NUCLEAR DEVELOPMENT STRATEGIES WITH LIMITED NATURAL URANIUM REQUIREMENTS

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PREFACE

In view of the fact that the world's high-grade natural uranium resources are limited, alternative ways of using these resources more efficiently are of interest in the line of research undertaken by IIASA's Energy Systems Program. Sole reliance on the currently predominant Light Water Reactors(LWRs) would mean to deplete these natural uranium resources rapidly.

The present paper considers different strategies of uranium use involving, in addition to burners (LWRs), Fast Breeder Reactors (FBRs) and Advanced Converter Reactors(ACR) with an extremely high efficiency in using natural uranium. Breeder reactors in fact require only depleted natural uranium (left over from enriched LWR fuel), once a certain endowment of fissile plutonium (from burnt LWR fuel) has accumulated. Given such an endowment, the breeder output can be increased on the basis of self-generated plutonium. Although the efficiency in using natural uranium is less in advanced converter reactors, their uranium savings are enormous compared to the amounts used up in burners. Such considerations of a more efficient future uranium use by deploying advanced reactors in addition to burner reactors are based on a hypothetical trajectory of a total installed nuclear capacity increasing to 10 TW(e) by the year 2030. The analysis shows that a combination of advanced and burner reactors, as compared to the use of burners only, could lead to cumulative, high-grade uranium savings greater than 70% from 1980 to 2030.

CONTENTS

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INTRODUCTION

The objective of this report is to analyze global nuclear strategies, involving different reactor configurations and associated fuel cycles. The strategies are for a time horizon of 50 years, and the results indicate how much of the world's limited natural uranium endowment the various strategies would require. The prime limiting factors considered in the report are the market penetration constraints imposed on the buildup rates of different reactor types and the associated fuel cycles. The goal is to decouple the installed nuclear capacity and its net annual growth from the natural uranium supply. The numerical calculations should be interpreted qualitatively, but they demostrate that with fixed nuclear installed capacity trajectories up to the year 2030 it is possible to limit the cumulative natural uranium demand. A number of different strategies and reactor configurations can achieve this goal. In such cases we can speak of a limited one-time natural uranium "endowment" which is to be invested, leaving no further uranium requirements for the future. However, all of these strategies involve spent fuel reprocessing, breeder and converter reactors.

The simpler once-through strategy involves only converter reactors. Low enriched natural uranium is simply burned, spent fuel is not reprocessed, and there is no recycling of fissile material. Unfortunately, this strategy cannot lead to an asymptotic cumulative natural uranium demand. Natural uranium is simply consumed, the demand grows with the growth of nuclear power, and the cumulative demand also continues to increase. We will describe this strategy first since it is the simplest, and then we will illustrate a few alternatives involving hybrid reactor configurations.

These calculations were not intended to give a forecast of the future. They serve to illustrate the *potential* of nuclear energy as realized through different reactor configurations. Many other strategies are possible and have been calculated. Our calculations are based on a fixed reference trajectory of postulated nuclear installed capacity for the world.

In all calculations we account for the input demands of low enriched natural uranium only insofar as U235 is required. Depleted uranium is assumed to be abundant, available from stored "tails" after U235 has been separated. We also account for fissile plutonium and U233 demand and supply. Thorium as a fertile material is not not accounted for explicitly since it is also assumed to be abundant, and is therefore consumed very slowly, as is U238.

REFERENCE TRAJECTORY FOR POTENTIAL WORLD NUCLEAR INSTALLED CAPACITY

In order to compare quantitatively alternative nuclear strategies we made some assumptions about the future growth of the total nuclear installed capacity. We assessed the *potential* growth up to the year 2030 using a trajectory shown in Figure 1 together with installed nuclear power projections from the literature (see Häfele, Nakicenovic, and Schikorr 1977). We assume that worldwide nuclear capacity will reach 1630 GW(e) in the year 2000 and will grow to 10,000 GW(e) by the year 2030 increasing thereafter (at least until 2050) at a constant rate of one percent per year. Table 1 gives the installed capacities of the reference trajectory including required net annual additions, total annual additions which include replacements of power plants after an average useful plant life of 30 years in commercial service, and also annual growth rates. The growth rates decrease from about 15% per year in 1980 to 1% per year in 2030. They represent an extension in the short run of the observed growth rates up to 1978 and expected growth rates up to the 1990s resulting from present construction and power plant orders, which are given in Table 2.

The resulting net and total annual additions in Table 1 are reproduced in Figure 2. Since the reference trajectory assumes a 1% growth per year after 2030 the installed capacity additions level off after the 2020s. They show with the maximum additions of 150 GW(e)/yr in the year 2000 and about 300 GW(e)/yr between 2010 and 2025 that it is possible to decrease the annual growth asymptotically from about 36%/yr (35 GW(e)/yr) in 1978 to 1%/yr starting 2030 and still achieve a potential, high installed capacity of 10 TW(e) in 2030. Thus, the actual construction rate would be less in the early years and more in the latter part of the period. While this rate seems high (larger than the total present generating capacity of all but one or two countries), it may be noted that annual additions of electric generating capacity of all types are already close to 100 GW(e)/yr (an average of about 80 GW(e)/yr from 1970 to 1977). Present construction capability for

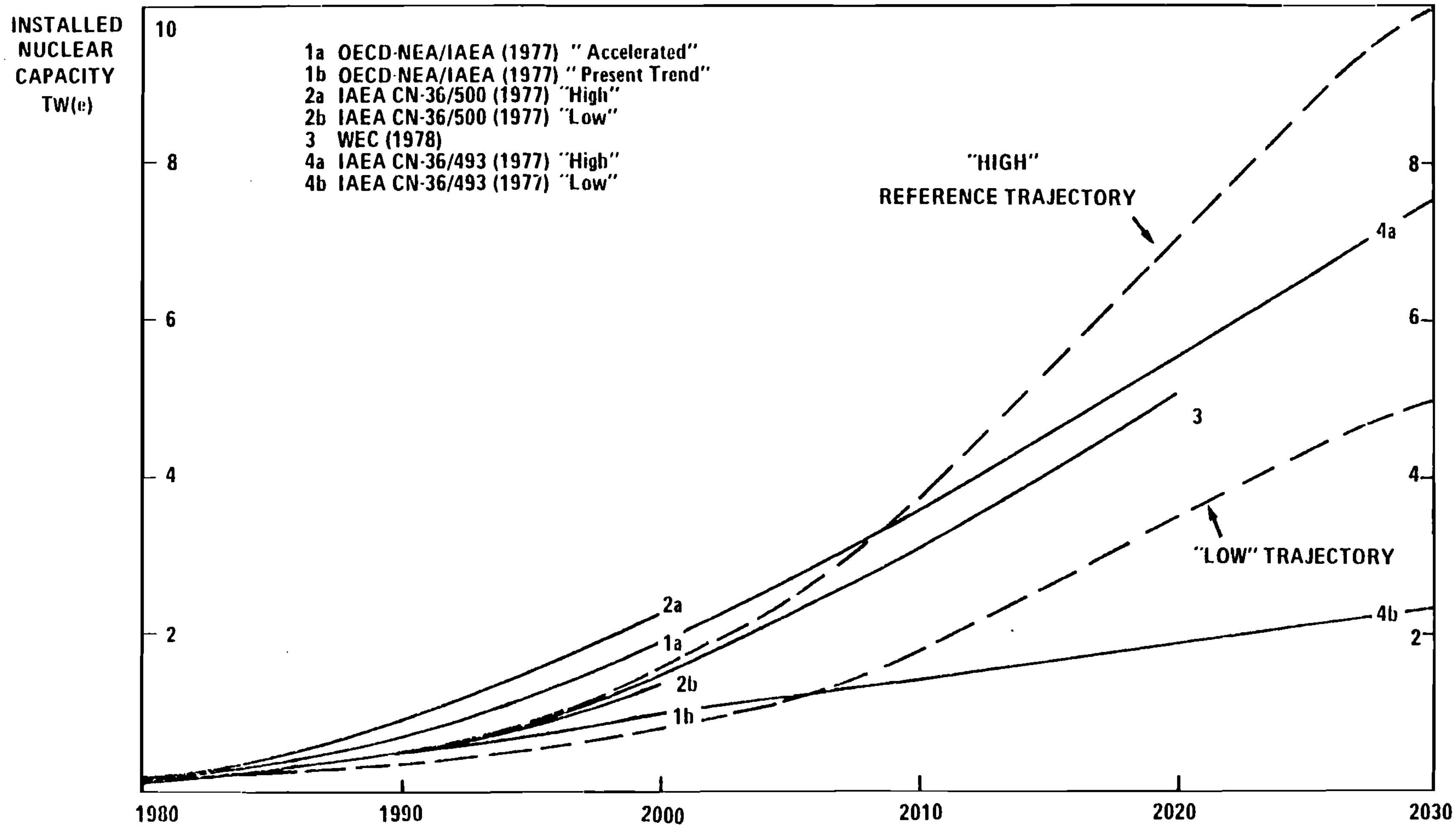

Figure 1. Reference trajectories for potential world nuclear installed capacity compared with installed nuclear power projections

Table 1. Reference trajectory for potential world nuclear installed capacity including annual installation additions and growth rates

	1980	1985	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035
Installed GW(e)[1]	160	320	580	980	1630	2452	3642	5279	7029	8639	10000	10500
Net Annual Additions GW(e)/a	24	40	64	102	148	202	281	311	295	257	98	98
Total Annual[2] Additions GW(e)/a	24	40	64	105	154	214	305	351	359	362	252	312
Growth Rate (%)[3]	14.9	12.6	11.1	10.7	8.5	8.2	7.7	5.9	4.2	3.0	1.0	0.9

[1] Installed capacity in GW(e) without implication of how this capacity may be allocated between distribution on electical grids and other uses, e.g. production of synthetic fuels.

[2] Net annual additions plus capacity replacements after 30 years of service.

[3] Net annual percentage growth calculated on the basis of exponential growth during five year intervals.

Table 2. World nuclear installed capacity
(Operable, under construction, or on order as of December 31, 1977)[1]
Source: Nuclear News (1978).

	1966	1968	1970	1972	1974	1976	1978	1980	1982	1984	1986	1988	1990
Installed GW(e)	5.5	8.4	17.0	34.2	58.5	84.0	130.4	197.7	261.2	326.5	369.2	381.3	391.4
Total Annual Additions GW(e)/a	1.7	2.2	3.1	11.4	15.7	12.2	34.4	37.1	35.4	33.2	13.9	5.5	4.5
Growth rate (%)	31.5	25.8	22.2	50.1	36.8	17.0	35.8	23.1	15.7	11.3	3.9	1.5	1.2

[1]Cumulated upon the actual or expected date of first commercial operation. Additional eleven power plants on order are not included since the expected date of commercial operation is not known.

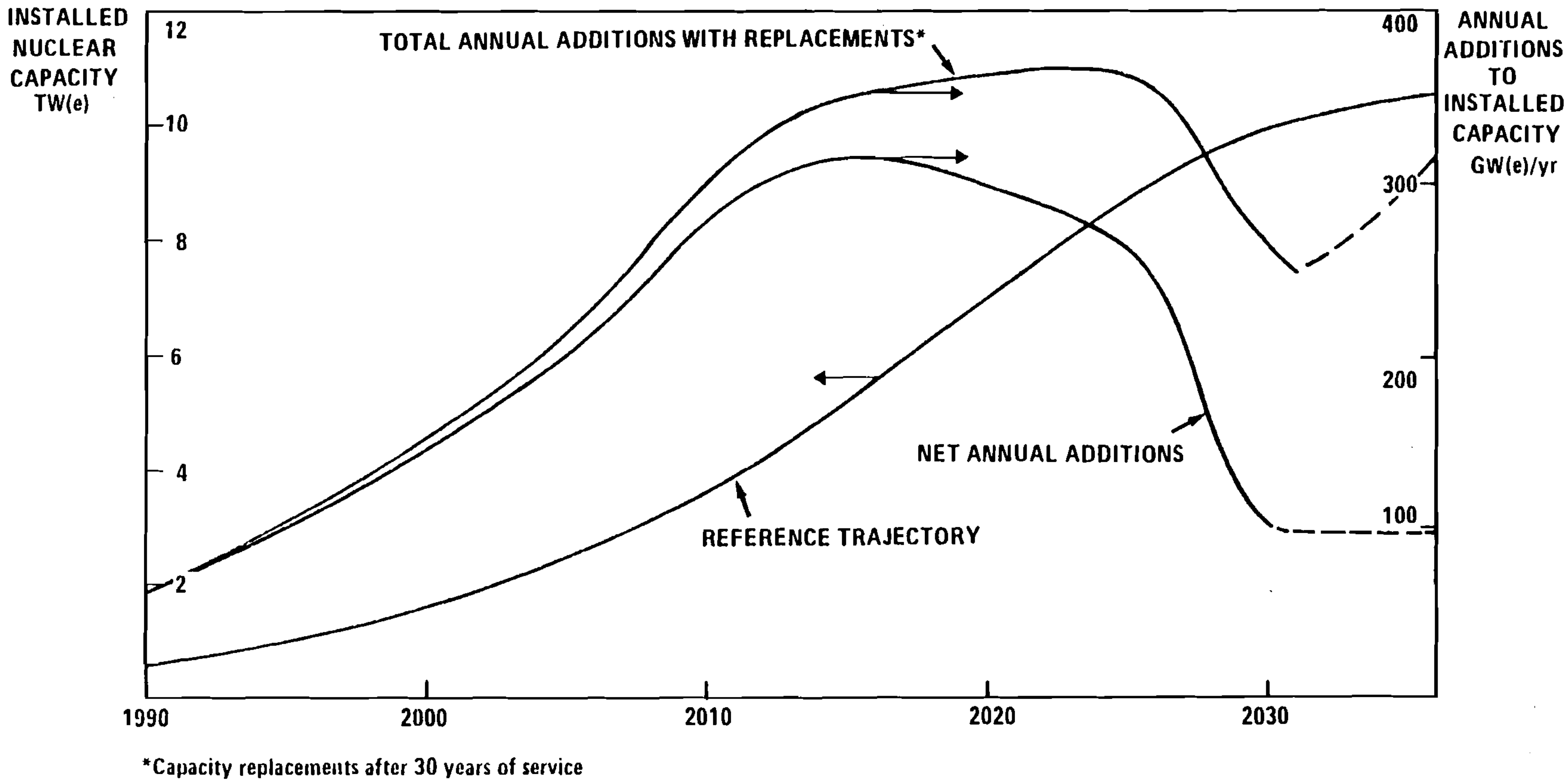

Figure 2. Reference trajectory for potential world nuclear installed capacity including annual installation additions

all types of electric plant is estimated to be at least 100-200 GW(e)/yr. Construction capability for nuclear plants is estimated to be at least 30 GW(e)/yr.

POWER REACTOR CHARACTERISTICS

In order to conduct the numerical comparisons of different reactor strategies with the fixed reference trajectory in view of natural uranium requirements up to the year 2030, we had to make some assumptions about the nuclear power reactor characteristics over this long time horizon. The most important of these characteristics are listed in Table 3, starting on the left with more conventional reactors already in extensive use today and going gradually to more advanced converter reactors to the right of the table. The two last columns on the far right of the table show two envisaged breeder reactors. Three fast breeder power reactors for commercial use have been already installed and four additional ones are firmly planned, two of them are presently under construction (Nuclear News 1978). Thus, commercial experience in the operation of the Liquid Metal Fast Breeder Reactors (LMFBR), for short FBR, has been gained up to date, however the high breeding gains have not been achieved yet.

To some extent the reactor characteristics given in Table 3 are hypothetical, except for the Light Water Reactor (LWR) on the natural uranium (U235/U238) fuel cycle. However, this is unavoidable in evaluating nuclear strategies over such a long time horizon. On the other hand, commercial experience up to date, test reactor experiments and theoretical calculations have been used as guidelines. For example, Schikorr (1979) has shown, in a collaborative study with IIASA, that it is possible to use Th232 in the radial blanket of FBRs and convert it to U233, instead of converting U238 to PU239, without any essential changes of the reactor characteristics.

The rows of the table also give respective inventory, annual makeup, and annual discharge of fissile materials. In addition to the direct U235 requirements, corresponding requirements of the low enriched natural uranium with 0.15% and 0.1% enrichment plant tails assay are given. Natural uranium contains 0.7115% U235, and since the content of U235 has to be increased to 2-3% for the LWR fuel, the amount of U235 left in the enrichment plant tails assay also governs the natural uranium requirements. Thus, a considerable saving can be achieved by going to lower tails assay: however, this has its costs and therefore cannot be reduced indefinitely. Table 4 gives tails assay decreasing from the left to the right of 0.3-0.1%, corresponding enrichment factor increase, and decrease of the natural uranium requirements per required kg of U235. The indicated cost factors are relative taking 0.15% enrichment plant tails assay to have a cost of unity per kg U235. In this respect we will first use 0.15% tails assay and then decrease it to 0.1%.

Table 3. Power reactor characteristics[1]

Reactor Type	U235/U238 LWR			U235/Th232 LWR			U233/ Th232 LWR		U235/U233/Th232 LWR[2]				U238/ Th232 FBR	
Recycle	No	U	U+Pu	U			U		U					
CR: Conversion Ratio	0.6	0.6	0.6	0.7	0.8	0.85	0.85	0.9	0.7	0.8	0.85	0.9	1.3	1.3
L: Load Factor[3]	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
I: Inventory Requirements[4]														
Natural Uranium (0.15% tails assay) $\mathrm{Mg/GW(e)_{inst}}$	400	400	400	550	606	661			561	716	804	903		
Natural Uranium (0.1% tails assay)[5] $\mathrm{Mg/GW(e)_{inst}}$	365	365	365	500	550	600			510	650	730	820		
U235[6] $\mathrm{kg/GW(e)_{inst}}$	2237	2237	2237	3063	3369	3676			3124	3982	4472	5023		
U233 $\mathrm{kg/GW(e)_{inst}}$							3500	4000						
Pu239 $\mathrm{kg/GW(e)_{inst}}$													5000	5000
B: Annual Makeup Requirements														
Natural Uranium (0.15% tails assay) $\mathrm{Mg/GW(e)_{inst}\,yr}$	131	102	80	60	35	26								
Natural Uranium (0.1% tails assay)[5] $\mathrm{Mg/GW(e)_{inst}\,yr}$	119	93	73	54	31	24								
U235[6] $\mathrm{kg/GW(e)_{inst}\,yr}$	729	570	447	333	193	144								
U233 $\mathrm{kg/GW(e)_{inst}\,yr}$							144	96	280	184	144	96		
D: Annual Fuel Discharge														
U233 $\mathrm{kg/GW(e)_{inst}\,yr}$													240	
Pu239 $\mathrm{kg/GW(e)_{inst}\,yr}$	156	156												240

1. Thorium and depleted uranium requirements are not considered since these two resources are not scarce in relation to limited supply of U235 (from natural uranium), Pu239 (from LWR on natural uranium fuel cycle and from radial blankets of FBR using depleted natural uranium), and U232 (from radial blankets of FBR using thorium).
2. LWR with low enriched natural uranium inventory and U233 annual makeup.
3. Load factor 0.7 is assumed throughout, meaning that 1 GW(e)yr [à L = 0.7]= 6132 GW(e)h, to obtain higher or lower load factors appropriate conversions should be used.
4. Inventory requirements also include ex-reactor inventory.
5. Separative work factor increase in going from 0.15% to 0.1% enrichment plant tails assay is 1.2, see also Table 4.
6. Actual fissile U235 content of natural uranium not counting the amount left in depleted natural uranium (tails assay).

Table 4. Separative work factor increase with reduction of enrichment plant tails assay and decrease of kg natural uranium needed per kg of separated U235

Tails Assay	0.3%	0.25%	0.2%	0.15%	0.1%
Cost Factor[1]	0.69	0.77	0.87	1.00	1.20
kg Nat.U/kg U235[2]	243	217	196	178	163

[1]Assuming separative work factor 1 for 0.15% tails assay. The calculation method is given in Section 7.5.1 of Grümm, H., et al. (1966).

[2]U235 content of natural uranium is 0.7115%, i.e. U238/U235 ratio is 140.55.

It should be noted that annual makeup requirements and discharges of fissile material have been based on a 0.7 load factor. For higher or lower load factors, appropriate conversions must be used, however in all nuclear strategies this is not straightforward as it might charge fissile material balances, but we will discuss this below. We do not specify precisely how this capacity is allocated between electricity for utility grids and for other, nonutility applications. However, on the assumption that a significant and, possibly, a major fraction may be used for the latter purpose, e.g. for the production of synthetic fuels, we have also increased the overall capacity factor to 0.8* in some of the converter-breeder strategy calculations, as will be shown below.

NUCLEAR POWER STRATEGIES

We use the term "strategy" to denote a time-dependent mix of reactor types and performance capabilities that may be available to meet the nuclear power demands specified in the scenarios. Underlying these strategies is the evident need to improve the efficiency for utilizing natural uranium, which is presently only about 0.5%. With this efficiency, the (roughly) 20 million metric tons of uranium which we take as a nominal resource base (see Perry 1979) represents some 90-100 TW(e) yr., i.e. only a 12-year supply for the 10 TW(e) assumed in our trajectory. A central feature of certain strategies is the concept of an "endowment", by which we mean the investment of a limited quantity of natural uranium to

*For example, 40% at a 0.7 plant factor plus 60% at a 0.85 plant factor leads to an average plant factor of 0.8.

establish a nuclear power system that is essentially independent of any further external source of fuel. This can be accomplished with breeder reactors, and in fact has been for years the guiding principle of long-range planning for nuclear power in most countries with active nuclear power programs.

The magnitude of the endowment necessary to establish this self-sufficient energy supply system and the time of its completion depend both on the scenarios for nuclear power growth and on the mixture of reactor types and characteristics used. The types of reactors we have considered on our studies and the range of performance characteristics we have ascribed to them are not different from those contemplated in other such studies. However, we have been particularly concerned with practical constraints which we believe will limit the rate at which new reactor types are likely to enter the market. Thus, our strategies, while qualitatively similar to those considered in other studies, differ from them in certain important respects, notably the anticipated rates of technological change.

ONCE-THROUGH STRATEGY

The first strategy is the simplest. Only LWR reactors on the natural uranium fuel cycle are installed with essentially contemporary design and performance. This strategy has been called once-through since natural uranium fuel goes only once through the reactor, it is simply burned, and the spent fuel is discarded. We conceive the following scenario for the implementation of this strategy.

1. Natural uranium is enriched leaving 0.15% tails assay in depleted natural uranium.
2. Low enriched natural uranium is used to install and maintain LWRs with a conversion ratio of CR = 0.6 and a load factor of L = 0.7, according to the reference trajectory of the total installed nuclear capacity.
3. Spent fuel is sent directly to waste storage, i.e. without reprocessing, and thus fissile materials are not recycled.

Natural uranium requirements can be reduced if the residual U235 in spent fuel is recycled and additional savings can be obtained by recycling the plutonium (Pu239) from the spent fuel. In such a case our scenario must be extended:

4. Spent fuel is reprocessed and only residual U235 is recycled.
5. In addition, plutonium is also recycled from the spent fuel.

These cases (3,4, and 5) are considered chiefly for reference. However, in addition to their literal meaning, they may also be interpreted as representing a limited range of potential improvements in contemporary LWR performance, for example, in the fuel efficiency of once-through cycles.

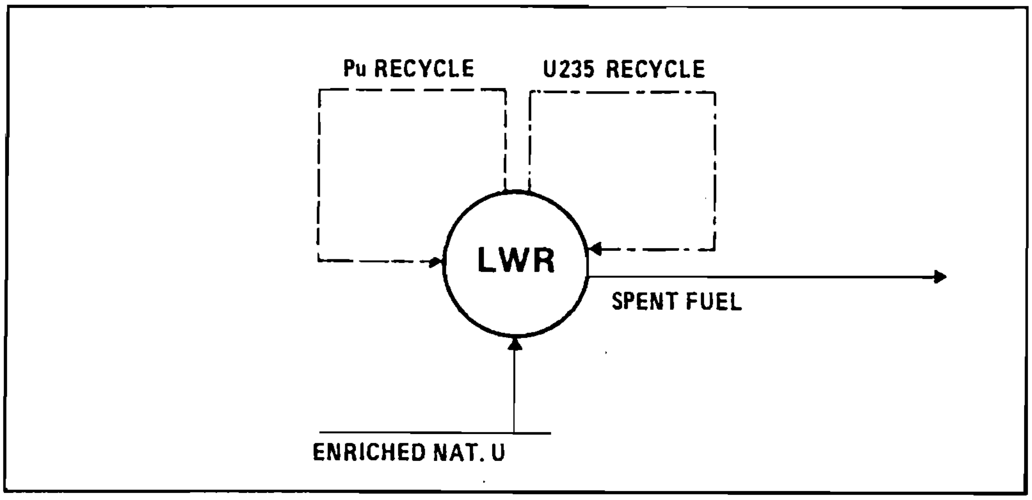

Figure 3. Once-through strategy with and without recycling. U235 recycling implies reprocessing of spent fuel, but allows about 22% savings in natural uranium needs. Pu-recycling also implies reprocessing of spent fuel, but allows about 17% additional saving in natural uranium needs, thus together with U235 recycling total savings up to 40% are achievable.

Figure 3 illustrates this strategy including the possibility of U235 and plutonium recycle. Unfortunately, even with savings from recycling, this strategy ultimately leads to excessive natural uranium demand.

Figure 4 gives the LWR installed capacities according to the reference trajectory and the cumulative natural uranium requirements with and without recycle. By 2030 the cumulative natural uranium demand would increase to 27.5 million tons, while with U235 recycle this amount would be reached five years later, and with additional plutonium recycle 10 years later.

It should also be mentioned here that higher tails assay and higher load factors would have led to even higher natural uranium requirements. For example, 0.2% tails assay leads to 33 million tons cumulative requirements by 2030. With recycle this figure would be reached 10 years later. On the other hand, with 0.8 load factor and 0.15% tails assay, 30.8 million tons are required by 2030, or with recycle 10 years later.

We have included this simple strategy as a point of departure, since it is based solely on LWRs with essentially contemporary performance characteristics (except for possible introduction of uranium and plutonium recycle). This strategy shows that the range of potential improvements in LWR performance and natural uranium requirements is basically limited to the introduction of recycle and further

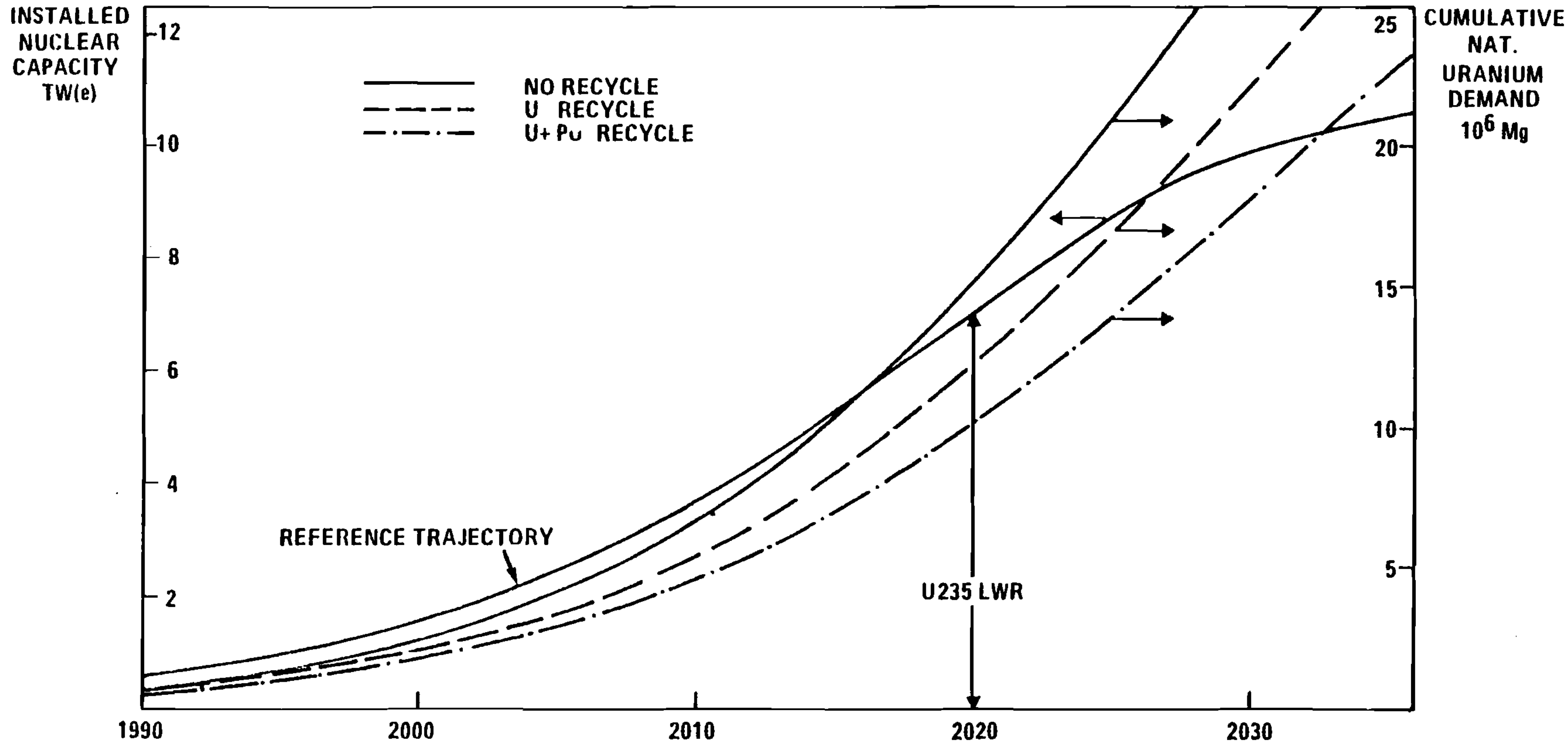

Figure 4. Once-through strategy with and without recycling

improvements in the fuel efficiency of once-through cycles. Next we will investigate strategies which do allow eventual decoupling from the natural uranium requirements.

THE CLASSICAL BURNER-BREEDER STRATEGY

Once-through is the simplest strategy and also widely propagated, but it does not fulfill the objective of eventually decoupling the fuel cycle from natural uranium supply. We have also seen that it unavoidably leads to enormous cumulative natural uranium requirements. The classical burner-breeder strategy is the other extreme case. Initially LWRs on natural uranium fuel cycle are also installed, but *all* plutonium from the spent fuel after reprocessing is used to install FBRs at the maximal rate, one that is constrained only by plutonium availability. Later, if surplus plutonium is available it may be recycled in the LWRs and eventually would displace U235 (in low-enrichment uranium) as fuel for all remaining LWRs. At this point, the combined LWR-FBR system would be free of any further fuel supply, and we would say that "the endowment is complete." Ultimately, all of the LWRs can be replaced by FBRs.

This is possible not only because the FBR produces more fuel (Pu) than it consumes, but also because the large amount of uranium (mainly U238) left unburned by the LWRs is a proper raw material from which the breeder can make plutonium. The breeder can therefore ultimately extract roughly 100 times as much energy from this uranium as could the LWRs. For this reason, the stored residues from LWR operations during the transition period represent a very large energy resource, sufficient for some centuries of continued operation and growth after the endowment is completed. The amount of uranium needed to create this endowment depends critically upon the rate at which the breeders can increase their share in the nuclear power market, and it is our assumptions in this respect that constitute a central aspect of this study. In this strategy, the growth rate of FBRs is constrained only by plutonium availabliity.

We conceive the following scenario for the implementation of this strategy:

1. Natural uranium is enriched leaving 0.15% tails assay in depleted natural uranium.
2. Low enriched natural uranium is used to install and maintain LWRs with CR = 0.6 à L = 0.7. At the beginning the total installed nuclear capacity consists only of LWRs.
3. Spent fuel is reprocessed and fissile uranium is recycled, lowering the LWR annual low-enriched natural uranium requirements. Fissile plutonium is used to install FBRs with CR = 1.3 à L = 0.7.

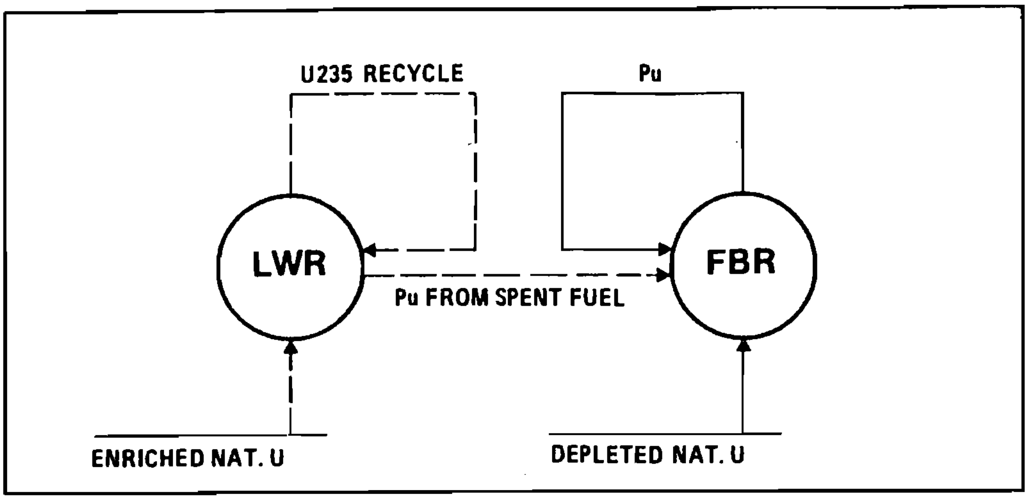

Figure 5. The classical burner-breeder stategy. Gradually all LWRs on low-enriched natural uranium (here in dashed lines) are replaced by FBRs. In the asymptotic state the system is independent of natural uranium, only depleted natural uranium left over from the LWRs is needed.

4. Spent fuel from the FBR radial blankets is also reprocessed and the excess fissile plutonium is used to install additional FBRs.
5. The FBR installment rate is limited only by the availability of fissile plutonium, i.e. annual plutonium balance is zero, after an allowance of 5 years delay for reprocessing (2.5 years after 2020).
6. In this way all the LWRs are slowly replaced by FBRs. In the asymptotic state of the system only FBRs are left, thus there is no low enriched natural uranium requirement, only depleted natural uranium is needed for FBRs and the system is selfsufficient.

Figure 5 illustrates the reactor configuration of this strategy. The LWR part of this configuration is drawn with dashed lines to stress the fact that in the asymptotic state only FBRs would be left achieving in this way the decoupling from natural uranium.

Figure 6 shows the dynamic development of this strategy based on our reference trajectory. Starting in 1990 there is enough plutonium from spent LWR fuel to start FBR installments. By 2040 all LWRs are replaced by FBRs. The cumulative natural uranium requirements level off at 15 million tons, which represents a onetime investment. The curve with consumptive use of natural uranium from the once-through strategy is also included in Figure 6 for comparison of these two extreme strategies. The reduction in the natural uranium demand is impressive: by 2035 34.4 million tons are needed in the once-through strategy, and only 15 million tons in the classical strategy.

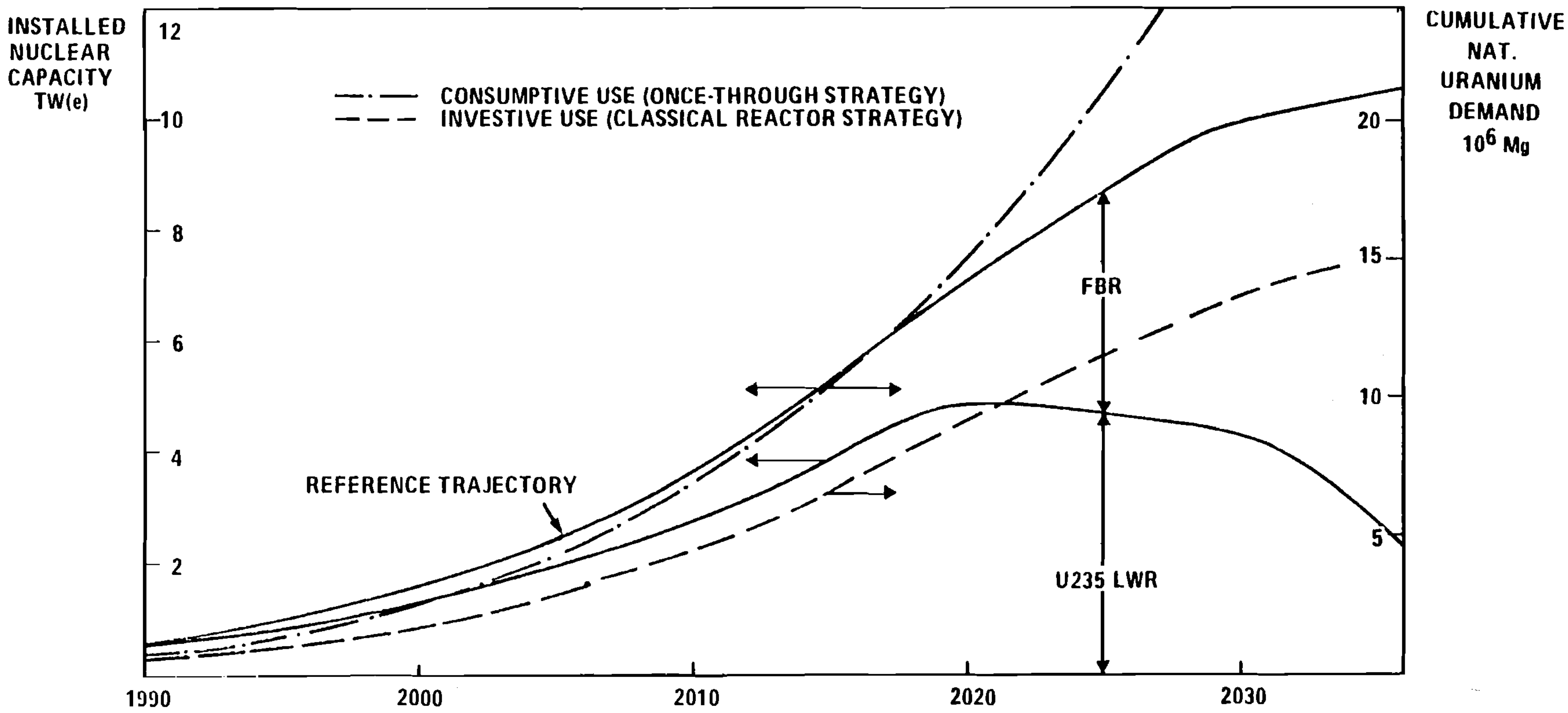

Figure 6. The classical burner-breeder strategy

Higher load factors of the FBRs would increase the speed of transition. For example, with 0.8 load factor all the LWRs would be replaced five years earlier since the plutonium balance would be less constrained, i.e. more plutonium would be converted from U238 in the FBR radial blankets. Higher enrichment plant tails assay would increase the required one-time natural uranium endowment, e.g. 0.2% tails assay leads to 16.6 million tons cumulative requirements.

While all these properties of this strategy make it appear very attractive because of the relatively low asymptotic natural uranium requirements, it implies extremely rapid FBR buildup rates during the first three decades of the next century. Annual construction rates in excess of 500 GW(e) installed capacity are called for according to Figure 2, the annual construction rates in our reference trajectory are limited to a maximum of 300 GW(e) per year which occurs between 2010 and 2020. Thus a construction rate of 500 GW(e) per year is inconsistent with our original assumptions.

We therefore modified the classical strategy in order to decrease the FBR buildup rates retaining the goal of also achieving eventual decoupling from the natural uranium demand by an exogenous FBR trajectory. This involved considering hybrid reactor systems including advanced converter reactors shown in Table 3.

A CONVERTER-BREEDER STRATEGY

Our first goal is to reduce the excessive growth rate of FBRs encountered in the classical burner-breeder strategy. For this purpose we introduce an exogenous FBR trajectory. This FBR trajectory is based on the reference trajectory. In it, the installed FBR capacities are larger by a factor 1.5 than the total nuclear installed capacities in the reference trajectory 25 years earlier, e.g., in 1980 the reference trajectory specifies 160 GW(e) total installed capacity, then the FBR trajectory specifies 240 GW(e) as maximal FBR installed capacity 25 years later in the year 2005.

Table 5 gives the installed capacities of the FBR trajectory including required net annual additions, with the total annual additions including replacements of power plants after 30 years of service and also annual growth rates. The table shows that the trajectory constrains the FBR growth radically. In the classical burner-breeder strategy it was necessary to replace almost all the LWRs with FBRs in order to eliminate further natural uranium demand. The converter-breeder strategy calls for replacement of only 40% of the total nuclear capacity

Table 5. Trajectory for potential world FBR installed capacity including annual installation additions and growth rates

	1980	1985	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035
Installed GW(e)[1]				45	114	240	480	870	1470	2415	3678	4288
Net Annual Additions GW(e)/yr				9	18	36	61	96	153	212	119	40
Total Annual[2] Additions GW(e)/yr				9	18	36	61	96	153	221	133	76
Growth Rate (%)[3]				20.4	16.1	14.9	12.6	11.1	10.4	8.8	3.1	0.9

[1] Installed capacity in GW(e) without implication of how this capacity may be allocated between distribution on electrical grids and other uses,e.g. production of synthetic fuels.

[2] Net annual additions plus capacity replacements after 30 years of service.

[3] Net annual percentage growth calculated on the basis of exponential growth during 5 year intervals.

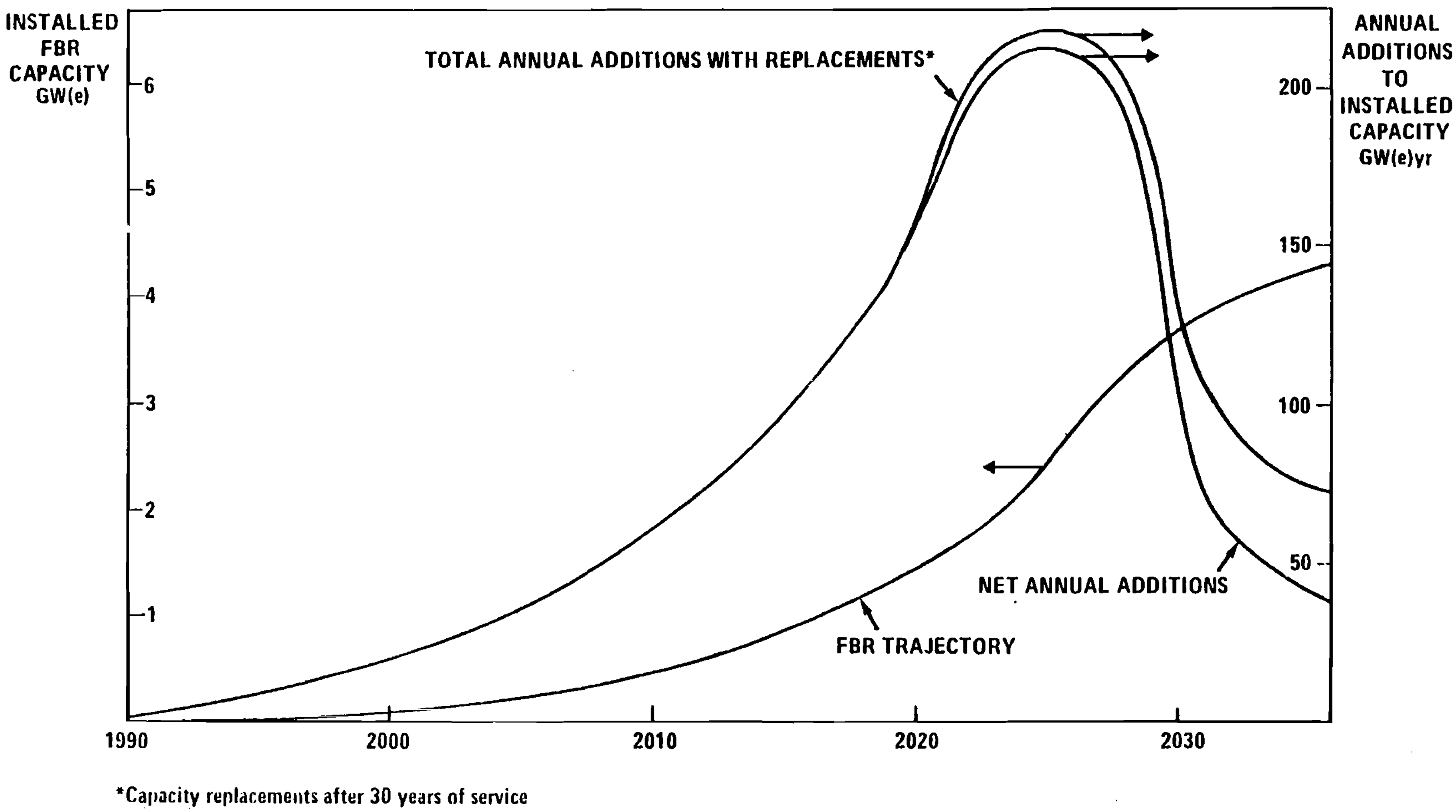

Figure 7. Trajectory for potential world FBR installed capacity including annual installation additions

by FBRs in order to achieve the same result. The annual growth of the FBR installed capacities decreases from 20% in 1995 to 1% by 2035. After 2030 both the total nuclear capacity and the FBR capacity grow at about the same rate, at 1%/yr, and thus an asymptotic, dynamic reactor configuration is achieved. This equilibrium reactor configuration can then grow indefinitely at 1%/yr without any further natural uranium requirements. Also, the annual FBR capacity additions have been reduced radically. This is illustrated in Figure 7 with the maximal additions approaching 200 GW(e) of FBR capacity per year in the 2020s.

We envisage the following scenario for the implementation of this strategy:

1. Natural uranium is enriched leaving 0.1% tails assay in depleted natural uranium.
2. Low enriched natural uranium is used to install and maintain LWRs with CR = 0.6 à L = 0.7. At the beginning the total installed capacity consists only of LWRs.
3. Spent fuel is reprocessed and fissile uranium is recycled, lowering the LWR annual low-enriched natural uranium requirements. Fissile plutonium is used to install FBRs with CR = 1.3 à L = 0.7, after an allowance of 5 years delay for reprocessing (2.5 years after 2020).
4. Spent fuel from the FBR radial blankets is also reprocessed, and after a 5-year reprocessing delay (2.5 years after 2020) excess fissile plutonium is used to install additional FBRs. However, the FBR construction rate is determined by the FBR trajectory so that some excess plutonium would be left over.
5. Instead of producing plutonium in excess of FBR construction rate needs, some of the FBRs using thorium in radial blankets produce U233 instead of plutonium. U233 too, after a reprocessing delay of 5 years (2.5 years after 2020), is used to install and maintain advanced converter LWRs at the beginning with CR = 0.7 à L = 0.7 gradually changing to CR = 0.9 à L = 0.7 by the year 2030. In this way, the fissile material (Pu and U233) balances are closed.
6. Gradually all LWRs on the natural uranium fuel cycle are replaced by FBRs and LWRs on the U233 fuel cycle. In the asymptotic state the fissile material balance between the FBRs and LWRs is closed, their ratio being governed by this balance, and no additional inputs of fissile material are required. The system is independent of natural uranium, only depleted natural uranium and thorium are needed.

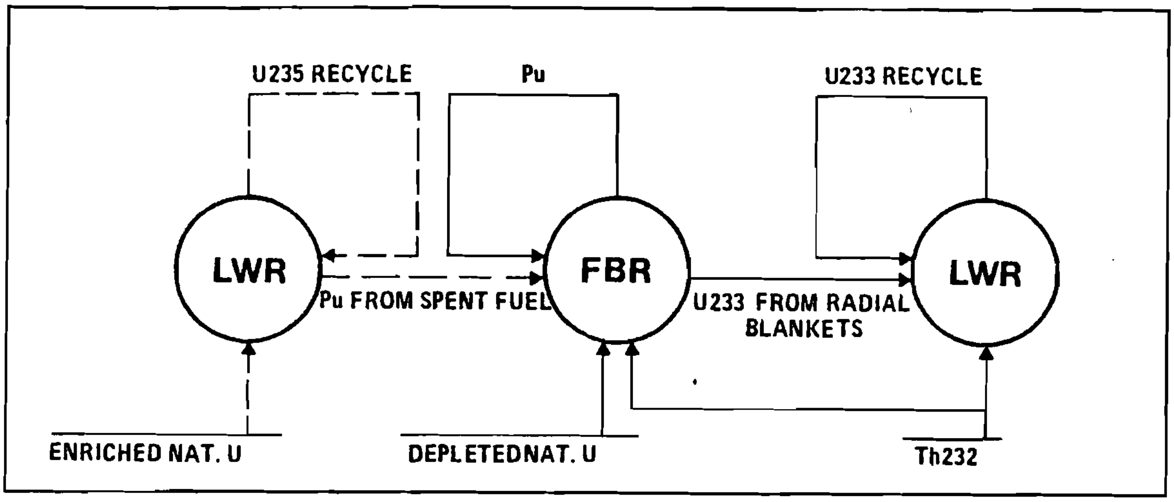

Figure 8. A converter-breeder strategy. Gradually all the LWRs on low-enriched natural uranium fuel cycle (here in dashed lines) are replaced by FBRs and LWRs on U233 fuel cycle. In the asymptotic state the material balance is closed between FBRs and U233 LWRs, their ratio being governed by the fissile material balance, and no additional inputs of fissile material are required. The system is independent of natural uranium, only depleted natural uranium left over from the U235 LWRs and thorium are needed.

Figure 8 illustrates the reactor configuration of this strategy. The part of the fuel cycle configuration showing the LWRs on natural uranium is drawn with dashed lines to stress the fact that in the asymptotic state it would be replaced by advanced LWRs on the U233/Th232 fuel cycle and by FBRs.

In the classical strategy, substitution of FBRs for the LWRs was only constrained by the closing of the fissile plutonium balance. In this strategy the growth of the FBR capacity is constrained by an exogenous trajectory. Therefore, if all FBRs were to convert U238 to Pu239 excess fissile plutonium would accumulate. In order to close the plutonium balance, i.e. to avoid the breeding of fissile plutonium in excess of the amount needed to sustain the prescribed FBR construction rate, most of the FBRs would convert Th232 in the radial blankets to U233 and less than 20% of the installed FBRs would convert U238 to Pu239, in order to sustain the 1% annual growth of FBR capacity. This is possible since thorium can be substituted for uranium in the blankets of the FBR with little or no adverse affect on the breeding performance. U233 produced by the FBRs is then used to fuel the advanced converter LWRs on the U233/Th232 cycle.

Converter reactors are characterized by an improved fuel efficiency approaching the advantages of breeder reactors. Advanced Converter Reactors (ACR) can then, to a certain degree, relieve the natural uranium requirements. However, these reactors do not breed, so that the cumulative natural uranium requirements cannot be limited with time, and capacity increases if breeder reactors are not used in conjunction. However, since ACRs can relieve the pressure on uranium supply for many decades, they can, at least for that time period, remove the need to consider vigorous breeder buildup rates.

ACRs are thermal-neutron reactors operating usually on the thorium fuel cycle with recycle and enriched U235 topping. The notable representatives of this class of high converter reactors are the High Temperature Reactor (HTR) and the Heavy Water Reactor (HWR). However, also the improved LWR can be designed as a high converter reactor either through changes in reactor design (e.g. SSCR, LWBR) or primarily through fuel cycle modifications (e.g. use of the thorium cycle) with relatively minor changes in reactor technology. We judge that modified LWRs could enter the market much more quickly than a new reactor type, especially if the modifications could be applied to reactors already in operation with little or no loss of availablility.

We consider in this strategy converter LWRs on the thorium-natural uranium and the thorium-U233 fuel cycle, their characteristics are given in Table 3. However, the improvements in LWRs need not be restricted to the thorium fuel cycle. Indeed, there are numerous possibilities, already rather well explored, for improvement of LWRs using plutonium and natural or depleted uranium (Edlund, 1975). Some of these possibilities include modifications of fuel design with little or no change in plant design or technical characteristics external to the pressure vessel. By reducing the volume fraction of water in the reactor core, (in ways entirely compatible with the thermal-hydraulic performance of contemporary LWRs) the neutronic performance can be significantly improved. Indeed, the conversion ratio can probably be increased to nearly unity (e.g. 0.95) without compromising either the safety of the system or the economics of the fuel cycle.

In this way LWRs on the natural uranium fuel cycle are substituted by both the FBR and the advanced LWR on the U233 thorium fuel cycle. But FBR substitution is constrained by the FBR trajectory, so that the substitution process is governed by the growth of the LWR capacity on the U233 fuel cycle and this growth is constrained only by the availability of U233 from FBRs. Thus, here two fissile material balances (PU239 and U233) have to be closed simultaneously, where the closing of the U233 balance is dependent on the Pu239 balance through the exogenous FBR trajectory. An additional complicating factor like in the classical strategy is that we have to account for the delay in the availability of the fissile materials because they can be used only after reprocessing. We have assumed that this delay would be five years up to 2020 and 2.5 years afterwards.

With such advanced reactor configurations the element of timing is important. First we analyzed a hypothetical case where high converters with CR = 0.9 (see Table 3) on the U233/Th232 fuel cycle are introduced as soon as U233 becomes available from the FBRs.

Initially we conducted the calculations for this strategy using higher load factors for all power plants L = 0.8 instead of L = 0.7 used so far. Thus, we managed to decouple the resulting reactor configuration from the natural uranium demand by 2035 with 15.4 million tons cumulative requirements. It should be noted that we also lowered the tails assay to 0.1% from 0.15%. With 0.15% tails assay, 16.9 million tons would have been required.

However, since the converter LWR starts substituting the LWR on the natural uranium fuel cycle as of 2010, we felt that such high conversion ratio of 0.9 might not be achievable, and therefore reduced it to 0.85. The calculations showed that the resulting reactor configuration could also be decoupled from natural uranium demand by 2035. Naturally, substitution of the converter LWR was somewhat slower due to the higher U233 annual makeup requirements, not offset by the lower U233 inventory requirements of the converter LWR, see Table 3. This of course also somewhat changed the closing of the U233 balance. The resulting cumulative natural uranium requirements were 16.7 million tons with 0.1% tails assay. This variation of the conversion ratio of the converter LWR showed that this strategy is not very sensitive to slight changes in the critical reactor characteristics.

The converter reactors used in the calculations, with characteristics that approach breeding, are more advanced than contemporary LWRs, so that it seems unlikely that they could be introduced as early as 2010. Even the lowered conversion ratio of CR = 0.85 appears not to be attainable by 2010, the time when U233 converter LWRs are introduced in this strategy. In order to alleviate this aspect of the strategy, we introduced two modifications.

Essentially we assumed that the design of the converter reactors introduced initially would be slightly modified, compared to contemporary LWRs. The conversion ratio would continuously increase from 0.7 to 0.9 by 2030. In addition, introduction of converter LWRs is started in the year 2000, i.e. ten years earlier than previously assumed. However, by this time no excess FBR capacity is available to convert Th232 to U233, and all the FBRs still have to convert U238 to Pu239 in order to achieve the annual capacity additions specified by the FBR trajectory. On the other hand, the earlier introduction of converter LWRs guarantees smoother and lower initial buildup rates. We resolved this initial lack of U233 by introducing at the beginning some converter LWRs on the U235/Th232 fuel cycle with CR = 0.7 which also guarantees subdued development of converter reactors. Thus, the early converter LWR would be similar to the LWR on the natural uranium fuel cycle, and the primary changes would be a slightly modified fuel cycle. Therefore, we expect that such reactors could be introduced earlier and perhaps more rapidly than an entirely new reactor type, especially if some modifications could be applied to LWRs already in operation. This may have a two-fold advantage: a smoother and earlier introduction of converter reactors and the continued use of old but modified LWRs originally based on the natural uranium fuel cycle. Such LWRs in a way represent a "free bonus" since with FBR substitution they are discarded in the classical burner-breeder strategy.

These reactors would be gradually improved and modified to the U235/U233/Th232 fuel cycle. As more U233 is available this line of reactors would change to converter LWRs on the U233/Th232 fuel cycle without natural uranium topping, as was outlined above, while the conversion ratio would approach 0.9 by 2030. These two modifications permit slower and smoother buildup rates and lower and more realistic conversion ratios during the first 30 years of converter LWR operation. The U235 used initially in these reactors is charged to the natural uranium account. The characteristics of these reactors are given for CR = 0.7, 0.8, 0.85, 0.9 in Table 3.

The calculations of this modified converter-breeder strategy show that decoupling from the natural uranium supply is also possible by 2035 with cumulative requirements of 16.6 million tons. The asymptotic state of the reactor configuration is also achieved by 2035, which shows the flexibility of this strategy under significant changes of the converter LWR characteristics. From 2035 on the converter LWR-to-FBR ratio remains constant at 1.45, and still allows a potentially indefinite 1% annual growth of the total nuclear capacity.

Finally, the last change we introduced was to lower the load factor of all reactors from 0.8 to L = 0.7. This last modification somewhat alters fissile material (Pu and U233) balances, and therefore calls for an only slightly changed LWR-to-FBR converter ratio in the asymptotic reactor configuration after 2030, but it allows direct comparison of this strategy with the classical burner-breeder and once-through strategies. Figure 9 gives the installed capacities of all three reactor types used in this strategy and the cumulative natural uranium requirements of 15 million tons based on 0.1% enrichment plant tails assay. Higher growth rates of the total nuclear installed capacity are also achievable but would necessitate different converter LWR-to-FBR ratios. Only in this way can the fissile material balances be closed without exogenous fissile material inputs. In general, the higher the growth rate, the lower would be the LWR/FBR ratio, since the FBR reactor produces U233 to sustain and

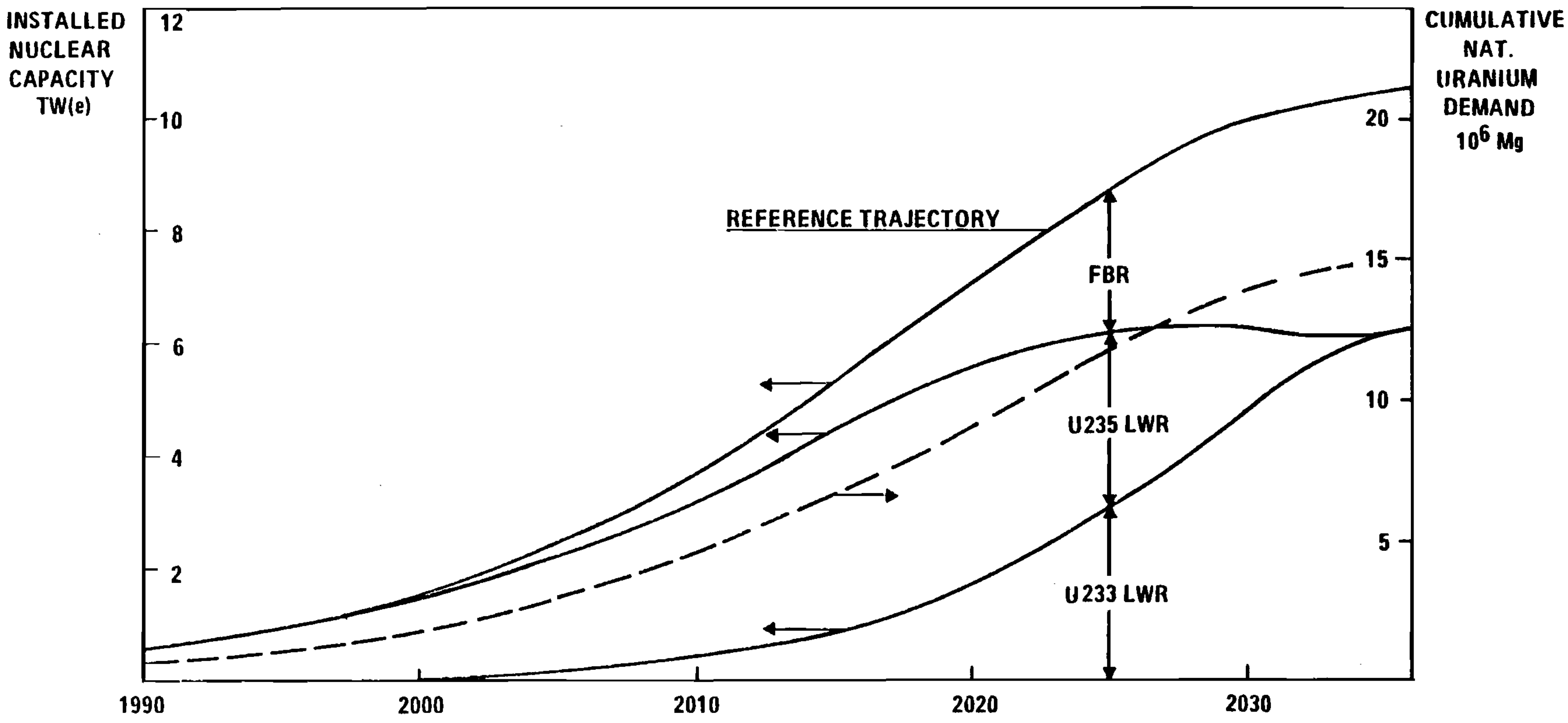

Figure 9. A converter-breeder strategy

Table 6. A converter-breeder strategy

	1980	1985	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035
Reference Trajectory												
Installed GW(e)	160	320	580	980	1630	2452	3642	5279	7029	8639	10000	10500
Growth Rate (%)[1]	14.9	12.6	11.1	10.7	8.5	8.2	7.7	5.9	4.2	3.0	1.0	0.9
Cumulative Nat.[2] Uranium 10^6 Mg	0.2	0.3	0.6	1.0	1.8	2.9	4.5	6.6	9.0	11.9	13.9	15.0
U235 LWR												
Installed GW(e)	160	320	580	935	1440	1991	2688	3527	3891	3112	1581	
Growth Rate (%)[1]	14.9	12.6	10.0	9.0	6.7	6.2	5.6	2.0	-2.0	-7.3	-20.4	
Shares (%)	100	100	100	95.4	88.3	81.2	73.8	66.8	55.4	36.0	15.8	
U233 LWR												
Installed GW(e)					76	121	474	882	1668	3112	4741	6212
Growth Rate (%)[1]					23.8	16.5	13.2	13.6	13.3	8.8	5.6	0.9
Shares (%)					4.7	9.0	13.8	16.7	23.7	36.0	47.4	59.2
FBR												
Installed GW(e)				45	114	240	480	870	1470	2415	3678	4288
Growth Rate (%)[1]				20.4	16.1	14.9	12.6	11.1	10.4	8.8	3.1	0.9
Shares (%)				4.6	7.0	9.8	13.2	16.5	20.9	28.0	36.8	40.8

[1] Net annual percentage growth calculated on the basis of exponential growth during 5 year intervals, negative numbers imply a decrease in installed capacity.

[2] Cumulative natural uranium requirements in million tons (10^6 Mg), with no further requirements after 2035.

increase the LWR capacity and plutonium necessary for FBR capacity increases.

The most significant results of the calculation of the converter-breeder strategy of Figure 9 are reproduced in numerical form in Table 6. These calculations show that the strategy requires a limited natural uranium endowment of 15 million tons necessary to complete the transition, from a contemporary largely LWR global nuclear program, with decreasing annual capacity growth, to a postulated asymptotic growth of 1% per year while achieving a potential of 10 TW(e) installed by the year 2030.

This is achieved with a significantly lower FBR share than in the classical burner-breeder strategy since each FBR can service more than one converter reactor. The FBR shares, specified by an exogenous trajectory, approach 41% of the total installed capacity by 2030 without further increase. Yet the primary reliance on the LWR technology is maintained throughout the transition period. Up to 1995 all of the installed capacity consists of the LWR on the natural uranium fuel cycle decreasing gradually to a 59% share consisting entirely of advanced converter LWRs by 2030. Also the growth rates of the advanced converter LWRs decrease from 24% per year when they are introduced in the year 2000, with only slightly modified characteristics as compared with contemporary LWRs, to 1% growth per year by 2030 when the development of the converter reactor is assumed to be completed with a high conversion ratio of 0.9. This has been achieved while maintaining both the assumed FBR construction schedule and closing of both components of the fissile materials balance (U233 and Pu239).

The asymptotic character of the strategy also guarantees a potentially unlimited annual growth of 1% total nuclear capacity and both of its components (FBR and LWR) without further natural uranium requirements. Only the abundantly available depleted natural uranium (or low-grade natural uranium ores) and thorium are required to sustain this reactor configuration and its postulated further growth.

CONCLUSION

Contemporary nuclear power reactors use uranium very inefficiently (< 1%). Unless demand for nuclear energy grows much more slowly or uranium resources (and our capability to extract them) prove much larger than we can prudently assume, a large improvement in fuel efficiency will be required within the next few decades.

The "classical endowment strategy" would permanently solve the problem of fuel supply and could be very effective if fast breeder reactors could be introduced (to the extent of perhaps 60-70% of total nuclear capacity) about as rapidly as plutonium availability would allow. However, the effectiveness of this strategy will be substanially reduced if breeder reactors enter the market rather more slowly than in the plutonium-limited case. (The effectiveness of this strategy depends mainly on when breeders reach 60-70% of total capacity, rather than on the date of first entry into the market).

The early and rapid introduction of advanced converter reactors, with fuel efficiencies of several percent (e.g. 5-10%), could long defer (but not ultimately prevent) a uranium supply problem. However, as with breeders, the strategy is seriously compromised by practical constraints on attainable rates of market penetration for new reactor types. In addition, it appears that economic considerations will not favor presently-identified advanced converter reactors, operating at the postulated high fuel efficiencies, until uranium prices (in real terms) rise substantially) above their present levels.

We think it very likely that improvements in light water reactors can penetrate the nuclear market much more quickly than could a new reactor type, particularly if they involve minimal changes in established LWR technology. This is especially so if the improvements can readily be fitted to existing reactors without prolonged shutdowns. This would facilitate a more rapid improvement in the average fuel-efficiency of the overall nuclear power system than would be possible with other advanced converter reactors. However, this strategy does not ultimately resolve the uranium supply question.

We have shown in this report that it is possible to limit the natural uranium endowment necessary to sustain the transistion to a reactor configuration that is capable of expanding at a postulated 1% per year beyond 2030, without further external fissile materials supply. This result is based on a converter-breeder nuclear strategy following an assumed trajectory of potential total nuclear installed capacity leading to 10 TW(e) by the year 2030. This strategy, while qualitatively similar to those considered in other studies which also foresee eventual decoupling from natural uranium supply, differs from them in that it specifies slow and smooth buildup rates of all reactor types. This was possible because U233 for converter reactors can be produced in the blanket of an FBR about as efficiently as can plutonium, and also because we assumed that converter reactors based on LWR technology could be introduced more quickly than could an altogether different reactor type. Thus, the required technological changes need not be very rapid because the strategy relies primarily on LWR technology throughout this century and necessitates only gradual improvements afterwards.

By 2030 FBRs would substitute about 41% of the total installed capacity along an exogenous trajectory, i.e. a significantly lower share than in the "classical endowment strategy." At the same time, these results show that advanced high converter reactors cannot eliminate the need for breeder reactors if the decoupling from the natural uranium supply is to be achieved during the next 50 years. It also shows that gradual development and introduction of these reactors can operate in a complementary mode with breeder reactors, and in that way contribute to the eventual decoupling from external fissile materials supply. On the whole a gradual and steady evolution of LWRs with a gradual introduction of FBRs to the upper limit of about 40% can lead to an eventual decoupling. Unfortunately, this gradual and therefore probably potentially feasible transition from consumptive to investive uses of natural uranium resources also has its costs. This cost has to be paid by a relatively large cumulative amount of natural uranium necessary to master the transition since the transition is likely to be long.

While this strategy ultimately requires the use of plutonium, it is not very sensitive to delays of several years in the actual implementation of plutonium recycle so long as the unused fuel values in spent fuel are stored in retrievable form. We have not made a comparative economic evaluation of this strategy, and do not indeed suppose that we have reliable economic data for a precise analysis. We believe, however, that this strategy, among the available alternatives, is likely to be most compatible with normal economic forces. Important conclusions include the following:

1. Technology changes are not likely to be very rapid.
2. Heavy reliance will continue to be placed on LWR technology throughout this century and well into the next.
3. FBRs are unlikely to enter the market as rapidly as many prior studies have suggested.
4. The transition from a consumptive to an essentially self-sufficient nuclear energy supply will be completed neither as soon nor at as low a level of cumulative uranium consumption as many prior studies have suggested.
5. Advanced converter reactors cannot significantly alter this situation because, like the breeders, they cannot enter the market quickly enough.
6. A promising nuclear development strategy can be based on a steady evolution of the performance of light water reactors, coupled with a gradual introduction of breeders to the extent of 20-40% of total nuclear capacity.
7. This strategy is not exclusive; it is compatible with a more rapid introduction of advanced technologies, if that proves feasible, and with admixtures of other reactor types; but it does not rely on them.
8. As a result of the expected slow growth in breeder reactor capacity, it is urgent to continue with the preliminary phases, i.e. technology development and initial, small-scale deployment.

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