RESOURCE-EFFICIENT NUCLEAR SCENARIOS

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July 1979
WP-79-62

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PREFACE

Most studies of uranium use in nuclear build-up strategies consider early build-up of light-water reactors (LWR). Then, the plutonium produced in them is used to fuel fast breeder reactors (FBR). This method has been described as the "classical" reactor strategy.

LWR's are not resource-efficient reactors. Strategies which substitute reactors of higher fissile-material "conversion" for them are known to require less uranium. However, most qualitative studies incorporating high-conversion reactors still begin with a high deployment rate of LWR's, and the improved resource-efficiency is not very noticeable.

Some illustrative cases of the more efficient strategies became desirable, so as to make the presentation more general, in the chapter on nuclear power of the forthcoming IIASA book "Energy in a Finite World". This working paper documents the material that was generated for that puprpose.

CONTENTS

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INTRODUCTION

Most classical reactor strategies start with light-water reactors, milking the plutonium from them to fuel breeders. From the point of view of resource conservation this is a poor strategy. LWR's do not produce as much plutonium as reactors of higher conversion, per unit useful power generated. Advanced converters, such as HWR's or GCR's, could produce more. But the best converters of ^{235}U to plutonium are those which, when fueled with plutonium, are themselves breeders.

Several reactor strategies have been worked out. We use for comparison strategies exhibited and computed by Perry and Nakicenovic (19). There results are summarized in Table 1. In all cases, the results are in terms of a total installed capacity of 10 TWe nuclear by 2030, the curve of capacity vs. time being given in Figure 1 as the curve labeled "Perry".

In the work presented here, even more resource-efficient strategies than the best given in Table 1 are worked out. It is seen that there are considerable improvements available. The key feature is early substitution of resource-efficient converter and breeder reactors for less resource-efficient ones.

AN ALL-BREEDER STRATEGY

In order to find the more realistic range of uranium demands to reach a breeder economy, I have looked at lower limits obtained when one builds the system using only breeders, but fueling them as necessary with ^{235}U until there is enough plutonium to have the required endowment. The breeder system is characterized by the parameters of Table 2.

Table 1. Uranium resource requirements for reactor strategies (from Perry and Nakicenovic (19)).

General Conditions: Reactors installed according to "Perry" trajectory of Figure 1
All reactors at capacity of 0.7
Conversion ratio of LWR, slightly enriched uranium: 0.6
Breeding ratio of FBR, plutonium fuel: 1.3

Case	Characterization	Uranium needed to reach steady state
1	Classical strategy	15×10^6 t (metric)
2	Converter-breeder	17×10^6 (a)
		15×10^6 (b)

Special Conditions and Comments:

Case 1 Enrichment-tails assay was 0.15% ^{235}U. FBR installed whenever enough plutonium became available. LWR installed and retired to make up the rest of the required trajectory. 60% of installed capacity was FBR by 2030.

Case 2 FBR installed more gradually, reaching 40% of total capacity by 2030. LWR's replaced or augmented by advanced converters on ^{233}U-Thorium cycle, using ^{233}U made in FBR's after plutonium needs are satisfied. ^{233}U-Th reactor conversion ratio is 0.9.

(a) With enrichment tails assay of 0.15%, as also assumed for Case 1

(b) Enrichment tails assay of 0.10%

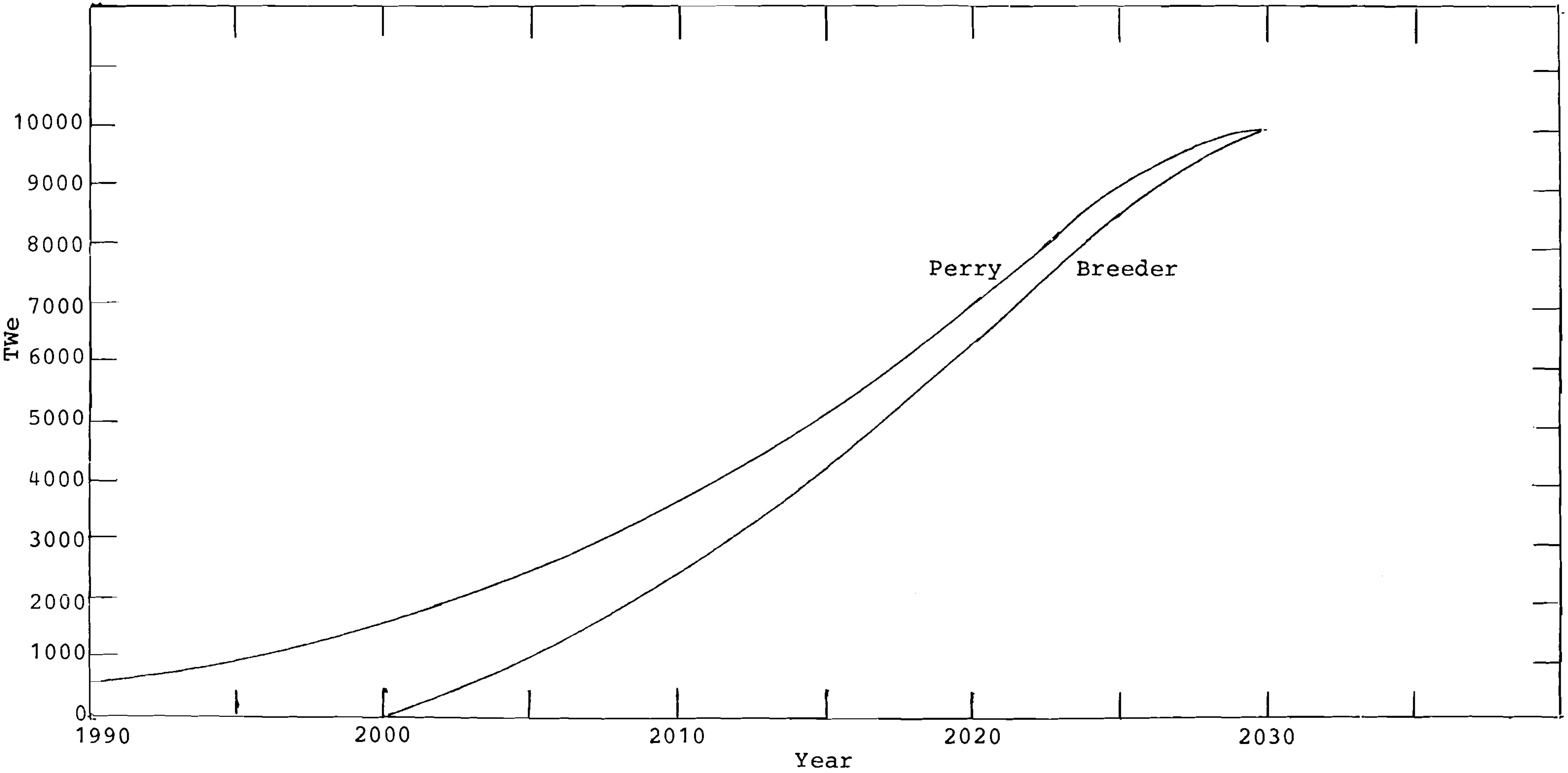

Figure 1. Breeder build-up trajectories

Table 2. Characteristics of a model breeder reactor.

Reactor loading: 16 metric tonnes (core) heavy metals

Critical concentration: 16 w/o Pu, 20 w/o ^{235}U, or any linear combination thereof

Pu/^{235}U fission cross-section ratio: 1.25

Fraction of fissions in ^{238}U: 10%

Reactor Power: 2,500 MW (thermal) or 1,000 MWe

Capacity factor: 0.7

^{235}U or Pu atoms destroyed/atom fissioned: 1.2

Time in core: 1 year

Fuel cycle turn around time, out of core: 1 year

Reactor burnup after 1 year: 4.2% of oringinal heavy metal

Breeding Ration, ^{239}Pu, net: 1.2

Conversion Ratio ^{235}U to ^{239}Pu, net: 0.85

Doubling time of Pu breeder: 35 years (simple)
25 years (compound)

Recycle characteristics:
Per kg of ^{235}U loaded, there become available, two years later, 0.7732 kg of ^{235}U
0.196 kg of fissile Pu

Per kg of ^{239}Pu loaded, there becomes available, two years later, 1.056875 kg of fissile Pu.

The computations have been performed under the assumption that all breeder reactors can be loaded either with ^{235}U or ^{239}Pu. We load as many of them with ^{239}Pu as can be accommodated from the available plutonium. The rest we load with ^{235}U. Those loaded with ^{235}U accept, first, recycled ^{235}U, and second, as much new 20% enriched uranium is needed for the deployment schedule. We assume that reenrichment of the recycled uranium, from 15.5% back up to 20%, is accomplished with insignificant ^{235}U loss; or, in other words, that the "capture" without fission of ^{235}U has been estimated conservatively enough to accommodate these losses.

If more ^{235}U comes available than is needed, it is simply returned to stockpile. Ultimately, there will be no need for any ^{235}U reactors. At this point, more Pu comes available than is needed, and it, too, is stockpiled.

Limiting Case

A limiting case can be computed as follows. Suppose we are to supply 10,000 GWe with breeders. The buildup is so rapid that we recycle no Pu by the time the build-up is completed. How much uranium is needed?

To build up this system, we have no choice but to supply each reactor with a two-years supply of 20% enriched uranium. Per GW, this is 3.2 tonnes of ^{235}U, or 15 tonnes of 20% enriched uranium per year, so that 32 tonnes of 20% enriched uranium is the required two-year supply.

At an enriched tails assay of 0.15%, it takes 1,131 tonnes of natural uranium to supply 32 tonnes of 20% product. Or, then,

10 TWe requires 11.31×10^6 tonnes of natural uranium.

We shall see that this is an upper limit. In fact, steady state recycle of this system ultimately returns out one-fifth of the ^{235}U to stockpile, so that the net requirement is under 10 million tonnes.

Steady Buildup Case

For a more realistic case, a breeder economy was built up along a trajectory. The trajectory was synthetic, but adjusted so that the buildup period was about 30 years, the system reached 10,000 GWe in year 30, was growing at the rate of about 1% at that time, and reached its maximum installation rate in the 20th year. This trajectory is compared with A.W. Perry's "Reference Trajectory" for nuclear power between 2000 and 2030, in Figure 1. The Perry trajectory is always above the breeder trajectory. The difference is a maximum around the year 2000, when 1,600 GWe of LWR may be assumed to be in operation.

Figure 2 shows the results of the calculation of ^{235}U-^{239}Pu breeder ratio. The ^{235}U breeders dominate the picture for the first fifteen years. Thereafter, most of the breeders are fueled with plutonium. A maximum of 2,600 GWe of ^{235}U breeders are reached in 2022-2023, and by 2034 none are needed.

Figure 3 shows the cumulative consumption (commitment) of ^{235}U and of natural uranium for the breeder system. The peak in commitment is reached in 2020, after which uranium is returned to stockpile until 2035.

Table 3 presents the peak uranium demand and net balance-sheet at the beginning of the year 2035 after all the material required to reach steady state has been invested and allocated.

The existence of a ^{235}U requirement which, at peak, is almost 18% higher than the net investment needed indicates that the trajectory did not make optimum use of the uranium. In an optimum trajectory, the uranium would not show a peak requirement, but rather approach an asymptotic requirement. The net value of 40, 000 tonnes of ^{235}U is a zero-order estimate of that asymptotic requirement.

Variants of Steady Buildup

To iterate, no ^{235}U was supplied after the year 2023. Up to that point, 40,540 tonnes of ^{235}U obtained from 7,166,000 tonnes were committed, and there were 7,734 GW of breeders, 2,594 GW being fueled with ^{235}U and 5,140 GW fueled with ^{239}Pu. It was allowed to grow on the fuel from its own recycling and breeding after that. It reached 10 TWe in 2035, with considerable ^{235}U (2,740 tonnes of ^{235}U) still available for return to stockpile.

As another alternative, a minor amount of coupling with Pu produced in LWR's was permitted. The target trajecotry of this paper was maintained by supplying plutonium from LWR's after 2021. By 2029, no extra plutonium was required and the system had 3,990 tonnes of ^{235}U to return. The total amount of plutonium could be replaced by 6,584 tonnes of ^{235}U in LWR's.

Table 4 gives the balance sheet of these alternative schemes.

One final computation must be recorded. The difference between the sample trajectory of this paper and the reference trajectory of Perry, noted in Figure 1, is assumed to be filled with LWR's, operating on total recycle. A crude estimate of the required LWR energy is 50,000 GWe-years of operation. On total recycle, each GWe-year consumes about 83 tonnes of natural uranium; so the 50,000 GWe-years of LWR consume about 4.15×10^6 tonnes of natural uranium. This is to be contrasted with the breeders, which produced 140,000 GWe-years of electricity during the buildup period at an <u>investment</u> of $6\text{-}8 \times 10^6$ tonnes of natural uranium.

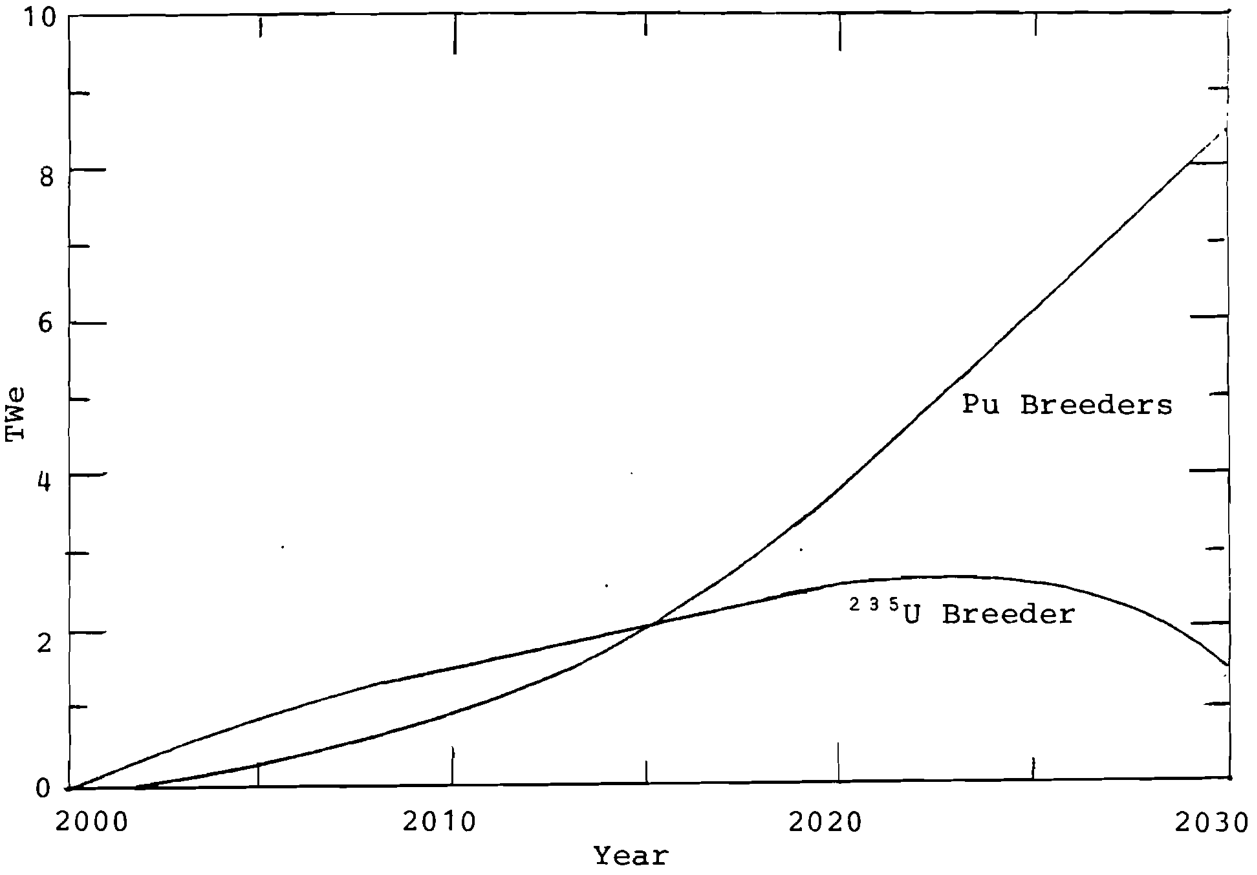

Figure 2. Breeder trajectories, by fuel type

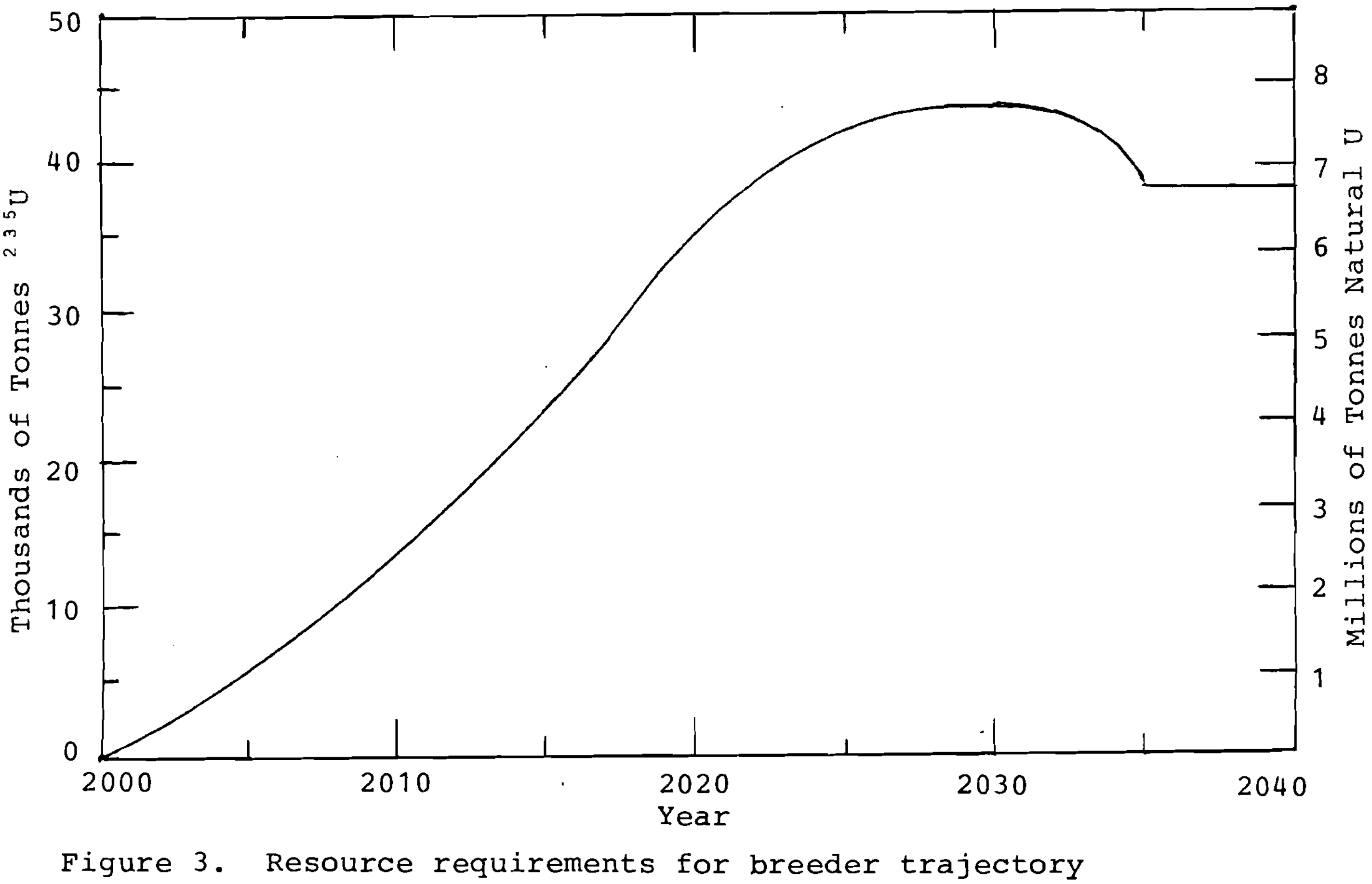

Figure 3. Resource requirements for breeder trajectory

Table 3. Resource investment and distribution in a 10 TWe breeder economy.

Total ^{235}U requirement	47,505 to	(peak, 2029)
	40,345 to	(net, 2035)
Natural uranium invested*	8,400,000 to	(peak, 2029)
	7,130,000 to	(net, 2035)

*@ 0.15% enrichment-plant tails assay

Table 4. Resource investments in alternative routes to a 10 TWe breeder economy.

<u>(a) Delayed approach</u>			
Breeders in 2030	8,777 GWe		
2035	10,360 GWe		
Resource investment, ^{235}U	40,540 to	^{235}U	(Gross)
	37,800 to	^{235}U	(Net)
Resource investment, natural uranium*	7,166,000 to		(Gross)
	6,682,000 to		(Net)
<u>(b) Late Pu investment from LWR's</u>			
^{235}U investment	36,534 to		(Gross)
	32,540 to		(Net)
Pu investment	7,242 to		
Equivalent LWR ^{235}U	6,584 to		
Total equivalent ^{235}U investment	43,120 to		(Gross)
	39,025 to		(Net)
Natural uranium investment*	7,572,000 to		(Gross)
	6,853,000 to		(Net)

*@ 0.15% enrichment-plant tails assay.

Taking the results of Table 4 as semiquantitative, we can then estimate that 6.65-7.65 million tonnes of natural uranium are needed to establish an all breeder economy, if we concentrate all construction efforts on breeders after 2000. The breakdown of total uranium requirements, including the uranium for LWR's, is given in Table 5. The amount needed is 11-12 million tonnes.

Table 5. Resource investment and energy generated in alternative routes to a 10 TWe breeder economy.

Natural uranium, LWR's, 1970-2030	4,150,000 to
Natural uranium, FBR's, 2000-2030	6,650,000-7,650,000 to
Total	10,800,000-11,800,000 to
Energy, LWR's	50,000 GWe-years
FBR's	140,000 GWe-years

Comments on All-Breeder Strategies

One could run endless cases in which trajectories and system parameters were varied, and cases with quite low uranium resource requirements could undoubtedly be identified. From what has been exhibited so far, however, we can infer that early, but orderly buildup of breeders makes great progress in conserving uranium. Further, we have always been aware that very great strides in uranium conservation are available by investing plutonium in breeders--and the sooner, the better. Finally, the time over which the breeder buildup occurs can be important: if the buildup period is forced to be short relative to the doubling time of the breeders, then not enough opportunity is taken of the ability of a breeder system to manufacture the fuel supply for its own expansion.

A MULTIPURPOSE STRATEGY

Breeders are not an end unto themselves. They are a vital component of any nuclear strategy, since they make it possible to build up an energy supply system which, after the required investment of uranium, can endure for an extremely long time with only trivial resource requirements. They also produce their energy at high enough temperatures to be efficient converters of heat to final energy forms, such as electricity, hydrogen, or other chemicals. However, they are currently more capital-intensive than other reactor types, and their economy is more dependent on economies of scale than is the case with--say--LWR's. Further, HTR's promise even higher thermal conversion efficiencies than breeders. The upshot of these considerations is that a nuclear scenario must contemplate a variety of reactor types operating simultaneously.

There is no way of projecting reliably what the mix might be. It clearly must include enough breeders so that no inputs of uranium are required once the system equilibriates. It should also include HTR's, because of their potential for being useful in chemical processes, their relatively high conversion when operated on a ^{233}U-Th cycle, and their greater likelihood of being acceptable at sites chosen for convenience of application. It could include LWR's, which seem now to be developable as dispersed community or district energy sources; LWR's will probably always have the lowest capital costs of any nuclear system, and are the best known reactors. Finally, it could include "pure burners": reactors which have essentially no fuel conversion at all, for which the extra design freedom thereby allowed makes it easier to provide reliable energy sources for shipboard, undersea, space and other specialized applications.

Such a mix is explored in what follows. Reactor characteristics for each type are given in Table 6. The breeder properties are slightly different from those presented in Table 2; the difference is a higher fuel burnup, and this is considered to be more realistic. The enrichment plant tails assay has been dropped to 0.1% ^{235}U, so as to make the results comparable to the best case of Nakicenovic and Perry.

The reactor mix chosen as a target by 2030 was: 5% pure burners, 10% LWR's, 50% HTR's, 35% breeders. This mix has been adjusted so that it breeds very slightly when the HTR's and LWR's are fueled with ^{233}U. The overall system breeding gain under these conditions is 1.009, using beginning-of-life conversion for each sector. It was hoped that the ^{235}U in the tails uranium used to dilute ^{233}U-fueled LWR's would give a "free bonus" to the system to compensate for losses of conversion and breeding under average burnup conditions, and this seemed to be the case. However, the exact balance is only significant after a very long time, and requires only adjustments between breeders and HTR's.

Figure 4 shows the arbitrarily chosen trajectories of reactor buildups which were used. These trajectories are all rather relaxed, except for the HTGR. Maximum LWR installation rate is 40 GWe/yr between 1988 and 1991, a number which is well within the capability of the existing supply industry, although many consider it an unlikely eventuality. FBR installation rate peaks at 190 GWe/yr in 2019, a number which is considered achievable if nuclear power has been accepted and standardized by 2000. HTGR's, however, would require stimulation in order to achieve 400 GWe by 2000 and a peak installation rate of 200 GWe/yr by 2011.

Figure 4 also shows the uranium investment curve for this mix. It appeared to have leveled off by 2035, and the curve thereafter is just sketched in. However, as noted, there is a possibility that there is a continued, very small, annual requirement for uranium, which was lost in the roundoff of the data. Of the 12.5 million tonnes of uranium required to achieve this approximate steady state, approximately 1,000,000 were required by the burners, 4,000,000 by the LWR's, 6,000,000 by the HTR's,

Table 6. Characteristics of reactors in the multipurpose strategy.*

A. Fast Breeder Reactor

Core loading: 16 tonnes heavy metal
Core concentration: 16 w/o ^{235}Pu or 20 w/o ^{235}U
^{238}U fission fraction: 10%
Heat to electricity, conversion efficiency: 0.4
Thermal power: 2500 MW
Capacity factor: 0.7
Time in core: 1 1/2 years
Time cut of core: 1 year
Average burnup: 6.3% of core heavy metal at discharge
$\alpha^{25} = \alpha^{49} = 0.2$
BR, net: 1.25 with ^{239}Pu fuel, 0.95 with ^{235}U fuel

Cycle Properties--material recovered 2 1/2 years after loading:

- For ^{239}Pu fuel, 1.10664 kg of ^{239}Pu or ^{233}U/kg of ^{239}Pu loaded
- For ^{235}U fuel, 0.6598 kg of ^{235}U + 0.32319 kg of ^{239}Pu/kg of ^{235}U loaded

  1.40757 to ^{235}U + 0.68947 to ^{239}Pu/GWe fueled

B. High Temperature Reactor

Core loading: 3.6 tonnes ^{233}U or 40 tonnes ^{235}U
Burnup, fissions per initial fissile atom: 1.0 for ^{233}U cores
0.9 for ^{235}U cores
Heat-to-electricity, conversion efficiency: 0.4
Thermal power: 2500 MW
Capacity factor: 0.7
Time in core: 5.36 years
Time out of core: 2.14 years
$\alpha^{25} = 0.18$
$\alpha^{23} = 0.09$
Cr, net: 0.9 with ^{233}U fuel, 0.68 with ^{235}U fuel
Annual reloads/GWe: 0.7463 to ^{235}U or 0.6716 to ^{233}U

Cycle Properties--material recovered 7 1/2 years after loading:

- For ^{233}U fuel, 3.208 kg ^{233}U/kg ^{233}U loaded

  0.5985 to ^{233}U/GWe fueled
- For ^{235}U fuel, 0.469 kg ^{235}U + 0.312 kg ^{233}U/kg ^{235}U loaded

  0.3507 to ^{23} + 0.2328 to ^{233}U/GWe fueled

Table 6. Characteristics of reactors in the multipurpose strategy (cont'd)

C. Light Water Reactor

Core loading: 110 tonnes heavy metal/GWe
Core enrichment: 3 w/o ^{235}U
Heat-to-electricity conversion efficiency: 0.31
Capacity factor: 0.45
Natural uranium for core inventory: 522 tonnes
Burnup: 3% of heavy metal
Time in core: 5.97 years
Time out of core: 1.53 years
$\alpha^{25} = 0.2$; $\alpha^{23} = 0.09$
CR (net): 0.5 (^{235}U cycle), 0.8 (^{233}U cycle)
Feed requirements: 18.42 to 3% material, from 87.38 to natural U, per GWe-year; <u>or</u> 0.5342 to ^{233}U, blended with tails uranium, per GWe-year

Cycle Properties--material recovered 7 1/2 years after loading

- For ^{235}U fuel, 18.42 to natural U + 0.1476 to ^{239}Pu/GWe fueled
- For ^{233}U fuel, 0.2445 kg ^{233}U + 0.3158 kg ^{239}Pu/kg ^{233}U loaded

D. Pure Burners

Core loading: 5 tonnes fissile/GWe
Capacity factor: 0.333
Burnup: 40% of fissile atoms
Heat-to-electricity conversion efficiency: 0.31
Total cycle time (in and out of core): 6.5 years
Annual feed: 1.031 tonnes fissile/GWe
Recovered after 6.5 years: 0.536 tonnes fissile/GWe

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*Wherever the unit GWe is used, it is a unit of capacity. For electrical energy generation in GWa, multiply by capacity factor.

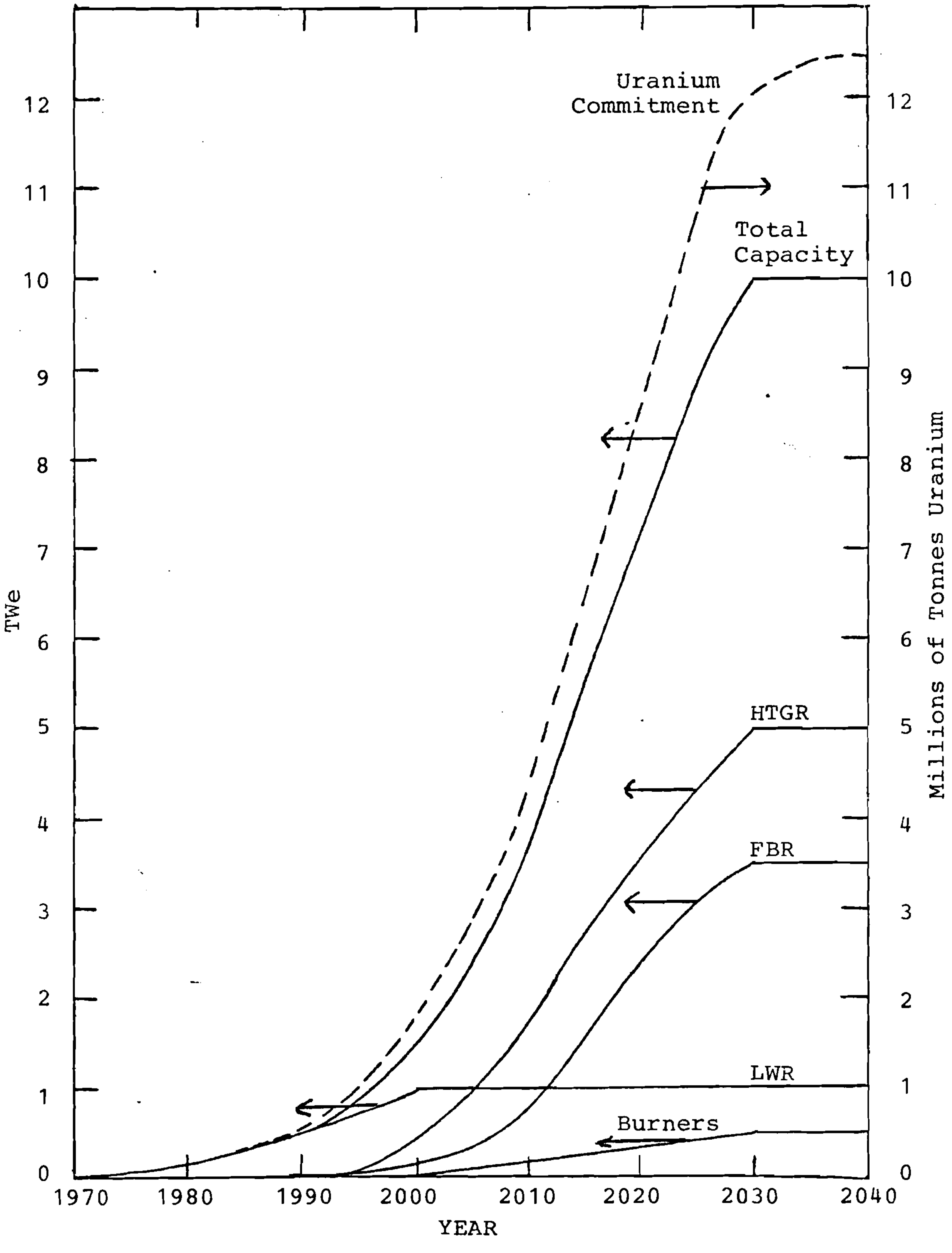

Figure 4. Multipurpose strategy

and 1,500,000 by the breeders. However, this is not fair to the LWR's in particular, as they were assumed to operate in a uranium-recycle mode, feeding plutonium to the breeders; perhaps as much as 1,500,000 tones of uranium for the LWR's could have been saved by Pu recycle, and this quantity should therefore be charged against the breeder account.

Indeed, the mode of fueling was complex. The burners and LWR's were fueled with (highly for burners, slightly for LWR's) enriched uranium until 2026. The LWR-produced plutomium was fed to the breeders. The breeders were fueled with this plutonium until 2005, by which time the construction rate of breeders outstripped available plutonium, and some breeders fueled with enriched ^{235}U became necessary. Plutonium supply began catching up with demand by 2021, and from there to 2028 it replaced the ^{235}U that existed in the breeder cycle. This ^{235}U, as it became available, was fed back to the burners, with a small quantity also going to LWR's. After 2028, the breeders became entirely self-supporting on plutonium, and became net ^{233}U producers. Meanwhile, the HTR's were being fueled with enriched uranium and their own recycled ^{233}U. Only in 2028, did the supply of ^{233}U start also coming from the breeders. At this point, there was more ^{233}U than the HTR's needed, and some of the ^{235}U in the HTR system began to move into LWR's. The system was followed in detail only out to 2033, at which point it appeared to be a net producer, but had not yet reached steady state.

Lessons from the Multipurpose Strategy

The multipurpose strategy ends up about where the Nakicenovic-Perry converter-breeder strategy does: 35% breeders vs. 40% breeders in their case. It seems to require less commitment of uranium: 12.5 million tonnes vs. 15 million in their case. It also accommodates some reactors which are not fuel-efficient: the LWR's, and particularly, the pure burners. How can this be?

The answer seems to be twofold. First of all, the LWR's and burners were assumed to run at low capacity factors; there is less of them than the gigawatts of capacity show. But more important, as compared with the Perry-Nakicenovic converter-breeder strategy, the less fuel-efficient reactors are introduced later, and fewer of them are deployed. The concentration on building fuel-efficient reactors--HTR's and FBR's--early seems to have paid off.

CONCLUSIONS

A number of different reactor strategies for a buildup to 10 TWe have been examined. They illustrate principles which are generally known, but have not been explored very thoroughly before. These are:

- Other things being equal, it always pays to build breeders rather than other reactors, if the criterion is to minimize uranium usage.

- The better a breeder system's period of rapid growth is matched to its doubling time, the less uranium is needed.
- Advanced converters, of high conversion ratio, permit a synergistic breeder-converter system that requires no external fuel (fissile material) once steady state is reached; the better the converter, the smaller the fraction of breeders that are needed.
- However, advanced converters do not much affect the amount of uranium needed to achieve steady state unless they are built up relatively early.
- Otherwise, the alternative system, such as LWR's of present fuel design, consume a very considerable amount of uranium before they are superseded.

A multipurpose reactor strategy, based on early buildup of breeders and high-conversion HTR's, limited buildup of LWR's, and delayed buildup of an appreciable quantity of pure burner reactors, shows savings in uranium requirements over a strategy which begins with a high LWR deployment. If the world's supplies of uranium turn out to be limited, early deployment of LWR's will have been detrimental to the further development of the nuclear option. While improvement of LWR fuel cycles is likely, and would mitigate this disadvantage, early development and deployment of both advanced converters and breeders would be still better. And, if one must plan for the contingency that converters will be preferred over breeders in a number of settings, then the early development and deployment of advanced converters becomes even more desirable.

REFERENCES

Nakicenovic, N. and A.M. Perry (1978) Installed capacity. Nuclear strategies with limited natural uranium requirement. Draft paper (unpublished), IIASA Energy Project.