0.3897
Average Linear Power, kW/ft	8.2	18.2	16.1
Core Specific Power, kWth/kgHM			
Uranium	92	101	90
Thorium	104	126	99
Cycle Length, fpy	274	274	274
Fuel Residence Time, cycles	2	2	2
Radial Blanket Res. Time, Cycles	5	5	5
Average Core Discharge Burnup, MWD/kg			
Uranium	51	55	49
Thorium	57	69	54
Peak Fluence ($E \geq 0.1$ MeV), 10^{23} nvt	~1.6	~2.0	~2.6

The LMFBR breeding performance characteristics were analyzed for each fuel type (oxide, carbide and metal) and for the following fuel cycle options:

1. Reference Pu/U cycle
2. Pu-fueled thorium cycle
 - Thorium radial blanket only
 - Thorium axial and radial blankets
 - Thorium core and thorium blankets
3. Non-Pu thorium Cycle
 - ^{233}U /Thorium core
 - ^{235}U /Thorium core
4. Denatured Uranium Cycle
 - $^{233}\text{U}/^{238}\text{U}$ core
 - $^{235}\text{U}/^{238}\text{U}$ core
5. Heterogeneous Core: Pu/U Core, Thorium Internal Blanket

The cross sections used for the neutronics analysis were generated with the MC²-2/SDX code system^{3,17} based on ENDF/B-IV for each fuel type and for each fuel cycle type (uranium cycle and thorium cycle). Two dimensional, 11-group diffusion and depletion calculations were performed with the REBUS-2 code¹⁸ for an equilibrium cycle.

The results are summarized in Table V for the oxide, carbide and metal fueled LMFBRs under various fuel cycle options. The breeding ratio and initial core fissile inventory are also presented in Figs. 7 and 8. In Tables VI a-c, the fissile compositions at loading and discharge are presented for various fuel types and fuel cycle options. The breeding ratio and fissile gain for the thorium cycle included credit for ^{233}Pa discharges. The breeding performance for the thorium cycle is degraded significantly from the Pu/U cycle. In comparing the two extremes of fueling options, LWR-Pu/ ^{238}U vs. $^{233}\text{U}/\text{Th}$ we note that approximately one-third of the difference in breeding ratio is attributable to the type of Pu (LWR-Pu vs. ^{239}Pu), and another one-third due to chemical fissile type (^{239}Pu vs. ^{233}U), and the final one-third is due to the fertile type (^{238}U vs. Th).

For this study, the mechanical and thermal/hydraulic design parameters presented in Table IV were optimized for the Pu/U cycle and the same design parameters were assumed for other fuel cycles to compare the effect of various fueling options in evolutionary steps. Hence, the performance characteristics presented in Table V are not necessarily optimum for the thorium cycle.

Other studies¹⁹⁻²¹ indicate that a higher breeding ratio and a lower doubling time can be achieved for the thorium cycle by adopting a design with a much higher fuel volume fraction (~50%) than the Pu/U cycle. Various designs appear to be feasible which would yield a compound system doubling time in the range of 35-40 years, with the specific fissile inventories in the range of 4,500-5,000 kg/GWe.

TABLE V. Summary of Breeding Performance for Oxide, Carbide and Metal Fueled LMFBRs Under Various Fuel Cycle Options

		Pu/U Cycle		Pu Fueled Th Cycle			Non-Pu Th Cycle		Denatured Cycle		Heterogeneous Core With Th Int. Blkt
		Pure ^{235}Pu	LMR Pu	RB Only	AB + RB	Core + Blanket			^{233}U Makeup	^{235}U Makeup	
		$^{233}\text{Pu}/^{233}\text{U}$	LMR Pu/Dep. U	LMR Pu/Dep. U	LMR Pu/Dep. U	LMR Pu/Th	$^{233}\text{U}/\text{Th}$	$^{235}\text{U}/\text{Th}$	$^{233}\text{U}/\text{Dep. U}$	$^{235}\text{U}/^{233}\text{U}$	Pu/U:Th
Core Fissile/Fertile		^{233}U	Dep. U	U(AB): Th(RB)	Th	Th	Th	Th	Th	Th	Th
Blanket Fertile		^{233}U	Dep. U	U(AB): Th(RB)	Th	Th	Th	Th	Th	Th	Th
OXIDE	Initial Core, kg/GM										
	Fissile Pu	3824	3424	3443	3480	4016	0	0	0	0	4501
	^{233}U	0	0	0	0	0	3822	0	3135	0	0
	^{235}U	0	170	90	47	0	0	5947	49	4995	36
	Net Production, ^a kg/GM-yr										
	Fissile Pu	183	242	110	-77	-662	0	3	490	428	-331
	^{233}U	0	0	122	298	798	31	640	-348	260	568
	^{235}U	0	-15	-13	-9	1	3	-855	-6	-788	-5
	TOTAL	183	227	219	212	137	34	-212	136	-100	232
	Apparent Reactor DT, ^b yrs.	21	16	16	17	29	112	(C)	23	(C)	20
	Breeding Ratio ^b	1.211	1.277	1.269	1.265	1.195	1.041	0.786	1.159	0.885	1.298
CARBIDE	Initial Core, kg/GM										
	Fissile Pu		2734	2759	2782	3258	0	0	0	0	
	^{233}U		0	0	0	0	3263	0	2642	0	
	^{235}U		175	81	43	0	0	5080	44	4170	
	Net Production, ^a kg/GM-yr										
	Fissile Pu		346	172	-15	-614	0	7	477	425	
	^{233}U		0	151	319	779	33	632	-290	280	
	^{235}U		-16	-13	-9	1	3	-817	-6	-737	
	TOTAL		330	310	295	166	36	-178	181	-27	
	Apparent Reactor DT, ^b yrs.		9	9	10	20	91	(C)	15	(C)	
	Breeding Ratio ^b		1.421	1.397	1.381	1.229	1.044	0.817	1.225	0.966	
METAL	Initial Core, kg/GM										
	Fissile Pu		2622	2666	2711	3470	0	0	0	0	
	^{233}U		0	0	0	0	3741	0	2707	0	
	^{235}U		227	111	50	0	0	5785	51	4232	
	Net Production, ^a kg/GM-yr										
	Fissile Pu		486	280	20	-610	0	6	483	441	
	^{233}U		0	165	384	904	86	727	-238	337	
	^{235}U		-19	-15	-10	1	2	-827	-7	-719	
	TOTAL		467	430	394	295	88	-94	238	59	
	Apparent Reactor DT, ^b yrs.		6	6	7	12	43	(C)	12	(C)	
	Breeding Ratio ^b		1.629	1.575	1.525	1.381	1.105	0.906	1.296	1.060	

^aAt 75% capacity factor^bAll fissile isotopes are weighted equally^cThese balance data are based on once-through cycle. With self-generated recycle, the doubling time will approach the value given by Pu/U cycle or $^{233}\text{U}/\text{Th}$ cycle.

Fig. 7
Breeding Ratio for Various
LMFBR Fuel Cycle Options.
ANL Neg. No. 116-77-770.

Fig. 8
Initial Core Fissile Inventory
for Various LMFBR Fuel Cycle
Options. ANL Neg. No.
116-77-748.

TABLE VIa. Core Fuel Fissile Compositions (XHM) for Various Fuel Cycle Options^a
(a) Oxide Fueled LMFBRs

Fuel Cycle Type	Pu/U	Pu/Th	²³³ U/Th	²³³ U/U	²³⁵ U/U	Pu/U (ThIB)
Loading						
Fissile Pu	12.0	15.1	-	-	-	18.6
²³³ U	-	-	14.7	11.0	-	-
²³⁵ U	<u>0.2</u>	<u>-</u>	<u>-</u>	<u>0.2</u>	<u>17.5</u>	<u>0.2</u>
TOTAL	12.2	15.1	14.7	11.2	17.5	18.8
Discharge						
Fissile Pu	11.5	10.2	-	3.4	3.0	15.9
²³³ U	-	3.7	12.9	6.7	-	-
²³⁵ U	<u>0.1</u>	<u>-</u>	<u>-</u>	<u>0.1</u>	<u>12.0</u>	<u>0.1</u>
TOTAL	11.6	13.9	12.9	10.2	15.0	16.0

^aAverage of two enrichment zones (outer core/inner core ratio = 1.3).
Tightly-coupled single enrichment zone for heterogeneous core.

TABLE VIb. Core Fuel Fissile Compositions (XHM) for Various Fuel Cycle Options^a
(b) Carbide Fueled LMFBRs

Fuel Cycle Type	Pu/U	Pu/Th	²³³ U/Th	²³³ U/U	²³⁵ U/U
Loading					
Fissile Pu	10.7	15.2	-	-	-
²³³ U	-	-	15.4	10.3	-
²³⁵ U	<u>0.2</u>	<u>-</u>	<u>-</u>	<u>0.2</u>	<u>16.3</u>
TOTAL	10.9	15.2	15.4	10.5	16.3
Discharge					
Fissile Pu	10.6	9.5	-	3.7	3.3
²³³ U	-	4.1	12.9	5.8	-
²³⁵ U	<u>0.1</u>	<u>-</u>	<u>-</u>	<u>0.1</u>	<u>10.6</u>
TOTAL	10.7	13.6	12.9	9.6	13.9

^aAverage of two enrichment zones (outer core/inner core ratio = 1.45).

TABLE VIc. Core Fuel Fissile Compositions (ZHM) for Various Fuel Cycle Options
(c) Metal Fueled LMFBRs

Fuel Cycle Type	Pu/U	Pu/Th	$^{233}\text{U}/\text{Th}$	$^{233}\text{U}/\text{U}$	$^{235}\text{U}/\text{U}$
Loading					
Fissile Pu	9.0	12.1	-	-	-
^{233}U	-	-	13.3	9.3	-
^{235}U	0.2	-	-	0.2	14.5
	<hr/>	<hr/>	<hr/>	<hr/>	<hr/>
TOTAL	9.2	12.1	13.3	9.5	14.5
Discharge					
Fissile Pu	9.2	7.8	-	3.3	3.0
^{233}U	-	3.7	11.6	5.3	-
^{235}U	0.1	-	-	0.1	9.6
	<hr/>	<hr/>	<hr/>	<hr/>	<hr/>
TOTAL	9.3	11.5	11.6	8.7	12.6

^a Average of Two enrichment zones (outer core/inner core ratio = 1.45).

III. NUCLEAR POWER GROWTH POTENTIAL FOR FIXED URANIUM RESOURCES

System analyses of reactor deployment strategies involve interplay among four major parameters:

- Energy Demand
- Uranium Resources
- Economics
- Reactor Types

There are two general approaches to handling the economics. One is to select the deployment strategies based on the economic optimization. The other is to assume deployment independent of the economic incentives and compare the benefits in resource utilization, etc. with the economic penalties, where they can be identified. Economics are not addressed in this report because of the conceptual nature of many of the reactor and fuel cycle types and the correspondingly large uncertainties associated with their economics.

For the remaining three parameters, the usual approach is to impose the energy demand or growth rate and the output is the total uranium consumption over time for various reactor deployment scenarios. In this report, a different approach is taken, that is, the maximum power growth potential for each deployment scenario is determined for a fixed resource base. The advantages of this approach are; first, the sensitivity of the results with respect to the energy demand assumption is eliminated; second, the results for different resource bases can easily be extrapolated; and third and most importantly, large differences in the longer term potential, if they exist, are made very apparent.

The formal framework of this study was based on the ALPS, an LP optimization code.²² The specific assumptions employed in this study are described below.

1. Uranium Resources: For all scenarios the uranium consumption was fixed; no more and no less than 3.7 million ST U_3O_8 were used.
2. Alternative Reactor Introduction Date and Introduction Rate: All reactor types other than the LWR were introduced in 1995 with the introduction constraint of 20 GWe total during the period 1995-2000.
3. Nuclear Capacity: 300 GWe in year 2000 (this assumption is important only for the cases with more than one reactor type competing for the uranium). After year 2000, the capacity on-line was not limited but the following constraints were applied:
 - The uranium consuming reactors were introduced only until their 30-year forward requirements account for the 3.7 million ST U_3O_8 total.
 - Other reactor types were constrained in introduction by the fissile material (Pu or ^{233}U) availability at each point in time.

4. Mass Flow Data: Explicit year-by-year mass flow data for a 30-year plant lifetime were used for all reactor types. The mass flow data were adjusted for the following capacity factor history.

<u>Year</u>	<u>C.F., %</u>
1	60
2	65
3	70
4	75
⋮	⋮
20	75
21	72.5
⋮	⋮
30	50
Average	~70

5. Other Assumptions: The U_3O_8 requirements were calculated for a tails assay of 0.2%. One year external time for recycle and loss factors of 1% for reprocessing and 1% for fabrication were assumed for all reactor types.

A. Converter Only Scenario

The nuclear capacity on-line is presented in Figs. 9-11 as a function of time for selected converter reactor scenarios. The LWR once-through case is presented in Fig. 9; the LWR uranium and plutonium recycle case in Fig. 10; and the CANDU denatured thorium cycle with ^{235}U makeup case in Fig. 11. In Fig. 11, the area under the first curve represents the LWR capacity, the area between the two curves represents the CANDU capacity, and the top curve represents the combined capacity. The CANDU denatured thorium cycle sets an approximate upper bound for the various advanced converter reactor fuel cycle alternatives. Other converter reactor types and/or fuel cycle options will give results in between the two extreme cases presented here: Fig. 9 and Fig. 11.

As can be seen from Tables I and III, the CANDU denatured thorium cycle uranium requirements are almost a factor of four lower than the LWR once-through cycle. However, the cumulative capacity built is 670 GWe for the LWR once-through cycle and 1,520 GWe for the CANDU case, which is slightly more than a factor of two. The reason for this is that a large amount of U_3O_8 has been committed or consumed in the LWR by the time the advanced converter reactor is introduced. Further, the new plants built must first replace plants retiring after a 30-year lifetime. Hence, as shown in Fig. 11, the capacity on-line can be maintained at ~1000 GWe for only a short period of time.

Fig. 9. Nuclear Power Growth Potential for LWR Once-Through Cycle. ANL Neg. No. 116-77-738.

Fig. 10. Nuclear Power Growth Potential for LWR U and Pu Recycle. ANL Neg. No. 116-77-757.

Fig. 11. Nuclear Power Growth Potential for LWR Once-Through/CANDU-235U Makeup Denatured Th Cycle. ANL Neg. No. 116-77-756.

B. LMFBR Reference Scenario: Pu/U Cycle

In Fig. 12, the power growth potential for the pre-1977 reference deployment strategy is presented. Uranium recycle is assumed for the LWR and the plutonium discharged is utilized for LMFBR startup. Even with this conservative oxide-fueled LMFBR (~ 20 -year doubling time), the nuclear capacity could expand by 100 GWe/yr after year 2050. Higher growth rates can be achieved with advanced fuels as shown in Fig. 13 for the carbide fueled LMFBR.

In Fig. 14, the power growth potential is summarized for the various scenarios presented in Figs. 9-12. Each curve in Fig. 14 represents the total nuclear capacity on-line associated with each scenario. The high growth potential of the LMFBR reference Pu/U cycle is evident when compared with the limited role possible for the various converter strategies in the years beyond 2025.

Fig. 12. Nuclear Power Growth Potential for LWR-U Recycle/LMFBR-Oxide Pu-U Cycle. ANL Neg. No. 116-77-750.

Fig. 13. Nuclear Power Growth Potential for LWR-U Recycle/LMFBR-Carbide Pu-U Cycle. ANL Neg. No. 116-77-754.

Fig. 14. Comparison of Nuclear Power Growth Potential for Converter Reactor Scenarios and LMFBR Scenario (Resource Base = 3.7 million ST U_3O_8). ANL Neg. No. 116-77-766.

Of course, actual power growths in the LMFBR strategy can be tailored to the demand by reducing the fissile gain in the blanket or by fueling converter reactors with the excess plutonium.

C. Comparison of Denatured Reactor Types

In this section, the following denatured reactor types are compared:

- LWR Denatured Thorium Cycle
- LWR Denatured Uranium Cycle
- CANDU Denatured Thorium Cycle
- LMFBR-Oxide Denatured Uranium Cycle

For all of these cases, uranium recycle in the LWR is assumed and the plutonium discharge from the LWR as well as from the denatured reactors are utilized in the oxide-fueled LMFBR to produce ^{233}U from thorium axial and radial blankets. The ^{233}U produced in the LMFBR blankets is then utilized to for the various denatured cycles listed above. The results are presented in Figs. 15-18.

When the LMFBR fissile production is diverted to support denatured converter reactors, the overall system growth is limited by fissile Pu shortages for the breeder itself and an asymptotic capacity level is reached as shown in Figs. 15-17. The ultimate capacity level depends on the converter reactor fuel utilization characteristics. The denatured CANDU case can reach a higher capacity than the LWR case because of reduced fissile makeup requirements. In comparing the LWR denatured thorium cycle (Fig. 15) and the LWR denatured uranium cycle (Fig. 16), the uranium cycle performs as well as the thorium cycle, even though the conversion ratio is higher for the thorium cycle. In fact, the uranium cycle is slightly better in the long term. The reason for this is that in the denatured uranium cycle the additional plutonium produced is utilized very effectively in the LMFBR.

Fig. 15

Nuclear Power Growth Potential for
LWR-U Recycle/LMFBR-Oxide Th
AB+RB/LWR- ^{233}U Makeup Denatured Th
Cycle. ANL Neg. No. 116-77-767.

Fig. 16. Nuclear Power Growth Potential for LWR-U Recycle/LMFBR-Oxide Th AB+RB/LWR- ^{233}U Makeup Denatured U Cycle. ANL Neg. No. 116-77-743.

Fig. 17. Nuclear Power Growth Potential for LWR-U Recycle/LMFBR-Oxide Th AB+RB/CANDU- ^{233}U Makeup Denatured Th Cycle. ANL Neg. No. 116-77-742.

Fig. 18. Nuclear Power Growth Potential for LWR-U Recycle/LMFBR-Oxide Th AB+RB/LMFBR-Oxide- ^{233}U Makeup Denatured U Cycle. ANL Neg. No. 116-77-744.

The denatured LMFBR case, shown in Fig. 18, has a lesser fissile constraint than the denatured converter reactor cases, even though the growth potential is slightly degraded from the reference Pu/U cycle (Fig. 12). However, the LMFBR denatured reactor to ^{233}U producer reactor ratio is not as high as in the denatured converter reactor cases.

In Fig. 19 the total nuclear capacity on-line is compared for the four different denatured reactor types.

Fig. 19

Comparison of Nuclear Power Growth Potential for Various Denatured Reactor Types (Resource Base = 3.7 million ST U_3O_8). ANL Neg. No. 116-77-758.

D. Comparison of LMFBR Fuel Types for Denatured Scenarios

In this section, various LMFBR fuel types, oxide, carbide and metal, are compared for a given LMFBR fuel cycle option (Pu/U core, thorium AB and RB) and a given denatured reactor type (LWR denatured thorium cycle).

As compared to the oxide LMFBR (Fig. 15), the carbide and metal fueled LMFBRs shown in Figs. 20 and 21, respectively, can achieve a much higher capacity and there is good growth potential in the case of the metal fueled LMFBR. The total capacities achieved by the three fuel types are compared in Fig. 22.

In comparing Figs. 19 and 22, we note that the total capacity improvement achieved by the carbide fueled LMFBR over the oxide fueled LMFBR is about twice as much as that achieved by the introduction of an advanced converter (CANDU) in place of the LWR. *Even for LMFBR/Converter Reactor symbiotic strategies, the uranium fuel utilization can be improved more effectively by the breeder design improvements than by the converter reactor improvements.*

Fig. 20. Nuclear Power Growth Potential for LWR-U Recycle/LMFBR-Carbide Th AB+RB/LWR- ^{233}U Makeup Denatured Th Cycle. ANL Neg. No. 116-77-745.

Fig. 21. Nuclear Power Growth Potential for LWR-U Recycle/LMFBR-Metal Th AB+RB/LWR- ^{233}U Makeup Denatured Th Cycle. ANL Neg. No. 116-77-749.

Fig. 22. Comparison of Nuclear Power Growth Potential for Various LMFBR Fuel Types (Resource Base = 3.7 million ST U_3O_8). ANL Neg. No. 116-77-768.

E. Comparison of Pu-Fueled Thorium Cycle Options in LMFBR for Denatured Scenario

In this section, various Pu-fueled Th cycles are compared for the oxide LMFBR:

- Thorium Radial Blanket Only (Fig. 23)
- Thorium Radial and Axial Blankets (Fig. 15)
- Thorium Core and Thorium Blankets (Fig. 24)
- Heterogeneous Core: Pu/U Core, Thorium Internal, Radial and Axial Blankets (Fig. 25)

Fig. 23. Nuclear Power Growth Potential for LWR-U Recycle/LMFBR-Oxide Th RB Only/LWR- ^{233}U Makeup Denatured Th Cycle. ANL Neg. No. 166-77-760.

Fig. 24. Nuclear Power Growth Potential for LWR-U Recycle/LMFBR-Oxide Th Core/LWR- ^{233}U Makeup Denatured Th Cycle. ANL Neg. No. 116-77-752.

Fig. 25
Nuclear Power Growth Potential for LWR-U Recycle/LMFBR-Oxide Heterogeneous/LWR- ^{233}U Makeup Denatured Th Cycle. ANL Neg. No. 116-77-755.

For all cases the LWR discharge plutonium is used for the LMFBR fissile loading and the ^{233}U produced in the LMFBR is utilized to fuel the LWR denatured thorium cycle.

As can be seen from the summary comparison in Fig. 26, the thorium radial blanket only case has the highest growth potential, and the growth potential diminishes as more thorium is added, with the extreme being the full thorium core and blanket case. The heterogeneous core with thorium internal blanket case can be characterized as a compromise between the thorium blanket only case and the all-thorium core case. There is no inherent advantage associated with this concept for power growth potential or as an effective ^{233}U producer.

Another very important factor associated with the denatured converter/LMFBR- ^{233}U producer scenario is the ratio of the two reactor types. The higher this ratio, the greater the freedom to install capacity outside fuel center areas. This ratio is compared in Fig. 27 as a function of time for the four cases. The denatured-converter-reactor to LMFBR- ^{233}U producer ratio is directly opposite to the power growth potential shown in Fig. 26. The highest growth potential case has the lowest ratio, and vice versa. Here again, the heterogeneous core case lies in between the thorium core and thorium blanket cases.

Fig. 26

Comparison of Nuclear Power Growth Potential for Various LMFBR Th Cycle Types (Resource Base = 3.7 million ST U_3O_8). ANL Neg. No. 116-77-740.

Fig. 27

Comparison of Denatured Reactor to LMFBR- ^{233}U Producer Ratio for Various LMFBR Th Cycle Types. ANL Neg. No. 116-77-769.

F. Maximum Denatured-Converter to LMFBR- ^{233}U Producer Ratio Cases

As discussed in the previous section, the denatured-converter to LMFBR- ^{233}U producer ratio can be maximized by plutonium fueling in a full thorium cycle (both core + blanket) in the LMFBR. However, in this case the plutonium shortage severely limits the power growth potential. As shown in Fig. 28, this is true even for the metal fueled LMFBR with a high breeding capability ($\text{BR} = 1.381$), which turns out to be not much better than the oxide case ($\text{BR} = 1.195$) shown in Fig. 24. The reason for this is because the effective system breeding ratio is dominated by the converter reactor characteristics.

G. Non-Plutonium Thorium Cycles in the LMFBR

In previous sections, plutonium fueling was assumed for various thorium cycle options in the LMFBR. In this section, we examine LMFBR thorium cycles in which the plutonium fueling is banned. The LMFBR thorium cycle must then be started up with ^{235}U fueling. It is assumed that no further LWR capacity is built after the 1995-2000 period, and the remaining U_3O_8 resources (2.2 million ST U_3O_8) are all utilized in the LMFBR startup. No recycle is allowed for the LWR.

For the first case presented in Fig. 29, it is assumed that the initial LMFBR operation is based on a denatured $^{235}\text{U}/^{238}\text{U}$ cycle with thorium blankets, gradually transferring to the $^{233}\text{U}/\text{Th}$ cycle. The plutonium discharges are discarded; the ^{235}U and ^{233}U are recycled. The asymptotic capacity achieved for this case is only 500 GWe and self-sustaining.

Fig. 28. Nuclear Power Growth Potential for LWR-U Recycle/LMFBR-Metal Th Core/LWR- ^{233}U Makeup Denatured Th Cycle. ANL Neg. No. 116-77-753.

Fig. 29. Nuclear Power Growth Potential for LWR Once-Through/LMFBR-Oxide Denatured ^{235}U Startup going to $^{233}\text{U}/\text{Th}$ Cycle. ANL Neg. No. 116-77-739.

The next case presented in Fig. 30 assumes that the oxide fueled LMFBR is started up with highly enriched uranium (93%) in the thorium core, later transforming to self-generated $^{233}\text{U}/\text{Th}$ recycle operation. The total capacity achieved for this case is ~ 1000 GWe.

Fig. 30

Nuclear Power Growth Potential for LWR Once-Through/LMFBR-Oxide Highly Enriched ^{235}U Startup going to $^{233}\text{U}/\text{Th}$ Cycle. ANL Neg. No. 116-77-762.

Advanced fuel cases are presented in Figs. 31 and 32 for the case of highly enriched $^{235}\text{U}/\text{Th}$ cycle startup going to the $^{233}\text{U}/\text{Th}$ cycle. The carbide fuel case reaches ~ 1300 GWe, with very little growth potential. The metal fueled case exhibits moderate growth potential.

Fig. 31. Nuclear Power Growth Potential for LWR Once-Through/LMFBR-Carbide Highly Enriched ^{235}U Startup going to $^{233}\text{U}/\text{Th}$ Cycle. ANL Neg. No. 116-77-759.

Fig. 32. Nuclear Power Growth Potential for LWR Once-Through/LMFBR-Metal Highly Enriched ^{235}U Startup going to $^{233}\text{U}/\text{Th}$ Cycle. ANL Neg. No. 116-77-765.

The main reason for the poor growth potential of the thorium cycle, compared to the Pu/U cycle, is simply its poorer breeding performance. Another contributor could be that the plutonium discharged from the LWR is discarded instead of being utilized for the LMFBR startup as was the case for the reference Pu/U cycle. To test this effect, another case was analyzed in which the ground rules were made identical for both the thorium and Pu/U cycles. That is, the LWR plutonium is discarded for both cases and the LMFBR Pu/U cycle is started up with ^{235}U , going on to the self-generated Pu/U cycle. The result for the oxide fueled LMFBR is presented in Fig. 33, which shows an even higher growth rate than for the reference LWR plutonium startup case in Fig. 12, reflecting the fact that for this case there is a lesser fissile constraint on growth in the early years.

Fig. 33

Nuclear Power Growth Potential for LWR Once-Through/LMFBR-Oxide ^{235}U Startup going to Pu/U Cycle. ANL Neg. No. 116-77-751.

Various non-Pu thorium cycle cases are compared in Fig. 34. Also shown in Fig. 34 is the Pu/U cycle (dashed curve) for comparison purposes.

Fig. 34

Comparison of Nuclear Power Growth Potential for LMFBR Non-Pu Th Cycles (Resource Base = 3.7 million ST U_3O_8). ANL Neg. No. 116-77-741.

IV. SUMMARY AND CONCLUSIONS

Even the large number of deployment scenarios presented in Section III covers only a few of the permutations possible in deployment strategies. The scenarios examined cover the main classes of deployment strategies, however, and the basic trends show up clearly enough to support several key conclusions.

It should be kept in mind that the resource base of 3.7 million ST may be a high estimate. Sensitivity studies indicate the nuclear capacity potential is roughly proportional to the resource base. For the converter scenarios the cumulative capacity built is directly proportional to the resource base. For the Converter/LMFBR symbiotic scenarios, the LWR plutonium discharge is proportional to the resource base, which in turn controls the LMFBR capacity for Pu-fueled thorium cycle cases, and this limits the ^{233}U production and the denatured converter reactor capacity. Hence, the cumulative capacity built for these scenarios depends strongly on the resource base. Only the reference Pu/U breeder scenarios with high growth potential are immune from the resource base constraint. However, even for these cases the capacity growth through ~2025 is limited by fissile material availability. Hence, to a good approximation the power growth potential presented in Section III can be scaled up or down with the resource base.

For a limited resource base, the role of the converter reactors is very limited, and if nuclear is to make a significant contribution in the longer term, some kind of breeder is inevitable. The key question is one of timing. By the introduction of an advanced converter reactor, the need for a breeder economy can be delayed only if the uranium resources are very large and the energy demand is small. Significant stretchout of the resource base by the advanced converter reactor requires essentially complete depletion of all naturally occurring fissile material (^{235}U) as well as the bred fissile material (^{233}U in the thorium cycle). Fissile material used to fuel the converter reactor capacity is unavailable for the initial inventory requirements for eventual breeder systems, and may sharply limit deployment rates when the breeder is needed. This consideration should be carefully examined for the advanced converter strategies.

For the fast breeder system, plutonium fueling seems to be essential. Plutonium is the best fissile material in a fast neutron spectrum and it is provided naturally by the existing converter reactor system. The alternative to Pu-fueling is the ^{235}U startup thorium cycle. The $^{233}\text{U}/\text{Th}$ cycle has inferior breeding potential, compared to the Pu/U cycle, and with this cycle the fast breeder system competes with the converter reactor system for natural uranium during the period when resources become scarce.

Among the various alternative fueling schemes for the LMFBR, the thorium radial blanket option provides the best compromise between growth potential and ^{233}U production for the support of denatured converter reactors. However, if in some kind of international fuel cycle center concept the denatured converter to LMFBR- ^{233}U producer reactor ratio is to be maximized, this can be accomplished by the Pu-fueled thorium cycle in the LMFBR, but the growth potential for this case would be sharply constrained by fissile material availability. To ease this, more efficient advanced converter reactors would need to be deployed outside the fuel cycle center.

Whether the fuel cycle center concept is implemented or not, there are possible roles for the advanced converter reactor and/or for the thorium cycle. However, the fundamental issue does not appear to be so much whether an alternative concept can replace the LMFBR but rather the way LMFBR is to be used and how the deployment strategy should evolve. The need for development of a true breeder is largely independent of the deployment strategy, and LMFBR development to the point that it represents a realistic option is important to strategies that adequately cover uncertainties in future energy demand growth and resource availability. In parallel to LMFBR development, advanced converter reactor concepts and thorium fuel cycles should also be evaluated in detail. They could have a very useful place in low demand growth or limited-term nuclear future scenarios. In any event, they are needed if the fuel center breeder and client converter reactor deployment strategies are to be implemented. In addition to technological, economic and institutional factors, such evaluations must try to identify such real differences as exist between systems in their implications on non-proliferation goals so that decisions made on these latter grounds are based on substantive differences between systems and not on marginal factors that may later disappear upon closer examination.

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REFERENCES

1. Westinghouse Reference Safety Analysis Report, RESAR-3, Docket-RESARA-23, November 1973.
2. B. A. Zolotar and W. J. Eich, *"Advanced Recycle Methodology Program: Preliminary Specifications for a New Nuclear Computational Capability,"* EPRI SR-2 (July 1974); W. J. Eich, *"Advanced Recycle Methodology Program: Project Status Report,"* EPRI 118-1 (December 1975); W. R. Cobb and W. J. Eich, *"A New Cell Depletion Code for LWR Analysis,"* Trans. Am. Nucl. Soc. 24, 442 (1976); R. D. Mosteller, et al., *"UO₂ and MO₂ Assembly Analysis: Collision Probability and Few-Group Diffused Comparisons,"* Trans. Am. Nucl. Soc. 24, 443 (1976).
3. H. Henryson, II, B. J. Toppel and C. G. Stenberg, *"MC²-2: A Code to Calculate Fast Neutron Spectra and Multigroup Cross Sections,"* ANL-8144 (ENDF 239); June, 1976.
4. P. H. Kier and A. A. Robba, *"RABBLE, A Program for Computation of Resonance Absorption in Multiregion Reactor Cells,"* ANL-7326, April 1967.
5. J. Hardy and B. L. Palowitch, *"The Effective Resonance Integral and Doppler Coefficient of Thorium-Oxide Rods,"* Nuclear Science and Engineering, 29 111-121 (1967).
6. N. M. Steen, *"An Evaluation of the Radiative Neutron Capture Cross Sections of Thorium-232 for the Range 0.0 eV to 15 MeV,"* WAPD-TM-971, 1970.
7. N. L. Shapiro, J. R. Rec and R. A. Matzie, *"Assessment of Thorium Fuel Cycles in Pressurized Water Reactors,"* EPRI NP-359, February 1977.
8. H. A. Feiveson and T. B. Taylor, *"Security Implications of Alternative Fission Futures,"* Bulletin of the Atomic Scientists, P 14, December 1976.
9. T. Greenwood, H. A. Feiveson and T. B. Taylor, *"Nuclear Proliferation Motivations, Capabilities and Strategies for Control,"* McGraw-Hill, 1977.
10. D. Mars and D. Gans, Jr., *"Spectral Shift Control Reactor Design and Economic Study,"* BAW-1241, December 1961.
11. M. C. Edlund, *"Developments in Spectral-Shift Reactors,"* Proc. Third Int. Conf. on Peaceful Uses of Atomic Energy, 6, 314 (1964).
12. J. S. Foster and E. Critoph, *"The Status of the Canadian Nuclear Power Program and Possible Future Strategies,"* Annals of Nuclear Energy 2, 689 (1975).
13. S. Banerjee, S. R. Hatcher, A. D. Lane, H. Tamm and J. I. Veeder, *"Some Aspects of the Thorium Fuel Cycle in Heavy-Water-Moderated Pressure Tube Reactors,"* Nucl. Tech. 34, 58 (1977).

14. E. Critoph, S. Banerjee, F. W. Barclay, D. Hamel, M. S. Milgram and J. I. Veeder, *"Prospects for Self-Sufficient Equilibrium Thorium Cycles in CANDU Reactors,"* AECL-5501 (1976).
15. C. E. Till, E. M. Bohn, Y. I. Chang and J. B. van Erp, *"A Survey of Considerations Involved in Introducing CANDU Reactors into the U.S.,"* ANL-76-132, January 1977.
16. S. R. Hatcher, et al., *"Thorium Cycle in Heavy Water Moderated Pressure Tube (CANDU) Reactors,"* AECL-5398 (1976).
17. W. M. Stacey, Jr., et al., *"A New Space-Dependent Fast Neutron Multi-Group Cross-Section Preparation Capability,"* Trans. Am. Nucl. Soc., 15, 292 (1972).
18. J. Hoover, G. K. Leaf, D. A. Meneley, and P. M. Walker, *"The Fuel Cycle Analysis System, REBUS,"* Nucl. Sci. Eng. 45, 52 (1971).
19. R. B. Turski, Unpublished work on Th cycle in Oxide Fueled LMFBRs.
20. Y. Orechwa, Unpublished work on Th Cycle in Carbide Fueled LMFBRs.
21. P. S. K. Lam and S. F. Su, *"Pin Diameter Optimization of Homogeneous and Tightly Coupled Heterogeneous ^{233}U -Th Metal-Fueled LMFBRs,"* to be presented at San Francisco ANS Meeting, November 27-December 2, 1977.
22. R. W. Hardie, W. E. Black and W. W. Little, *"ALPS, A Linear Programming System For Forecasting Optimum Power Growth Patterns,"* HEDL-TME 72-31, April 1972.